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Final technical report of the Palaeovalley Groundwater Project for the Gawler–Eucla demonstration site

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Executive summary

Field operations for the *Palaeovalley Groundwater Project* in South Australia focused on the geological provinces of the western Gawler Craton and the eastern Eucla Basin. The Gawler–Eucla demonstration site covers an arid and sparsely populated area of approximately 215,000 km^2 in central South Australia. The region has minimal infrastructure and is predominantly covered by extensive plains and dunes of Quaternary sand which largely obscures the Archean to Proterozoic bedrock terranes. Despite the harsh and isolated environment this region has excellent potential for future mineral resource discoveries, with existing major mines (such as the Challenger gold mine and Jacinth-Ambrosia mineral sands mine) and significant exploration activities. An improved understanding of the regional groundwater resources and the characteristics of one of the main aquifer systems (palaeovalleys) is critical to future resource development.

The Geological Survey of South Australia (GSSA) conducted previous investigations (Hou, 2004, Hou et al., 2001, Hou et al., 2007) delineating major Cenozoic palaeovalley systems in the Gawler–Eucla region, including the Kingoonya, Anthony, Garford and Tallaringa palaeovalleys. Detailed stratigraphic studies based on multiple drilling transects confirmed that these palaeovalleys are predominantly infilled with fluvial-derived sediments (gravels, sands, silts and clays) in the upper and middle reaches. Estuarine and shallow marine sequences are common in the lower palaeovalley reaches near the palaeo-shoreline of the Eucla Basin (the position of which varied throughout the Cenozoic due to multiple episodes of marine transgression and regression). Sedimentary sequences were deposited during several distinct periods, with the main stratigraphic units being the Middle to Late Eocene Pidinga Formation and the Miocene Garford Formation. Sediments of the Pidinga Formation commonly form the basal infill sequence of many palaeovalleys in the Gawler–Eucla region, including gravel- and sand-bearing layers that may form significant aquifers.

The GSSA research program in the Gawler–Eucla region generated significant new insights into the location, depth, structure and stratigraphy of many palaeovalleys, especially the Garford and Kingoonya systems. Key outcomes were improved mapping of the palaeovalley boundaries, detailed understanding about the complexity and heterogeneity of the infill sediment sequences and identification of key stages in landscape evolution and palaeovalley development. However, no work had been undertaken to better understand groundwater characteristics of the palaeovalley aquifers, and fundamental water quality parameters were not assessed or collated for the Gawler–Eucla palaeovalleys. To address this lack of important groundwater data a comprehensive program of baseline hydrochemical analyses became the main focus of the Gawler–Eucla demonstration site. Following initial assessment of the available data and logistical considerations for groundwater sampling in the region, the **Kingoonya Palaeovalley** was selected.

Work program objectives

Following the regional assessment and selection of the Kingoonya Palaeovalley, the main objectives of the fieldwork program were to:

1. Characterise the hydrogeochemical composition of groundwater in the Kingoonya Palaeovalley, including standard physical and chemical parameters such as pH, Eh and temperature, major and minor (trace) ionic species, stable isotopes (oxygen and deuterium), and radiogenic isotopes (carbon-14 and radon-222);
2. Evaluate the spatial distribution and variability of hydrogeochemical data from the palaeovalley, relating observed patterns or trends in the data to the basement rocks or palaeovalley sediments;
3. Determine the dominant physical and chemical processes that affect the groundwater system in the palaeovalley, including the likely source of dissolved ions;
4. Compare new analyses with information available from major regional palaeovalley groundwater users, the Challenger gold mine and Ambrosia-Jacinth mineral sands mine; and
5. Interpret the evolution and development of the Kingoonya Palaeovalley aquifer, including radiocarbon dating of groundwater, and provide recommendations about the viability and sustainability of the overall groundwater resource.

About 60 of the existing bores (as listed in the South Australian Resources Information Geoserver; SARIG) within or near the known confines of the Kingoonya Palaeovalley were likely to be suitable for collecting groundwater samples. Detailed analysis of existing regional geoscientific, hydrological and remotely sensed datasets using Geographic Information Systems (GIS) was completed to identify these potential sample sites. Fieldwork was completed over the course of two 10-day fieldtrips in July and November 2010. The Geoscience Australia project team was assisted in the field by experienced staff from the GSSA, who provided pumps and sampling equipment. Difficulties involved in locating or sampling many bores, limited the final collection to 27 new groundwater samples. Standard sampling protocols were followed during field operations to collect the groundwater samples (Sundaram et al., 2009).

Hydrogeochemistry of the Kingoonya Palaeovalley

Groundwater from the Kingoonya Palaeovalley aquifer were analysed for ionic and isotopic compositions at various laboratories. Results show:

1. Highly elevated levels of electrical conductivity (EC) and total dissolved solids (TDS), with many of comparable salinity to seawater or hypersaline brines. Spatial analysis shows several distinct clusters of high salinity groundwater in both the upper reaches of the palaeovalley system (associated with nearby salt lakes) and in parts of the lower reaches.
2. Near-neutral, slightly acidic pH, with generally low alkalinity. Rare anomalous samples may be highly acidic (pH<4), probably due to dissolution of pyrite in lignite layers.
3. Predominantly oxidising groundwater, although the oxidation state ranges to slightly reducing and anoxic conditions (negative Eh).
4. Dominated by Na as the major cation species, commonly at concentrations Na > (Ca+Mg+K).
5. Cl is the main anion species, with sulfate the next most common anion, although with considerable variability due to its sporadic addition from inferred localised water–rock reactions. Other anions are mostly at very low levels and relatively unimportant (at the regional scale).
6. Using the hydrogeochemical facies concept, ~⅔ of the entire Kingoonya samples belong to the Na-Cl facies. Minor facies are broadly similar and include Na-Ca-Cl and Na-Mg-Cl,

indicating that some groundwater may be sourced from hydraulically connected aquifers such as adjacent fractured rock systems.

7. Trace metal enrichment is not common, although localised exceptions occur due to interaction of groundwater and the heterogeneous sediment package of the palaeovalley infill, or from bedrock-derived groundwater.
8. Oxygen and deuterium isotopes define a distinct evaporative trend away from the local meteoric water line (LMWL) and indicate multiple stages of evaporative cycling and relative enrichment of isotopic signatures from precipitation originally derived from nearby marine waters.
9. Sulfur isotope signatures are typically depleted relative to seawater, suggesting oxidation of reduced inorganic sulfur-bearing species contributes significantly to the overall sulfate load.
10. Moderately to slightly depleted ^{13}C isotope data form a fairly well constrained group that reflects buffering by dissolution of calcite in the aquifer.
11. Bi-modal radiocarbon distribution indicating some component of 'very old' groundwaters (>20,000 years old) from the deeper confined palaeovalley thalweg aquifer, and 'modern' recharge groundwater.
12. Generally low levels of radon-222.

Conceptual model of the Kingoonya Palaeovalley aquifer

The Kingoonya Palaeovalley system investigation yielded significant new hydrogeochemical data which can be used to interpret the origin and evolution of the groundwater system. They establish hydrogeochemical baseline conditions for the palaeovalley aquifer and provide evidence of the key groundwater processes in the Gawler–Eucla region (a key objective of this study). The interpretation of these data has led to a new hydrogeological conceptual model that illustrates salient features of the regional groundwater system and explains the dominant hydrologic processes.

Key aspects of the conceptual Kingoonya Palaeovalley conceptual hydrogeological model are:

1. The palaeovalley was incised into fractured and weathered Archean and Proterozoic basement rocks (Gawler Craton) during multiple stages of episodic fluvial activity, mainly in the Eocene and Miocene. Existing geological structures such as major faults played a significant role in the development of the valley morphology. During its evolution as a surface water system the climate was significantly different than today, being a temperate environment that received relatively high rainfall and had lower evaporation rates compared to present-day aridity.
2. Episodic sedimentation built up a varied Cenozoic sequence of fluvial sediments in the upper and middle reaches of the palaeovalley with estuarine systems prevailing further downstream proximal to the ancient Eucla Sea margins (Hou, 2004). A stacked succession of alluvial sedimentary facies up to several hundred metres thick formed in the incised valley.
3. Although the palaeovalley infill sequence is dominated by massive layers of fine-grained silt and clay, thinner horizons of relatively coarse-grained sand and gravel were deposited, especially as basal layers in the main active river channel (thalweg). These zones now represent the most transmissive and porous sediments in the valley-fill sequence, and thus form the main aquifer. Basal sediments are typically saturated and mostly confined by the overlying finer-grained sediment layers.

4. The thickness and width of the main thalweg aquifer (and other sedimentary sequences) vary considerably along the length of the palaeovalley. With relatively good aquifer continuity along most of the upper and middle reaches it forms an extensive aquifer network connected with many smaller tributaries that feed into the main trunk palaeovalley.
5. The hydrochemical signature of Kingoonya groundwater systems (including the main palaeovalley aquifer, other sedimentary aquifers and nearby fractured bedrock aquifers) indicates that the ultimate source of groundwater recharge is precipitation sourced by maritime evaporation from the nearby Southern Ocean.
6. The groundwater system receives very limited input from direct and diffuse recharge, estimated at 0.5–1 mm/year. Rainfall is sporadic and of limited extent (generally an order of magnitude less than the potential annual evaporation), and hydrologic system dynamics require significant rainfall to facilitate even minor volumes of recharge, i.e., recharge is only likely to follow heavy rain events (>50-100 mm) associated with major storm activity. Consequently, the regional groundwater system is sluggish with minimal throughflow. The most hydraulically transmissive aquifers are the relatively porous basal sand and gravel (thalweg) horizons of the Kingoonya Palaeovalley, as well as major structural zones (faults and fractures) in the fractured bedrock. These may be in direct hydraulic connection within some parts of the palaeovalley.
7. Despite low levels of recharge there is clear evidence from radiocarbon dating that modern rainfall does infiltrate to some regional aquifers. However, groundwater with a 'modern' radiocarbon signature occurs more commonly within the shallow non-palaeovalley aquifers of the region, such as weathered and fractured bedrock aquifers and localised perched watertable aquifers in Quaternary sediments. Based on the radiocarbon data, the deeper groundwater systems of the palaeovalley thalweg aquifers (which may occur at depths of 100-150 m below surface) have significantly longer residence times, i.e., groundwater residence times of >20,000 years before present. This suggests that modern recharge takes many thousands of years to reach the basal palaeovalley aquifers, as the overlying sediments are predominantly silts and clays with very low vertical hydraulic conductivity. Hence, the main palaeovalley aquifer contains a significant 'fossil' groundwater component.
8. The very high salinity levels (commonly greater than seawater) and the characteristic trend of stable isotope data provide clear evidence that evaporation is the major process driving the evolution of the regional groundwater system. Stable isotope evidence indicates that multiple cycles of evaporative concentration are a common and widespread feature of the regional hydrologic cycle.
9. Precipitation and dissolution of evaporites (halite and gypsum) and calcite in the aquifer sediments are the main water-rock reactions within the aquifer and they further modify groundwater composition.
10. Common widespread chains of salt lakes along the upper and middle reaches are large zones of groundwater discharge. Downstream, where the influence of marine transgressions is evident in the sedimentary facies of the valley infill, the palaeovalley widens and branches into distributary channels where salt lakes are less common.
11. The palaeovalley aquifer is, in places, likely to be hydraulically connected to the fractured and weathered bedrock aquifers. However, the nature and extent of hydraulic connectivity between aquifers is not well understood, although horizontal flow rates are likely to be very low except in areas of direct connection between major structures (with high hydraulic conductivity) and the palaeovalley thalweg aquifer.

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Abbreviations and acronyms

ADWG	Australian Drinking Water Guidelines
AEM	Airborne Electromagnetics
AVHRR	Advanced Very High Resolution Radiometer
AWAGS	Australia Wide Airborne Geophysical Survey
CFC	Chlorofluorocarbon
CP	Conservation Park
CSIRO	Commonwealth Scientific and Industrial Research Organisation
Czk	Cenozoic calcrete
DEM	Digital Elevation Model
DMITRE	Department of Manufacturing, Innovation, Trade, Resources and Energy
EL	Exploration Licence
ETM	Enhanced Thematic Mapper
EVI	Enhanced Vegetation Index
GA	Geoscience Australia
Ga	Billions of years ago
GAB	Great Artesian Basin
GIS	Geographic Information System
GL	Gigalitre: one billion litres (equivalent to 1000 megalitres, ML)
GMWL	Global Meteoric Water Line
GRV	Gawler Range Volcanics
GSSA	Geological Survey of South Australia
kL	kilolitre: 1000 litres (cubic litre: m^3)
LMWL	Local Meteoric Water Line
Ma	Millions of years ago
ML	Megalitre: one million (1,000,000) litres
MODIS	Moderate Resolution Imaging Spectroradiometer

MrVBF	Multi-resolution Valley Bottom Flatness Index
NCGRT	National Centre for Groundwater Research and Training
NOAA	National Oceanic and Atmospheric Administration
NP	National Park
NT	Northern Territory
NTIR	Night Time Infra-Red
NWC	National Water Commission
NWI	National Water Initiative 2004
pMC	percent Modern Carbon
PSC	Project Steering Committee
Qa	Quaternary alluvium
RAB	Rotary Air Blast
RN	Registered Number (in the NT government borehole database)
SA	South Australia
SF6	Sulfurhexafluoride
SIROTEM	CSIRO Transient Electromagnetic system
SMO	Standard Mean Ocean Water
SRTM	Shuttle Radar Topographic Mission
SWL	Standing Water Level
TAG	Technical Advisory Group
TDS	Total Dissolved Solids
TMI	Total Magnetic Intensity
WA	Western Australia
WASANT	WA – SA – NT

Units

cm	centimetres
m	metres
km	kilometres
L/s	litres per second
mg/L	milligrams per litre
mS/m	milli-Siemens per metre
S/m	Siemens per metre
µS/cm	micro-Siemens per centimetre
kL	kilolitre: 1,000 litres (cubic litre: m^3)
ML	Megalitre: one million (1,000,000) litres
GL	Gigalitre: one billion litres (equivalent to 1,000 megalitres, ML)
mGal	milligals (unit of gravity measurement)
Bq/L	Becquerels per litre
mBq/L	milli-Becquerels per litre

1. Introduction

1.1. Preamble

Palaeovalley groundwater systems are an important source of water for a variety of users throughout arid and semi-arid Australia. This is especially the case in outback areas of South Australia, Western Australia and the Northern Territory which lack access to the larger groundwater reservoirs of eastern Australia, such as the Great Artesian Basin and the Murray Basin. Ancient palaeovalley networks spread across the vast interior of central, southern, and Western Australia are presently used to supply water for pastoral activities, mining operations and remote indigenous communities. Ranging from the horticultural enterprises of the Ti-Tree Basin, to the processing of gold-bearing ore at Kalgoorlie, groundwater resources from palaeovalley aquifers are vital to the economic, social and environmental well-being of regional Australia.

The complex network of palaeovalley aquifers in arid and semi-arid Australia is largely the result of different climatic conditions that have affected the continent during the Cenozoic Era. Palaeogeographic reconstructions of Australia show how the landmass has evolved throughout the Cenozoic (e.g., Langford et al., 1995), and indicate that major river systems formed an inter-connected surface drainage network across large parts of what is now a perennially dry landscape (Figure 1). During this period, temperate climates characterised by higher rainfall patterns and lower rates of evaporation established major fluvial systems across the interior cratons and sedimentary basins of Australia. Extensive river valleys developed complex alluvial stratigraphic facies, with sediment sequences 150–300 metres thick formed in many inland drainage basins.

An important modern-day legacy of the major inland river systems that flowed across much of inland Australia during the past 65 million years are complex networks of palaeovalley aquifers. Although perennial surface water no longer flows atop most arid zone palaeovalleys, their sub-surface alluvial sediments are capable of storing and transmitting significant quantities of groundwater over long timeframes, i.e., up to tens of thousands of years (Magee, 2009). In particular, basal channel sediments (representing the original active river channel or valley thalweg), commonly consisting of coarse-grained gravels and sands, have enhanced porosity and hydraulic conductivity and represent high-quality water resource targets. In some areas, such as central Australia, palaeovalley infill sediments are significantly thick (several hundred metres) and capable of storing good quality groundwater in upper parts of the hydrostratigraphic sequence, e.g., the Ti-Tree Basin.

Despite their widespread distribution and critical role as major water resources in arid and semi-arid Australia, palaeovalley aquifers and their groundwater systems generally remain poorly understood. Although major palaeovalley reaches are mapped at the state and territory scale (1:2 million) in many Australian jurisdictions (e.g., Hou et al., 2007 for South Australia; Tickell, 2008 for Northern Territory), there have been no well-coordinated or comprehensive national-scale investigations to evaluate palaeovalley groundwater systems, characteristics or processes. There is also scant documentation on preferred methodologies for mapping and delineating palaeovalleys in the Australian context, or for conducting detailed groundwater resource assessments. Consequently, with further major developments projected at many sites in arid and semi-arid Australia, particularly focused on new resource discoveries and mining operations, it is imperative that more comprehensive and up-to-date information is available on the nature of palaeovalley aquifers. This will assist the spectrum of hydrogeologists, engineers and water resource managers working on exploration and assessment of these vital groundwater systems.

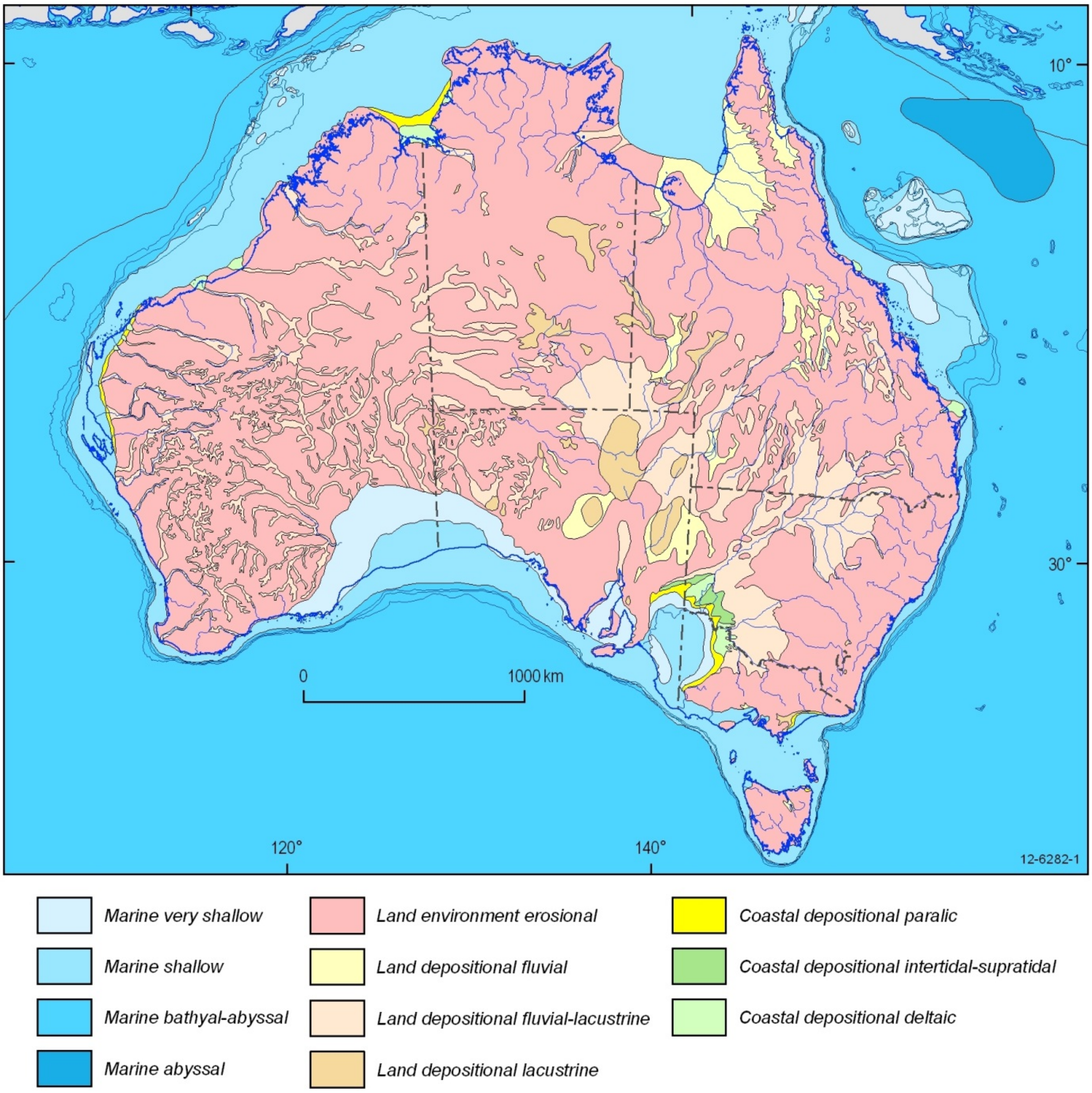


Figure 1: *Reconstruction of the Cenozoic palaeogeography of Australia during the Early Miocene, about 20 Ma (modified from Langford et al., 1995).*

1.2. The Palaeovalley Groundwater Project

This report is the summation of the main activities, findings, achievements and recommendations of the work program conducted in the Gawler–Eucla region of South Australia for 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*, this four-year investigation, supportive of the Intergovernmental Agreement on a

National Water Initiative 2004 (NWI) commenced in June 2008 and was completed in April 2012. Funding of $4.935M from the National Water Commission (NWC) was staged over eleven milestones, with in-kind contributions estimated at $10M provided by the consortium of project partners and industry stakeholders.

Arid Australia is about 48% of the continent, with a further 31% semi-arid, based on the Köppen-Geiger climate classification (Stern et al., 2008). The jurisdictions with the greatest proportion of arid environments, Western Australia (WA), South Australia (SA) and the Northern Territory (NT), were the exclusive focus of activities for the *Palaeovalley Groundwater Project* (Figure 2). Although some parts of Queensland and New South Wales are also arid or semi-arid, this project deliberately concentrated on central and western parts of Australia because of the strong reliance on palaeovalley groundwater resources. Notwithstanding, many of the key project findings are equally relevant to much of eastern Australia, as well as other arid zones of the world, such as parts of Saharan or southern Africa, and South America.

Geoscience Australia (GA) was the lead investigator and manager of the *Palaeovalley Groundwater Project*, 2008-2012. Significant project support was provided by WA, SA and the NT government water resource departments and geological surveys. Each government agency contributed expert geoscientific and hydrologic staff to the Technical Advisory Group (TAG) and Project Steering Committee (PSC). Additionally, several mining and exploration companies (e.g., Toro Energy, NuPower Resources, Uramet Minerals, Aditya Birla Minerals, Newcrest Mining and Cameco Australia), and various hydrogeological consultants associated with these companies, provided considerable support by allowing the project team to access geologic and hydrogeologic datasets relevant to palaeovalleys.

1.2.1. Objectives

The overall aim of the *Palaeovalley Groundwater Project* was to deliver an innovative and integrated national-scale approach for better understanding the capacity, quality, quantity and dynamics of groundwater systems in palaeovalley aquifers, thereby enabling improved management of these important groundwater resources. To fulfil this goal a number of specific objectives were developed, with the project seeking to:

- Fill very large gaps in the knowledge base of groundwater resources in arid and semi-arid regions;
- Appraise and improve methodologies currently used to assess groundwater resources in palaeovalleys by field and remote sensing studies at priority demonstration areas in WA, SA and the NT;
- Evaluate, in particular, the application of datasets derived from AEM, and ground-based gravity and seismic surveys with more conventional hydrogeologic techniques, hydrochemical analysis and groundwater dating methods;
- Develop a conceptual and spatial framework of key palaeovalley groundwater system ‘types’ within the range of geologic and climatic zones across arid and semi-arid Australia;
- Provide general recommendations and guidelines to assist government departments, communities and mining companies to develop improved management practices for palaeovalley groundwater systems; and

- Produce a range of user-friendly information products (e.g., reports, maps, and digital datasets) to improve the delineation of palaeovalley aquifers and definition of their groundwater resources. One of the most significant outputs is a Palaeovalley Thematic Map of the arid and semi-arid zones of WA, SA and the NT, and an accompanying GIS package of national-scale geologic and interpretative data layers for the 200 major palaeovalleys (Appendix 1).

1.2.2. Demonstration sites and outputs

Demonstration site locations in WA, SA and the NT (Figure 2) were selected following consultation with the project Technical Advisory Group (TAG):

1. Gawler Craton - Eucla Basin, SA;
2. Murchison Province, WA;
3. Paterson Province - Canning Basin, WA;
4. Ti-Tree Basin of central Australia, the NT; and
5. Wilkinkarra (Lake Mackay), with fieldwork around the remote Aboriginal communities of Kintore, Nyirripi and Papunya, the NT.

In addition, analysis of remote sensing data was undertaken for the Musgrave (WA-SA-NT) and Tanami regions (WA-NT). A comprehensive investigation program, comprising integrated office and field-based activities, addressed fundamental gaps in the national understanding of palaeovalley systems to achieve the goals of the *Palaeovalley Groundwater Project*. Site-based work programs and results for the other four regions (additional to the Gawler–Eucla) are outlined in a series of Geoscience Australia publications (http://www.ga.gov.au/cedda/publications/96).

Other published outputs include:

1. A project summary report published as part of the Waterlines series by the National Water Commission (http://archive.nwc.gov.au/library/waterlines/86);
2. The WASANT Palaeovalley Map (Appendix 1), produced by Geoscience Australia and freely available in pdf and ArcGIS shapefile format (http://www.ga.gov.au/cedda/maps/96); and
3. The Palaeovalley Investigative Toolbox, which provides information on the various methods used for delineating, assessing and characterising palaeovalley systems and their groundwater resources (Gow et al., 2012).

1.3. Focus, objectives and format of this report

This is the final report on the research program conducted for the *Palaeovalley Groundwater Project* in the Gawler–Eucla demonstration site in South Australia. This report provides a synthesis of new project work which mainly focused on improving knowledge of groundwater hydrogeochemistry within and around the Kingoonya Palaeovalley. In addition, relevant background information about the Gawler–Eucla region is also included to provide context for the new research findings. Although the *Palaeovalley Groundwater Project* began in 2008 most of the work at the Gawler–Eucla site took place in 2010–2011 due to the overall design and implementation schedule of the program.

The main objectives of this report are to:

1. Describe the key physical components of the Gawler–Eucla site, such as the climate, topography, land use and geology;
2. Introduce the principal palaeovalley systems known from the region and discuss the main features of their stratigraphic architecture and geological evolution;
3. Outline the investigative work program undertaken for the Gawler–Eucla site and present the various new datasets compiled for the project, with particular emphasis on the hydrogeochemistry of the Kingoonya Palaeovalley;
4. Analyse and interpret the hydrogeochemical data, focusing on the wider regional implications of the hydrogeological research program;
5. Outline the key conclusions and recommendations from the work program, particularly how this work has improved our understanding of the composition, origin and evolution of groundwater resources in the major SA palaeovalley systems; and
6. Provide suggestions for further research opportunities recognised from this investigation.

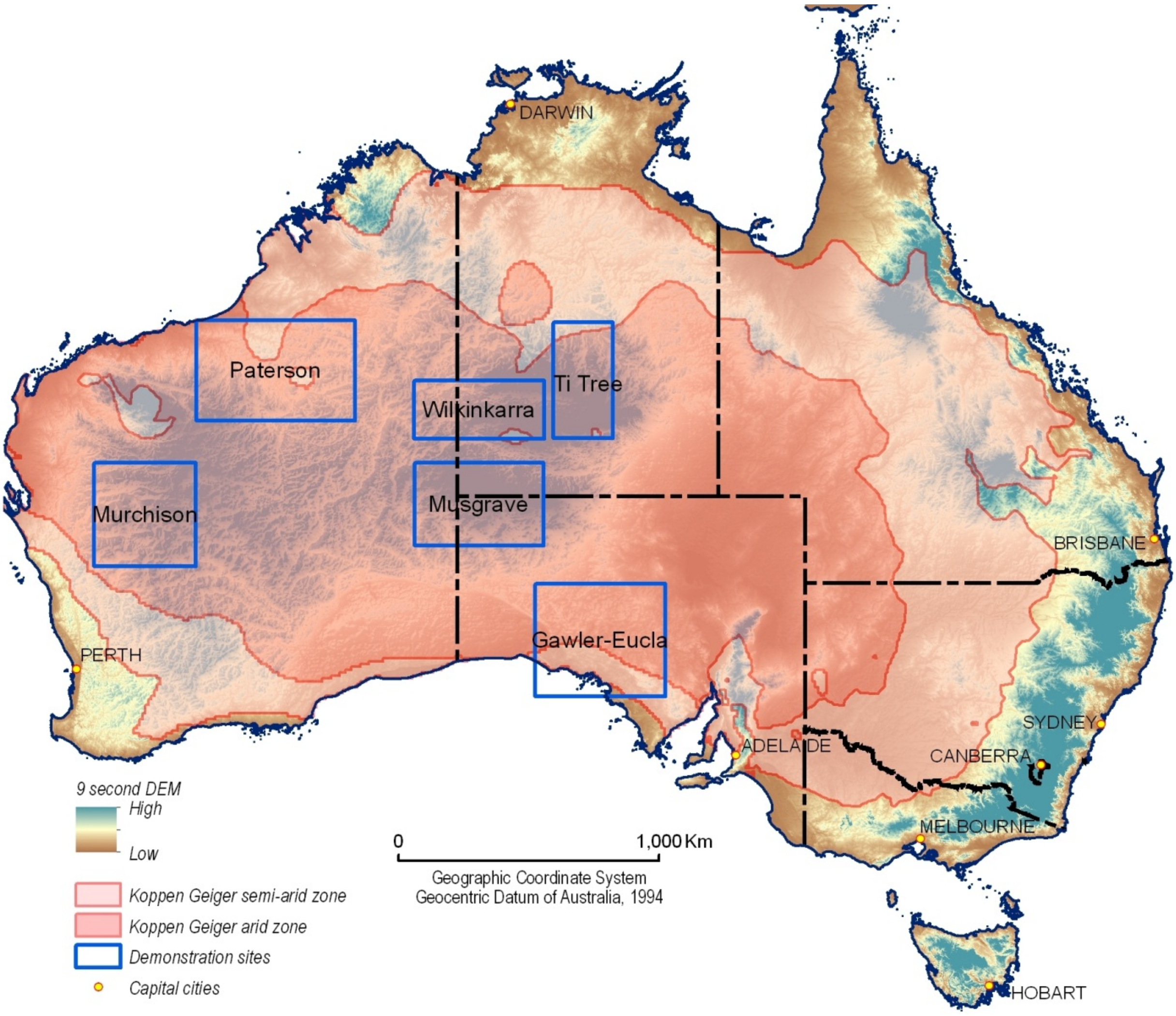


Figure 2: *Regional demonstration site locations for the Palaeovalley Groundwater Project.*

1.3.1. Report structure

Consistent with the project objectives there are seven chapters in this report. The introductory section (Chapter 1) is followed by review of the physical characteristics of the Gawler–Eucla site such as climate, topography and geology (Chapter 2). Chapter 3 focuses in more detail on the current understanding of palaeovalleys in this region and outlines previous hydrogeological studies of local palaeovalley systems, e.g., evaluation of water supply options for the Challenger gold mine and the Jacinth–Ambrosia heavy mineral sands deposit. Chapter 4 looks at several new attempts to improve or refine the existing regional palaeovalley map of the area using specialised manipulation and analysis of topographic and magnetic datasets. The key factors in developing the new research program in the Gawler–Eucla region, and specific fieldwork details and investigative methods, are described in Chapter 5. Chapter 6 outlines the laboratory techniques used, and the new hydrogeochemical data obtained for Kingoonya Palaeovalley groundwaters, presenting initial analysis and interpretation of these data. The final chapter (Chapter 7) provides further discussion of new data and integration with existing knowledge of the palaeovalley groundwater systems of the Gawler–Eucla, as well as outlining the main research conclusions and recommendations.

2. Characteristics of the Gawler–Eucla demonstration site

2.1. Introduction

The Gawler–Eucla study site covers an area of ~215,000 km^2 in central South Australia (Figure 3). This region was designated as the main South Australian study site for the *Palaeovalley Groundwater Project* following discussions at the 1st Technical Advisory Group (TAG) workshop, held in October 2008 at Glen Helen Station (Northern Territory). The TAG members endorsed the Gawler–Eucla as the priority site for new investigative work, mainly to improve the current poor understanding of palaeovalley groundwater resources.

Considerable research driven by the South Australian government had previously focused on mapping regional palaeovalley networks, as well as understanding their stratigraphic architecture, sedimentary facies, and geological evolution (Hou et al., 2001; Hou, 2004). This work was largely conducted by the Geological Survey of South Australia (in the Department of Manufacturing, Innovation, Trade, Resources and Energy, DMITRE) and focused on the significance of Cenozoic palaeovalleys in the Gawler–Eucla region for mineral exploration, such as gold and uranium deposits. Consequently, there was widespread agreement at the Glen Helen TAG workshop that the *Palaeovalley Groundwater Project* should investigate the groundwater systems of the Gawler–Eucla region, especially to address key aspects of the quality, origin and evolution of palaeovalley groundwater resources.

The boundaries of the Gawler–Eucla demonstration site were chosen to encompass several major palaeovalley systems previously investigated by Hou et al. (2007), including the Kingoonya, Garford and Anthony palaeovalleys. This region hosts two large mining operations that rely on palaeovalley groundwater resources, the Challenger gold mine and the Jacinth–Ambrosia heavy mineral sands deposit. Given its world-renowned resource prospectivity there is also good potential for future mining developments to occur in this area (Martin Fairclough, pers. comm. 2010), and these would likely require access to palaeovalley groundwater supplies for initial development as well as ongoing operations. Consequently, the Gawler–Eucla region is a suitable locality to focus new research efforts for the *Palaeovalley Groundwater Project.*

2.2. Climate

Most of the Gawler–Eucla site has an arid climate, although semi-arid conditions prevail along coastal zones and extend inland for up to100–125 km. The semi-arid climate zone is sub-parallel to the coastal strip and generally experiences slightly higher annual precipitation than inland areas. For example, the mean annual rainfall at Ceduna (coastal, semi-arid) is about 300 mm/year (Figure 4), whereas mean annual rainfall at Tarcoola (inland, arid) is approximately175 mm/year (Figure 5). Rainfall patterns are winter-dominated in the south, tending more sporadic and irregular towards the central and northern parts of the region, i.e., storm-dominated rainfall, with greatest storm frequency from February to May. Evaporation rates are very high across most of the Gawler–Eucla region, commonly >3,000 mm/year (http://www.bom.gov.au/climate/data/). Summer temperatures are commonly extreme (>30°C mean maxima), although moderated slightly near the coast (Figures 4–5).

The prevailing wind direction at Tarcoola is from the south-west (mean monthly wind-speeds vary from 9–13 km/h), whereas winds are commonly onshore from the south at Ceduna and range from 20–27 km/h (mean wind-speed).

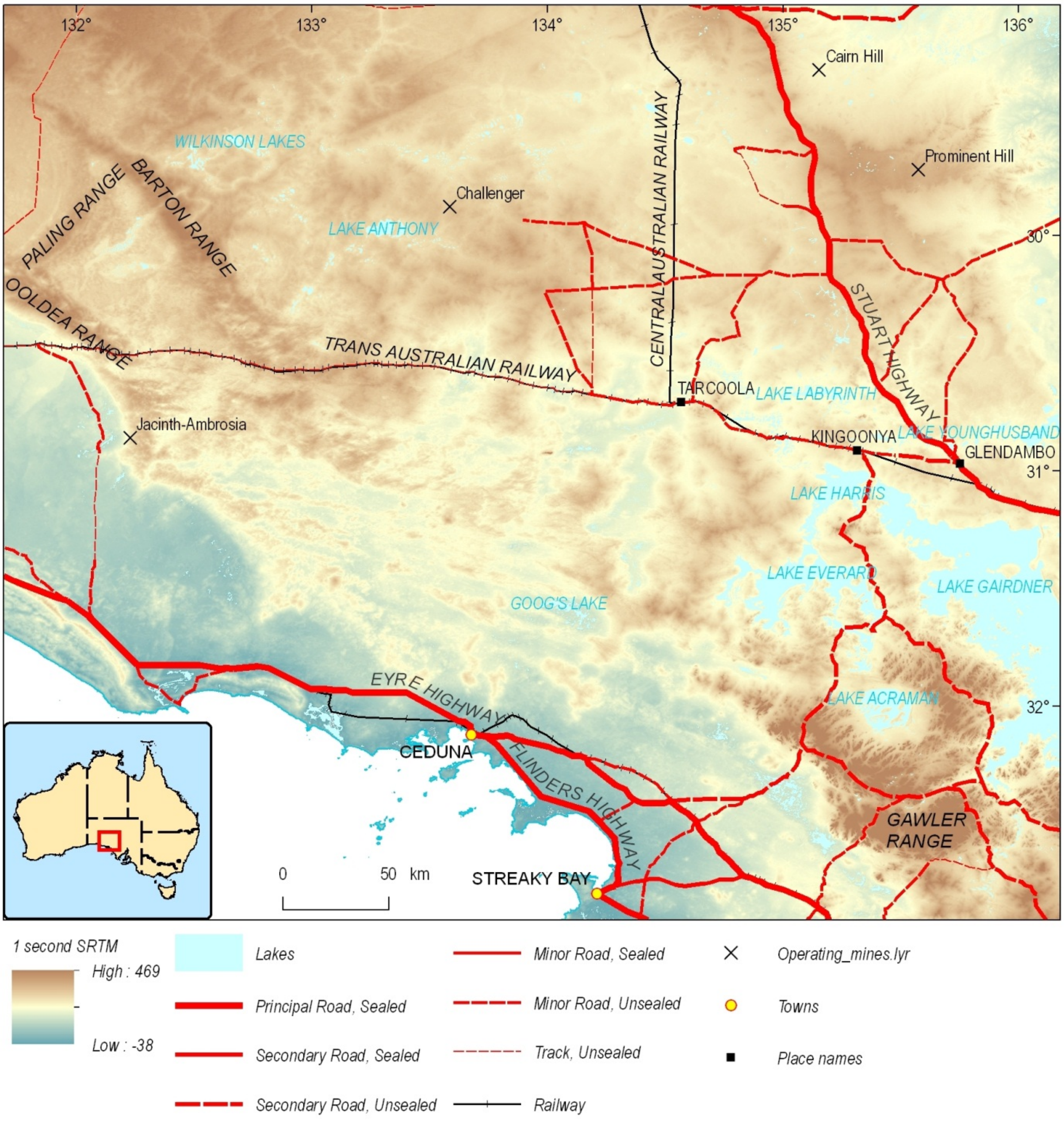


***Figure 3:** Locality map of the Gawler–Eucla demonstration site in South Australia. A shaded 1-arc second digital elevation model (DEM) based on the Shuttle Radar Topographic Mission (SRTM) dataset is used here as the backdrop to show topographic variations across the study site.*

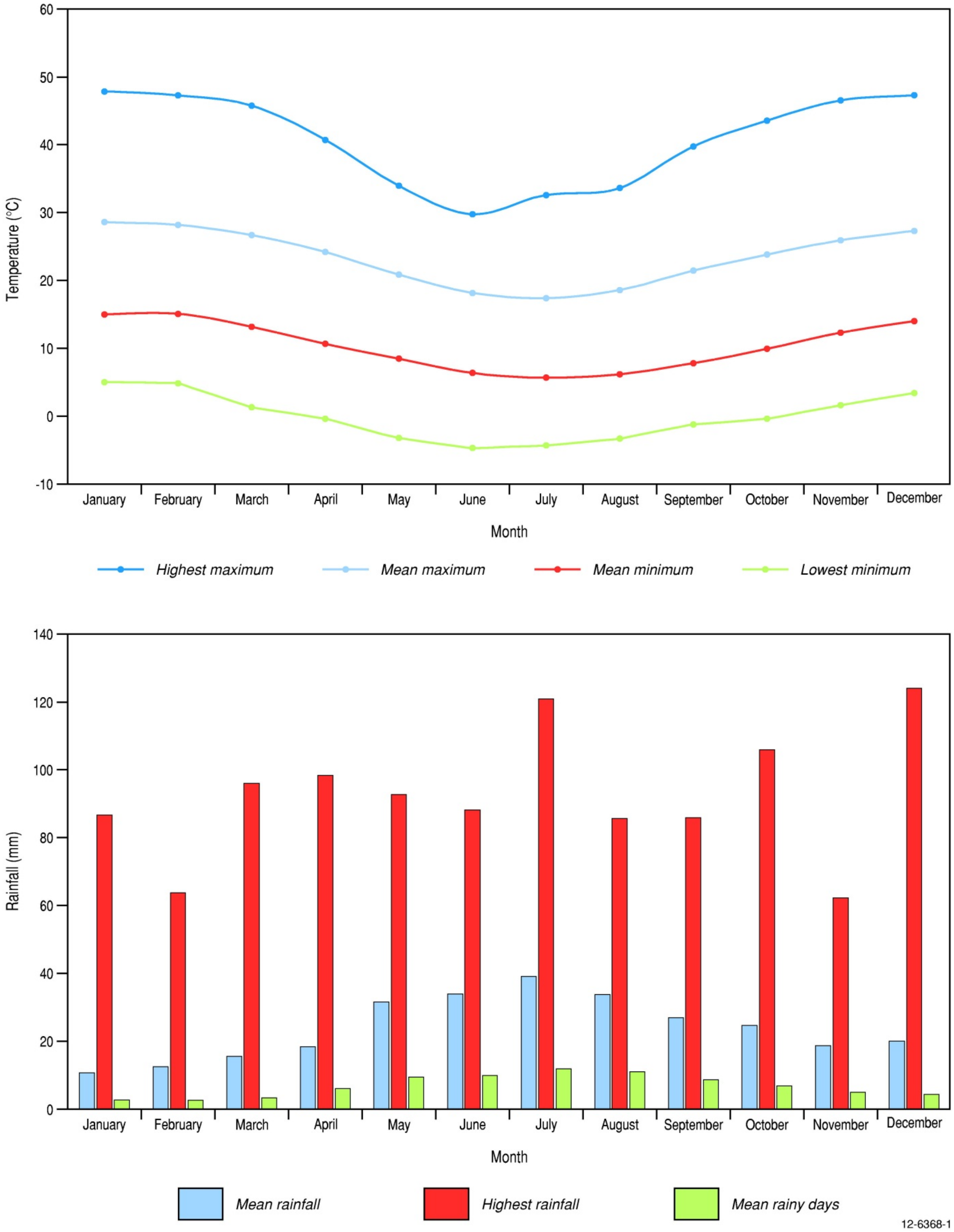


Figure 4: *Summary climate data (temperature and rainfall) for Ceduna. Data acquired from the Bureau of Meteorology for the Ceduna weather station (number 018012), 1939 to 2011.*

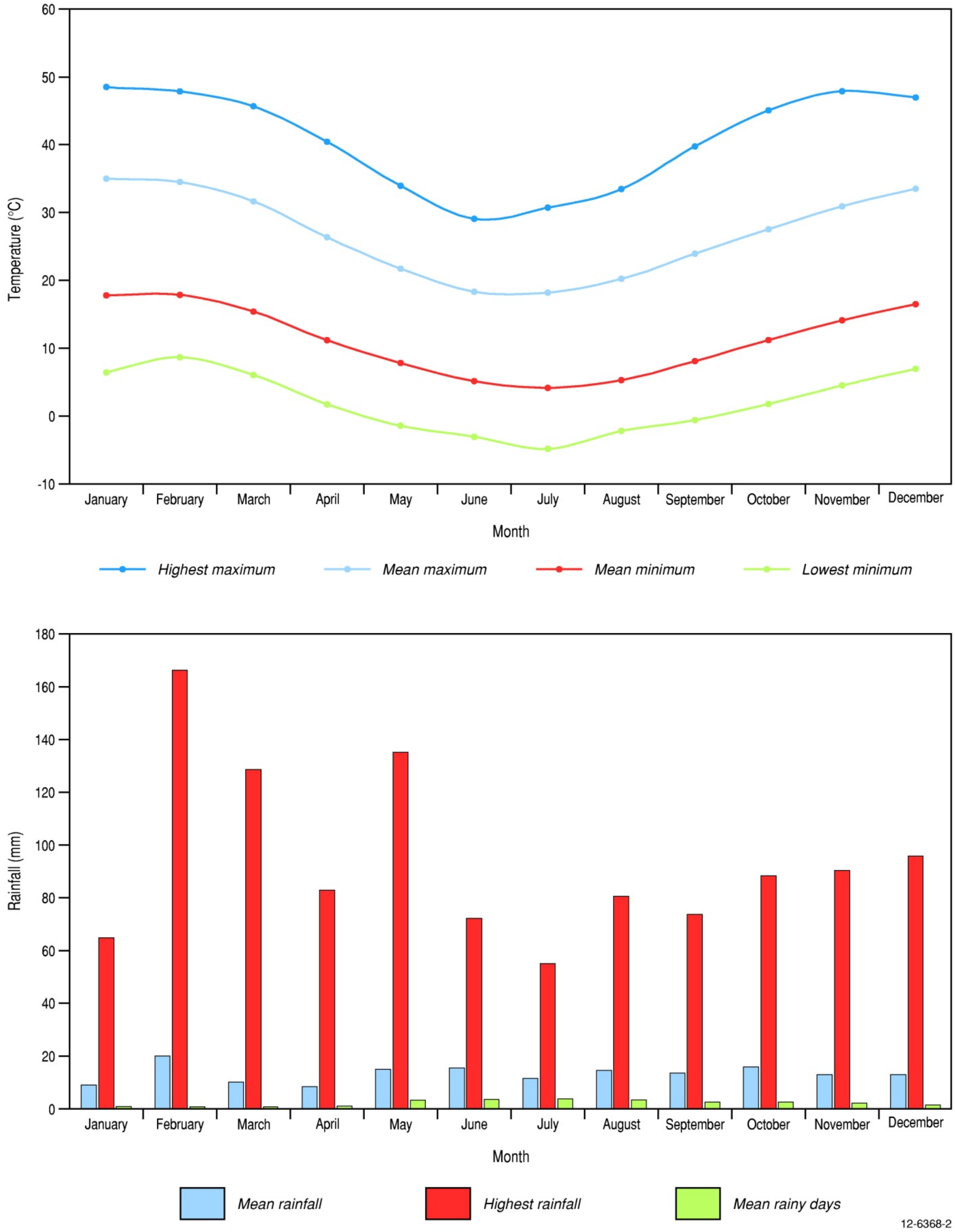


Figure 5: *Summary climate data (temperature and rainfall) for Tarcoola. Data acquired from Bureau of Meteorology for the Tarcoola weather station (016044), 1903 to 1999.*

2.3. Physiography and surface drainage

The Gawler–Eucla demonstration site occurs within the Eyre Peninsula and Sandland physiographic provinces of Australia (Pain et al., 2011). The region is characterised by extensive Quaternary sand cover with abundant dunes and ridges rising up to several metres above the plains. The widespread aeolian sediments obscure much of the regional Archean to Proterozoic bedrock and support typical low-lying arid zone vegetation such as mulga, bluebush and saltbush (Figures 6–7).

The terrain across most of the Gawler–Eucla site is relatively flat to moderately undulating. Prominent topographic highs are localised around the dissected rocky outcrops of the Gawler Ranges in the south-east, and the relict Cenozoic coastal sand barriers of the Barton, Ooldea and Paling Ranges near the eastern margin of the Eucla Basin. These elevated topographic features are clearly evident on the regional digital elevation model derived from the 1-second Shuttle Radar Topographic Mission (SRTM) dataset (Figure 3), with the Barton and Ooldea Ridges forming extensive topographic highs that extend for over several hundred kilometres. Other prominent natural landscape features include the large playas of Lake Gairdner and Lake Harris, north of the Gawler Ranges. The region also adjoins the coastline with the Great Australian Bight.

Figure 6: *Typical scenery in the Gawler–Eucla study region. Easterly view across flat terrain of the central Gawler Craton. Island Lagoon is evident in the background. Note the flat-topped mesa at the right of view (photograph courtesy of Ashraf Hanna, July 2010).*

The overall low rainfall and high evaporation rates across the region mean that there are no permanent fresh water resources of significant volume anywhere within the demonstration area. Poorly developed modern surface drainage systems are ephemeral features and most are spatially restricted to the north-east and south-east of the region. The distinctive landscape pattern evident in the north-east of the study site reflects extensive subcrop and minor outcrop of sedimentary rocks associated with the south-western margins of the Jurassic–Cretaceous Eromanga Basin, such as the Algebuckina Sandstone and the Bulldog Shale (Rogers and Zang, 2006). Mostly dry creek channels such as Millers Creek and Warriner Creek also occur in this region, draining internally towards Lake Eyre when rare flow events occur following major rains. Minor ephemeral surface drainage channels occur in some parts of the Gawler Ranges, with their orientation coinciding with the dominant bedrock structural pattern, i.e., south-west to north-east trend (Figure 3).

Figure 7: *Breakaway terrain at margins of subcropping Proterozoic rocks of the Gawler Craton, joining extensive flat sandy plain extending into the distance. The scrubby vegetation and poor soils are common to this region (photograph by John Wischusen, July 2010).*

The Enhanced Vegetation Index (EVI) time-series dataset acquired from the MODIS satellite (http://modis.gsfc.nasa.gov/) highlights several distinct zones across the study site which reflects key differences in vegetation patterns (Figure 8). In particular, the main sand-covered region shows marked contrast in EVI parameters (such as the mean, standard deviation and flatness) with the surrounding area of intensive agricultural land. Distinct variations are also evident in the MODIS image (Figure 8) between the main outcrop areas of the Gawler Range Volcanics, the Mesozoic sedimentary rocks subcropping in the Eromanga Basin, and larger salt lakes (playas) such as Lake Gairdner (Figure 3).

2.4. Land-use and tenure

The Gawler–Eucla site covers a remote and sparsely populated area of South Australia. The only major populated communities are Ceduna and Streaky Bay, both occurring along the coastal zone (Figure 3). Further inland, most of the region is uninhabited and there is minimal infrastructure. The Trans-Australian Railway Line cuts across the central part of the study site, the Flinders and Eyre Highways hug the coastal zone and part of the arterial Stuart Highway cuts across the north-east quadrant.

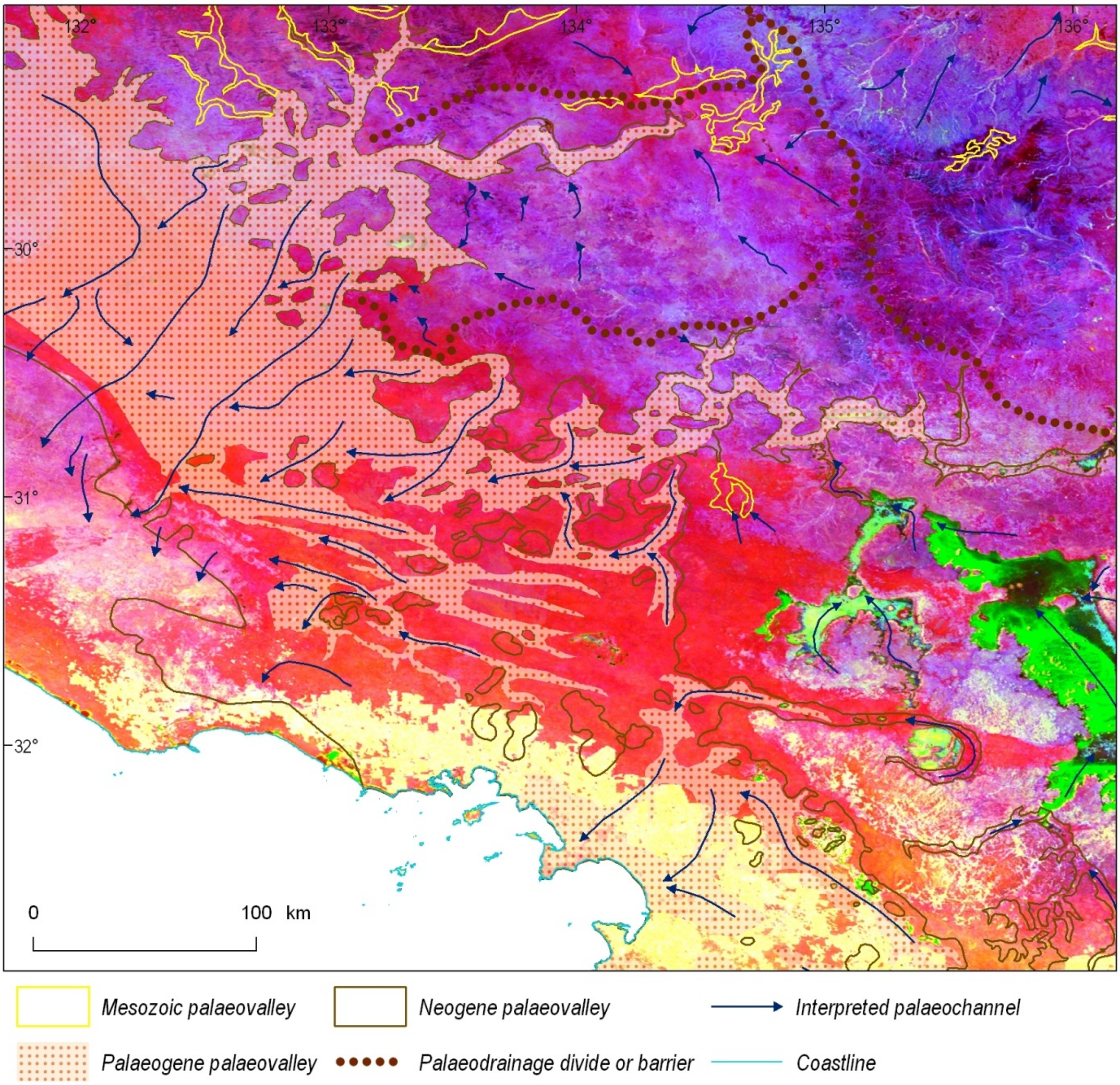


Figure 8: *EVI time-series data acquired by the MODIS satellite. In this image, red = signal mean, green = signal standard deviation, and blue = signal flatness. Several distinctive vegetation regions are defined using these data. The palaeovalley map data is derived from the work of Hou et al., 2007.*

Intensive farming (grazing and cropping) occurs along much of the narrow coastal strip, especially between Ceduna and Streaky Bay due to the slightly higher annual rainfall and more productive agricultural land (Figure 9). Larger pastoral stations running livestock are also scattered across the inland central-east of the region. Much of the remaining area is designated as:

- National Park (NP), e.g., the Lake Gairdner NP and the Gawler Ranges NP;
- Conservation Park (CP), e.g., the Yumbarra CP and the Tallaringa CP; or
- Regional Reserve (RR), e.g., the Yellabinna RR and the Nullarbor RR (Figure 9).

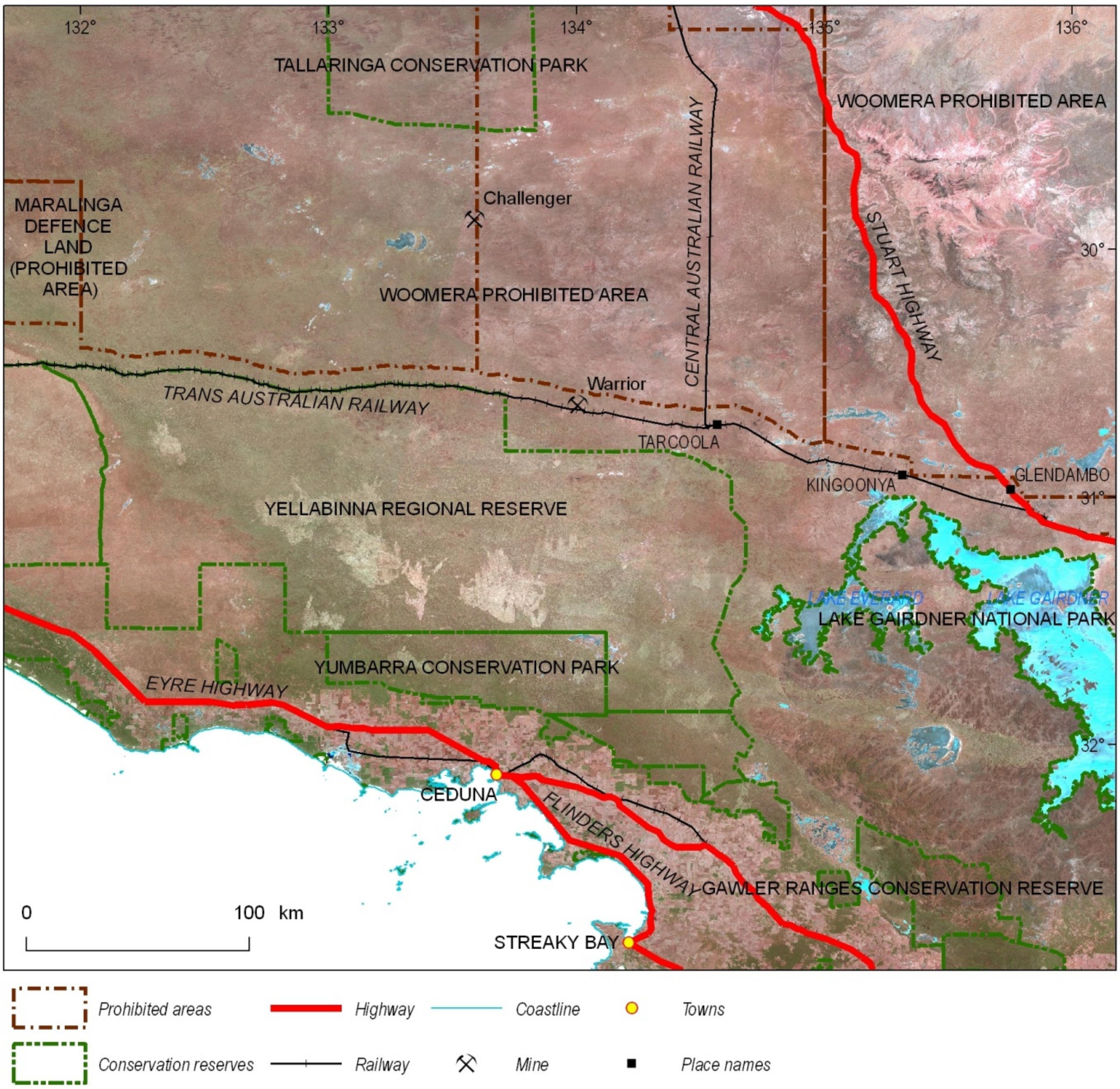


Figure 9: *Landsat Enhanced Thematic Mapper Plus (ETM+) image of the Gawler–Eucla site, derived from 2005 Australian continental mosaic. Diverse land-use types are evident across the region, including various conservation reserves and the Woomera Prohibited Area. Intensive agriculture has significantly modified the landscape in the near-coastal strip from west of Ceduna towards Streaky Bay. Prominent topographic features include the large salt lakes of Lake Gairdner and Lake Harris, and the dissected rocky outcrops of the Gawler Ranges in the south-east.*

Maralinga Tjarutja Aboriginal Lands occupy most of the western and north-western area, partly coincident with the Woomera Prohibited Area (which occurs north of the Trans-Australian Railway Line) and the former weapons testing facility at Maralinga. There are also several active mining sites, including the Challenger gold mine operated by Dominion Mining, and the Jacinth–Ambrosia mineral sands deposit owned by Iluka Resources Ltd.

2.5. Regional geology and geophysics

The major geological province of the Gawler–Eucla demonstration site is the Gawler Craton (also known as the Gawler Block, Figure 10). In the study area, most basement rocks of the Gawler Craton are obscured by a thin veneer of Cenozoic sediments and regolith, such as Quaternary dune sands, calcrete and colluvium (Figure 11). The main exception is the Gawler Range area in the south-east, where dissected outcrops of the Proterozoic Gawler Range Volcanics are common. Elsewhere, especially on the Tarcoola 1:250,000 mapsheet, there are minor basement outcrops of Archean metasedimentary rocks of the Mulgathing Complex. Across the north-east part of the demonstration site the Gawler Craton is overlain by thin sequences of Mesozoic sedimentary rocks (mostly <100 metres thick), which represent the south-western margin of the Eromanga Basin (part of the larger groundwater province of the Great Artesian Basin, GAB). In the study area the sedimentary rocks of the Eromanga Basin largely comprise of the Algebuckina Sandstone, the Cadna-owie Sandstone, and the Bulldog Shale (Rogers and Zang, 2006). At the western site margin, the Cenozoic Eucla Basin overlies the Gawler Craton boundary. Isolated parts of the Officer Basin and Stuart Shelf also occur in the study area, but are not discussed further due to their limited distribution.

2.5.1. Gawler Craton

The Gawler Craton covers about 440,000 square kilometres of central South Australia and forms an extensive geological province comprising of early Mesoarchean to Mesoproterozoic crystalline basement rocks (Fraser et al., 2010) (Figure 12). Three major orogenic events have strongly influenced the formation of the Gawler Craton:

1. Late Archean to Early Proterozoic Sleafordian Orogeny (~2,440 million years ago, Ma);
2. Palaeoproterozoic Kimban Orogeny (1,850–1,700 Ma); and
3. Mesoproterozoic Kararan Orogeny (1,670–1,540 Ma).

Since ~1,450 Ma the rocks of the Gawler Craton have remained essentially undeformed (Fairclough, 2005).

The major Archean rock units in the Gawler Craton consist of orthogneiss and paragneiss which have been variably affected by granulite facies metamorphism. The Gawler–Eucla study site occurs in the north-western Gawler Craton where the Mulgathing Complex is the main Archean rock unit. The Mulgathing Complex comprises of a variety of rock types, with banded iron formations, chert, and aluminous metasedimentary rocks being most common. Various meta-igneous rock bodies, komatiites, and basalts also occur.

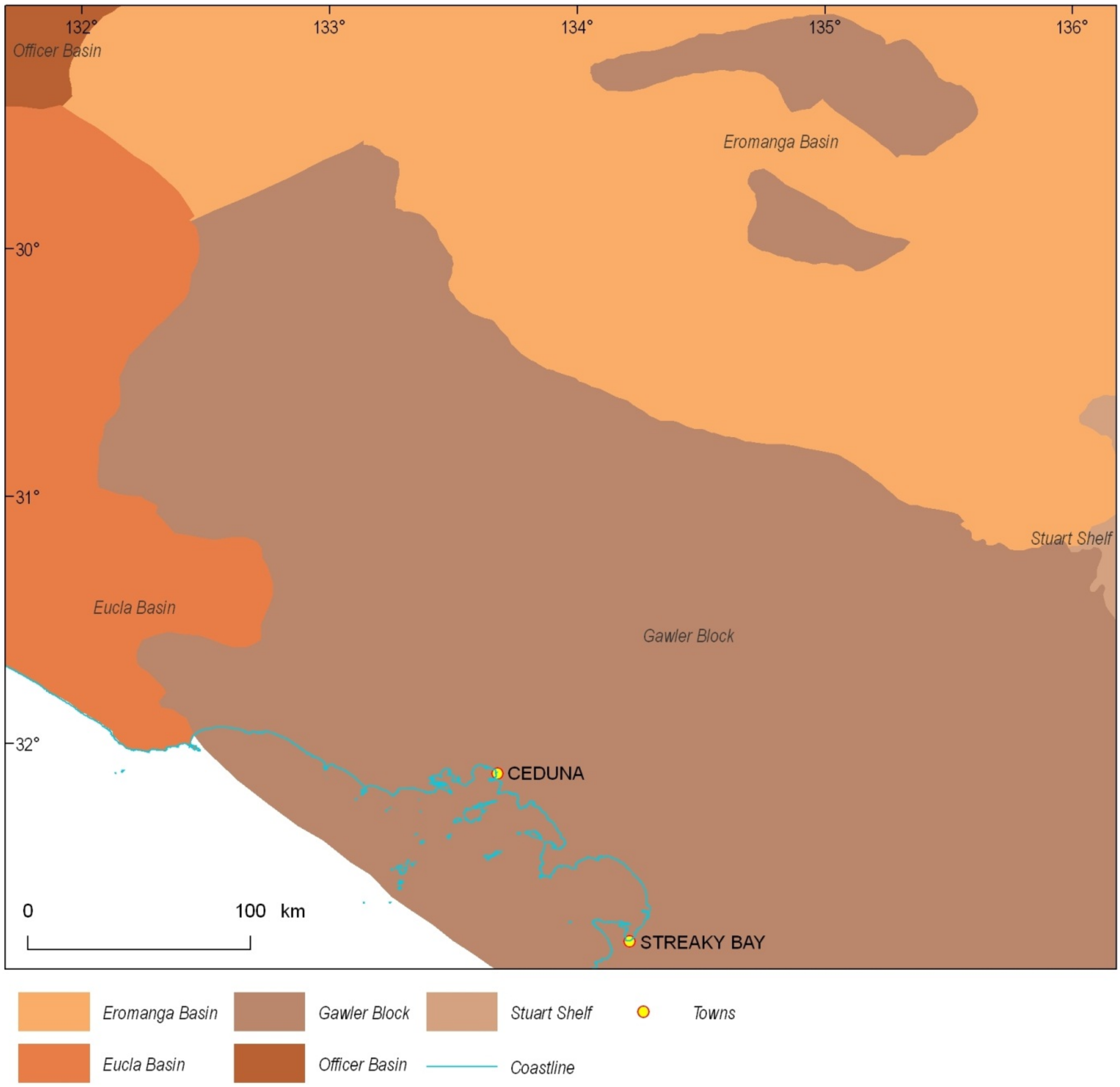


Figure 10: *Major geological provinces and sedimentary basins of the Gawler–Eucla demonstration site.*

Palaeoproterozoic and Mesoproterozoic rocks are widespread across the Gawler Craton. In the study area the main units are the Gawler Range Volcanics (GRV) and the comagmatic granitoids of the Hiltaba Suite. The GRV forms a massive felsic volcanic province which erupted about 1,590 Ma; >25,000 km^2 of outcrop occurs across the region, dominated by dacite to rhyolite volcanic rocks, ignimbrites and interlayered basaltic flows. The Hiltaba Suite is dominated by felsic granite plutons which have a distinctive pink hue due to hematite dusting of feldspar crystals (Martin Fairclough, pers. comm., 2009). The GRV and Hiltaba Suite are the ultimate source for the widespread copper-gold-uranium mineralisation across the Gawler Craton. Other Proterozoic granitoid suites that occur within the Gawler–Eucla site include the Donington Suite, dominated by granitic gneiss, charnockite and quartz-bearing gabbronorite, and the St Peters Suite which formed ~1,630–1,620 Ma (http://outernode.pir.sa.gov.au/minerals/geology/geological_provinces/gawler_craton/gawler_geology)

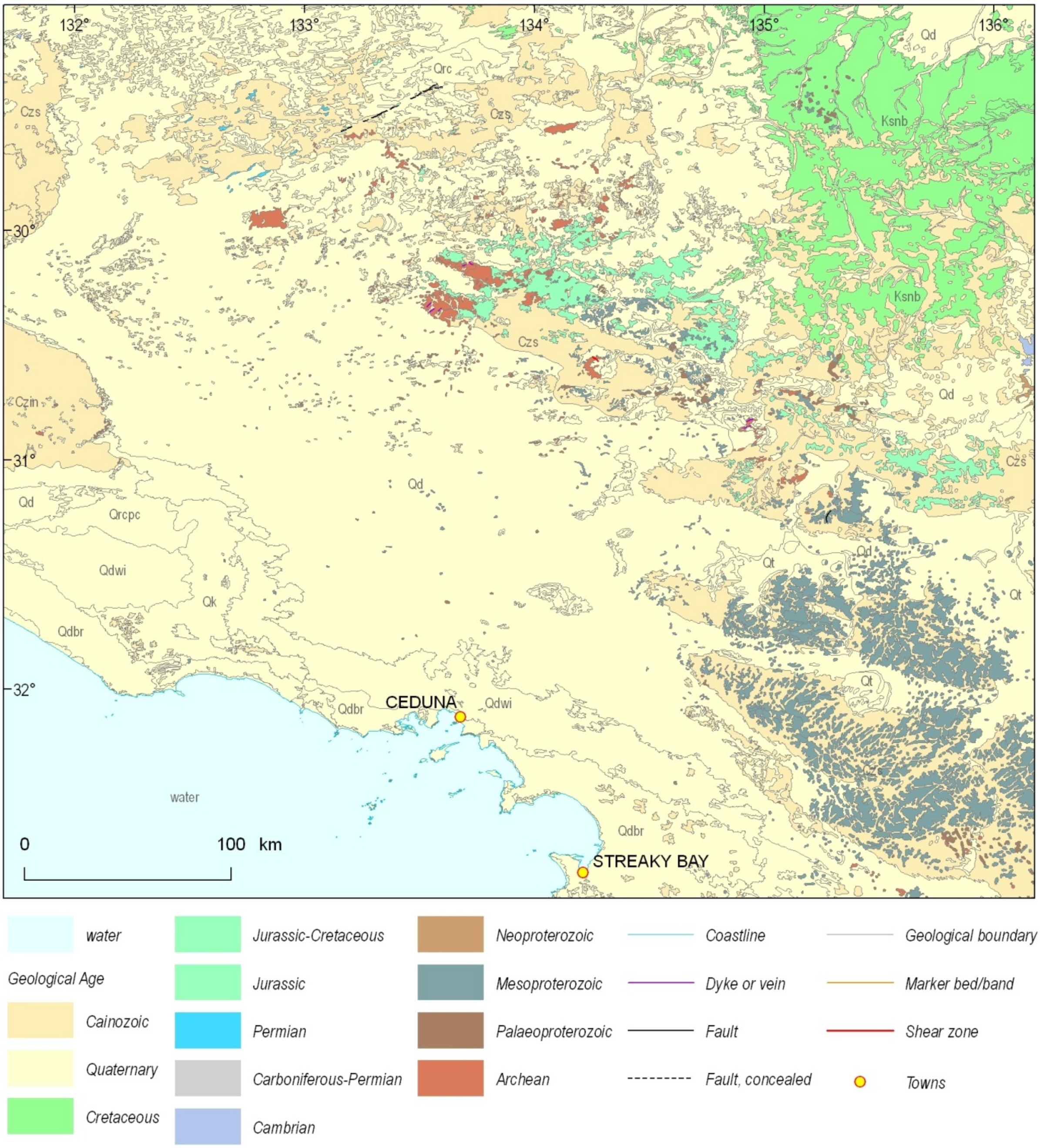


Figure 11: *Surface geology of the Gawler–Eucla demonstration site showing the widespread distribution of Quaternary and Cenozoic aeolian, alluvial, colluvial and lacustrine sediments. In comparison, outcrops of the Archean and Proterozoic basement rocks of the Gawler Craton have a restricted distribution.*

2.5.2. Eucla Basin

The Eucla Basin is the largest onshore Cenozoic basin in the world (Baohong Hou, pers comm., 2010). It formed an extensive marine sedimentary basin along the south coast of Australia during much of the Cenozoic (Benbow et al., 1995). The spatial extents of the basin margins (refer to the WASANT Palaeovalley Map in Appendix 1 for location) varied significantly during the Cenozoic as the region was affected by multiple cycles of marine transgression and regression.

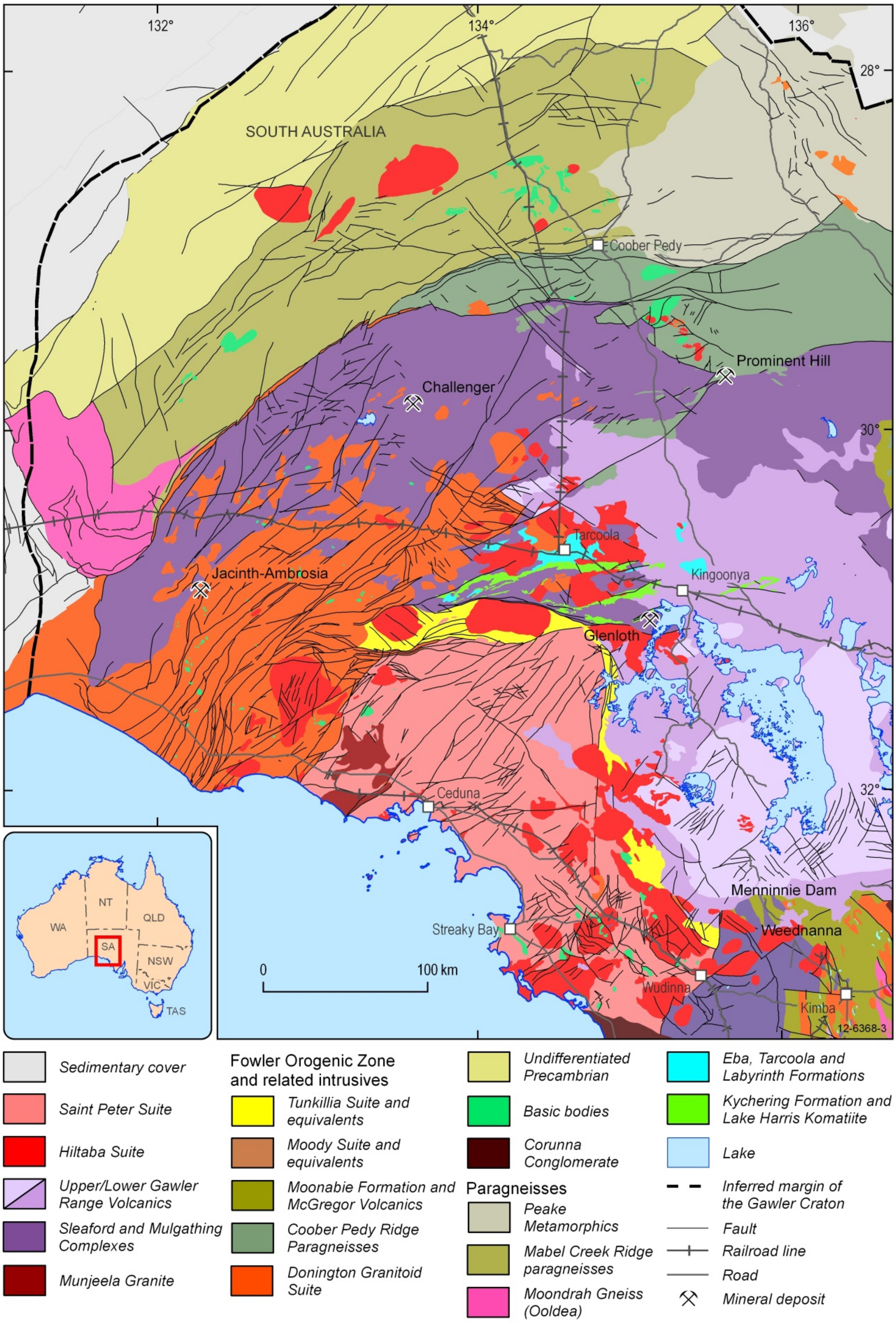


Figure 12: *Interpreted basement geology of the Gawler Craton highlighting the extent of the Gawler Range Volcanics and the Archean Mulgathing Complex across the project demonstration site (modified from Ferris et al., 2002).*

The distribution of sediments in the Eucla Basin presently extends from south-western South Australia to the south-east corner of Western Australia, and Middle to Upper Eocene (Wilson Bluff Limestone) and Lower to Middle Miocene (Nullarbor Limestone) marine carbonate sequences are the main rock types on the former marine shelf (Bunda Plateau). Around the margins of the basin estuarine and terrigenous sediments occur along the coastal plain and interfinger with buried palaeovalley deposits such as the Pidinga Formation and the Garford Formation.

2.5.3. Regional geophysical data

As part of the initial data compilation for the Gawler–Eucla study site regional geophysical datasets were obtained from custodians at Geoscience Australia and the Geological Survey of South Australia (GSSA). These regional data can assist in evaluating major geologic terranes and their dominant structural trends. For this study, the regional geophysical data were found to be useful for investigating major trunk palaeovalleys, as pre-existing basement structures can play an important role in determining the distribution and orientation of the ancient drainage systems. A selection of regional geophysical images showing airborne magnetic (Figures 13–14), Bouguer gravity (Figure 15), and radiometrics data (Figure16) are included below for reference. The magnetics and radiometrics data were compiled as part of the 2009 geophysical data release under the Australia Wide Airborne Geophysics Survey (AWAGS).

2.6. Mining operations and projected water demands

The Gawler Craton has an impressive world-class metallic mineral endowment and hosts several major mining operations which include the iron oxide-copper-gold ±uranium deposits at Olympic Dam and Prominent Hill, and the Challenger gold mine hosted in metasedimentary Archean rocks north-west of Tarcoola (Figure 12). Considerable geoscientific research conducted by the Geological Survey of South Australia and various academic institutions has shown that at least eight major mineral deposit exploration models are applicable to the Gawler Craton (http://www.pir.sa.gov.au/minerals/geology/geological_provinces/gawler_craton), including:

- Gold deposits hosted in Archean metasedimentary rocks;
- Nickel-gold deposits in Archean greenstones;
- Volcanic-hosted massive sulfide deposits in Archean rocks (Zn-Cu-Au);
- Proterozoic intrusive-hosted deposits of nickel-chromium-platinum-group elements;
- Broken Hill style sulfide deposits (Pb-Zn-Ag-Au);
- Mount Isa style lead-zinc deposits;
- Iron oxide-copper-gold ±uranium deposits, similar to Olympic Dam or Prominent Hill; and
- Polymetallic Hiltaba suite deposits (Au-Ag-Cu-Pb-Zn-As).

Economically viable deposits of other commodities also occur in nearby parts of the adjoining Eucla Basin, particularly the heavy mineral sand deposits discovered by Iluka Resources at Jacinth–Ambrosia and Tripitaka. These are high-grade deposits with abundant zircon and ilmenite, and lesser amounts of rutile and leucoxene (Hou et al., 2011). Additionally, uranium mineralisation is hosted in some Cenozoic palaeochannels incised into the basement rocks of the Gawler Craton, such as the Warrior Palaeochannel.

Several mining operations developed in the Gawler–Eucla demonstration site over the past decade have directly utilised palaeovalley groundwater resources for their water requirements. Detailed hydrogeological investigations carried-out in the vicinity of both the Challenger gold mine (REM, 2002; REM, 2003) and the Jacinth–Ambrosia mineral sands deposit (Parsons Brinckerhoff, 2005; SKM, 2006) recognised palaeovalley aquifers as the most viable source of sustainable groundwater to supply mining development and ongoing operations. The results of these investigations are discussed further in Chapter 3. On the basis of these groundwater assessments and our current understanding of potential groundwater sources in the Gawler Craton, palaeovalley aquifers clearly represent the key hydrogeological target to supply water for future mining operations. Additional, though lesser, demands for reliable groundwater supplies within this region may also come in the future from existing pastoral operations, indigenous communities and future infrastructure development (which may also be mining-related).

Given the excellent potential for significant resource discoveries to be made in the Gawler Craton and surrounding regions, practically all available land is currently held by various mining and exploration companies (under exploration licences (ELs) or EL applications administered by the South Australian government). Exploration efforts are ongoing throughout the region and focused on a diverse range of commodities, with significant annual exploration expenditure contributing to South Australia's economic security. However, the successful development of future mineral discoveries in the region will crucially depend upon the availability of reliable and sustainable water supplies. In arid and semi-arid areas such as the Gawler–Eucla region, access to sustainable water is vital for the success of any proposed mining venture, and may represent a limiting factor in the economic viability of resource development. Consequently, it is critical to have a comprehensive understanding of regional groundwater systems in such prospective mineral provinces, and a well understood methodology for identifying and assessing prospective water resources.

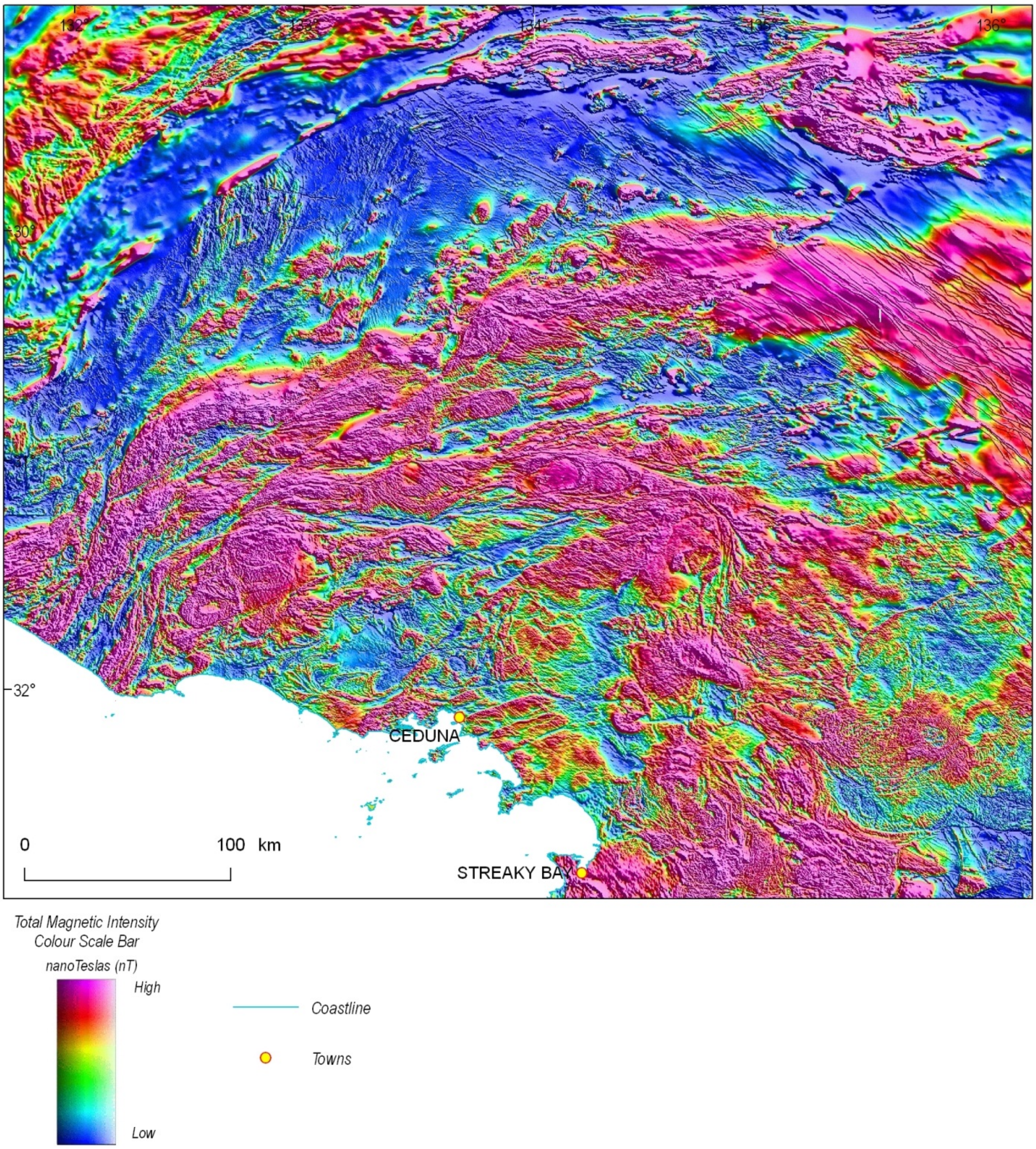


Figure 13: *Total magnetic intensity (TMI) image of the Gawler–Eucla study site highlighting distinct variations in the magnetic signature of the basement rocks of the Gawler Craton. Note the major north-west striking dyke swarm cutting across the north-eastern quadrant. Many individual dykes are up to several hundred kilometres long (after Milligan and Franklin, 2004, 4th edition).*

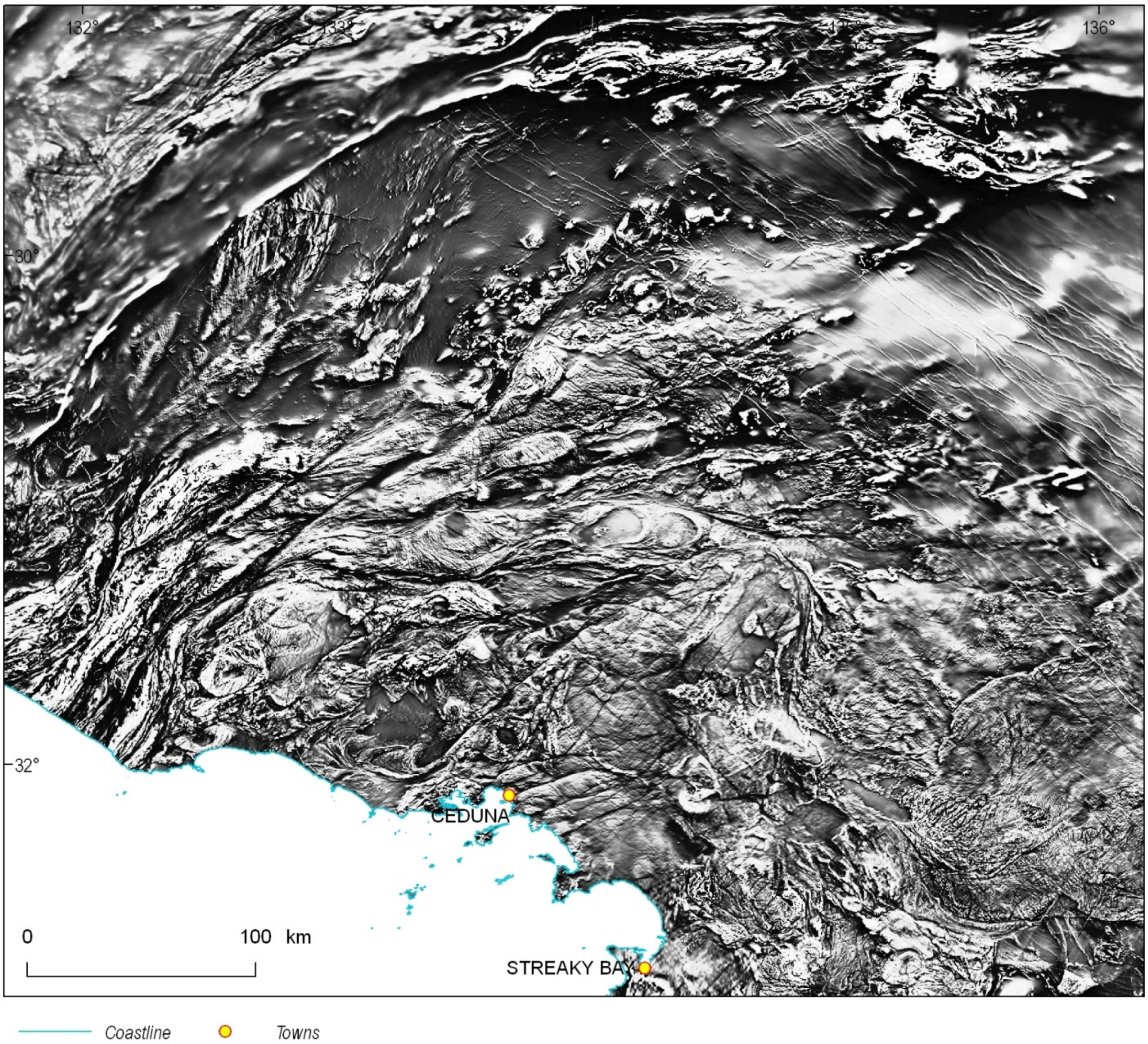


Figure 14: *The 1st vertical derivative of airborne magnetic data for the Gawler-Eucla demonstration site. This image enhances and highlights major structural features in the basement terrane of the Gawler Craton (original magnetic data after Milligan and Franklin, 2004, 4th edition).*

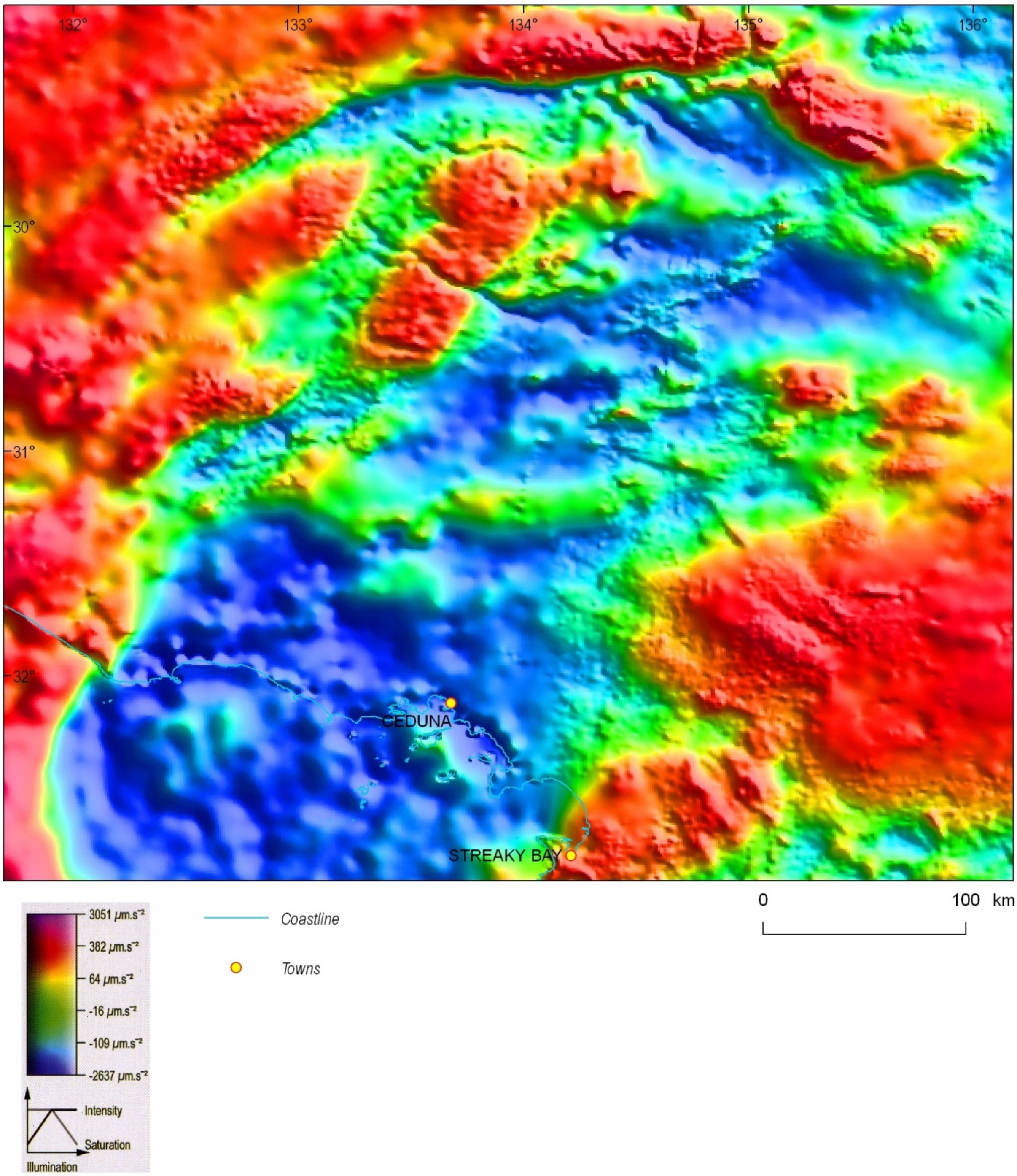


Figure 15: *Bouguer gravity image of the Gawler–Eucla demonstration site. The variation in the gravity image mainly reflects density contrasts in the major rocks units of the basement terranes. The dominant south-west to north-east structural trend evident in the gravity data correlates with the regional geology mapping and magnetics data. Gravity data after Bacchin et al., 2008.*

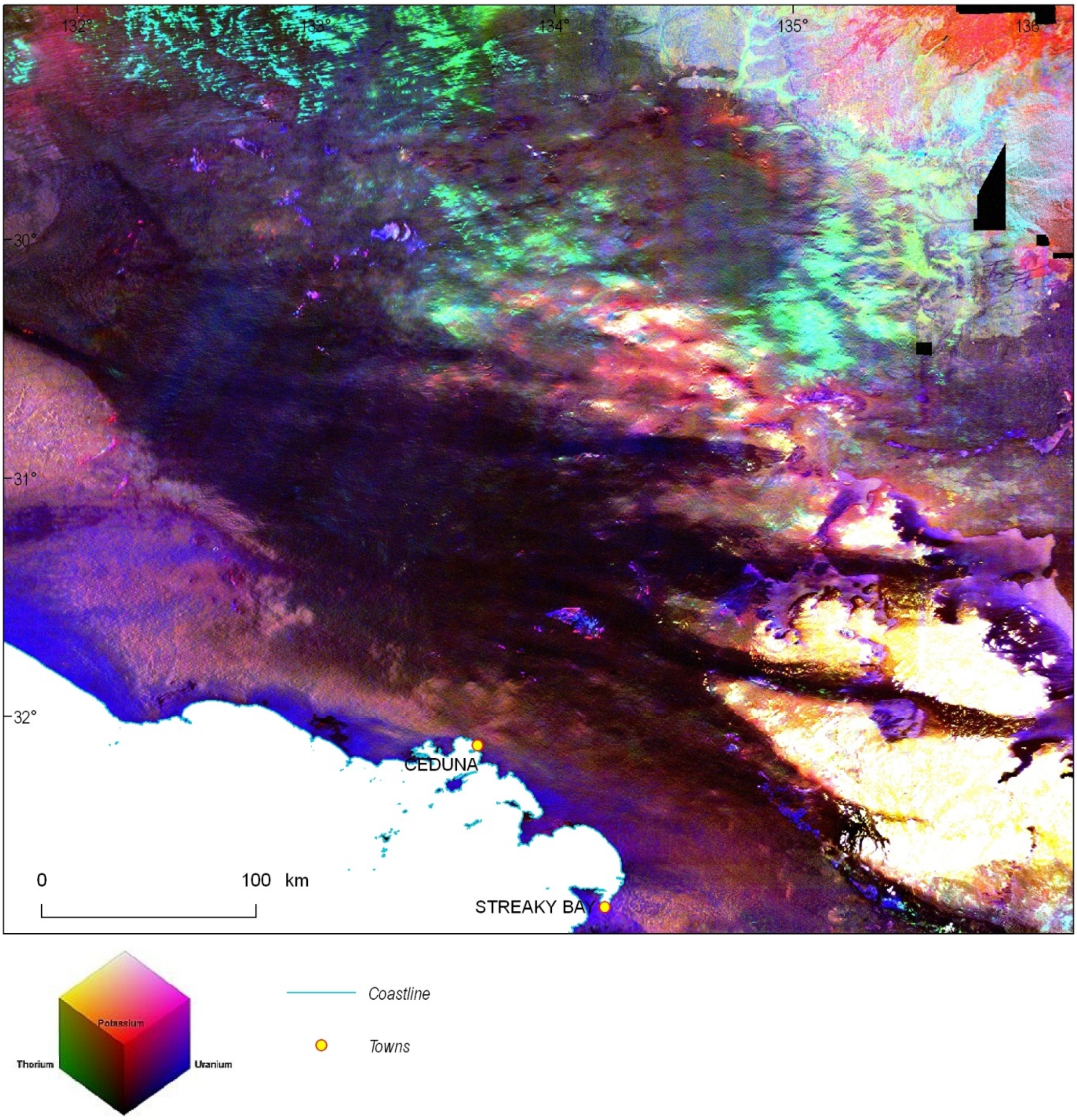


Figure 16: *Ternary radiometric image for the Gawler–Eucla demonstration site showing the variation in surface concentrations of the radioactive elements potassium (K), uranium (U) and thorium (Th). The widespread blue and purple tones indicate elevated levels of uranium in the surface cover, sourced from uranium-enriched basement rocks that occur in the Gawler Craton, such as the granites of the Hiltaba Suite. Data after Minty et al., 2010.*

3. Palaeovalleys and groundwater resources of the Gawler–Eucla region

3.1. Introduction

One of the initial outputs from the *Palaeovalley Groundwater Project* was a comprehensive literature review of Australia's arid zone palaeovalley systems and groundwater resources (Magee, 2009). This work presented the existing state of knowledge of palaeovalley aquifers across a number of large regional provinces, including the Gawler–Eucla and Musgrave regions of South Australia. A key recommendation by Magee (2009) was the need for consistent use and application of various palaeovalley-related terms which have been inconsistently applied in past scientific publications. It is worthwhile to reflect on these suggestions (Figure 17), as the terminology endorsed by Magee (2009) has been applied throughout this report to ensure a consistent approach:

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

Over the past decade exploration activity in South Australia has increased significantly, with particular focus on uranium and heavy mineral sand deposits associated with palaeodrainage systems and palaeocoastal sediments. To assist with this renewed exploration interest the South Australian Department of Manufacturing, Innovation, Trade, Resources and Energy (DMITRE) compiled a state-wide 1:2,000,000 scale thematic map entitled 'Palaeodrainage and Tertiary Coastal Barriers of South Australia' (Keeling and Hou, 2007; Hou et al., 2007). The mapping exercise used a variety of datasets including SRTM, Landsat 7 satellite imagery, National Oceanic and Atmospheric Administration (NOAA) night-time thermal imagery, as well as extensive drillhole logs and geophysical data. The map also included a revised stratigraphic correlation chart of Cenozoic sediments in South Australia.

Compilation of the thematic South Australian palaeodrainage 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 (Magee, 2009). Elsewhere in South Australia the surface expression is generally very poor and palaeodrainage systems are largely obscured by Quaternary sediment cover or regolith. In some places, the cover sequences are up to tens of meters thick, requiring integrated data from drilling, remote sensing (particularly night-time thermal imagery) and geophysical surveys (e.g., transient airborne electro-magnetics) to provide a detailed interpretation of palaeodrainage systems. These data were also combined with knowledge of continental sedimentation and the sedimentary history of Mesozoic, Palaeogene and Neogene channel sediments in South Australia to derive a comprehensive understanding of the spatial distribution and evolution of regional palaeovalley networks (Keeling and Hou, 2007).

The detailed geoscientific investigation and mapping of South Australian palaeovalleys has provided an excellent foundation for the new research program conducted for the *Palaeovalley Groundwater Project*. As the work undertaken by DMITRE was aimed specifically at understanding the evolution and architecture of palaeovalleys to assist with mineral exploration, considerable scope remained for our new study to specifically address groundwater systems and provide improved knowledge of the quality, quantity and evolution of palaeovalley groundwater resources.

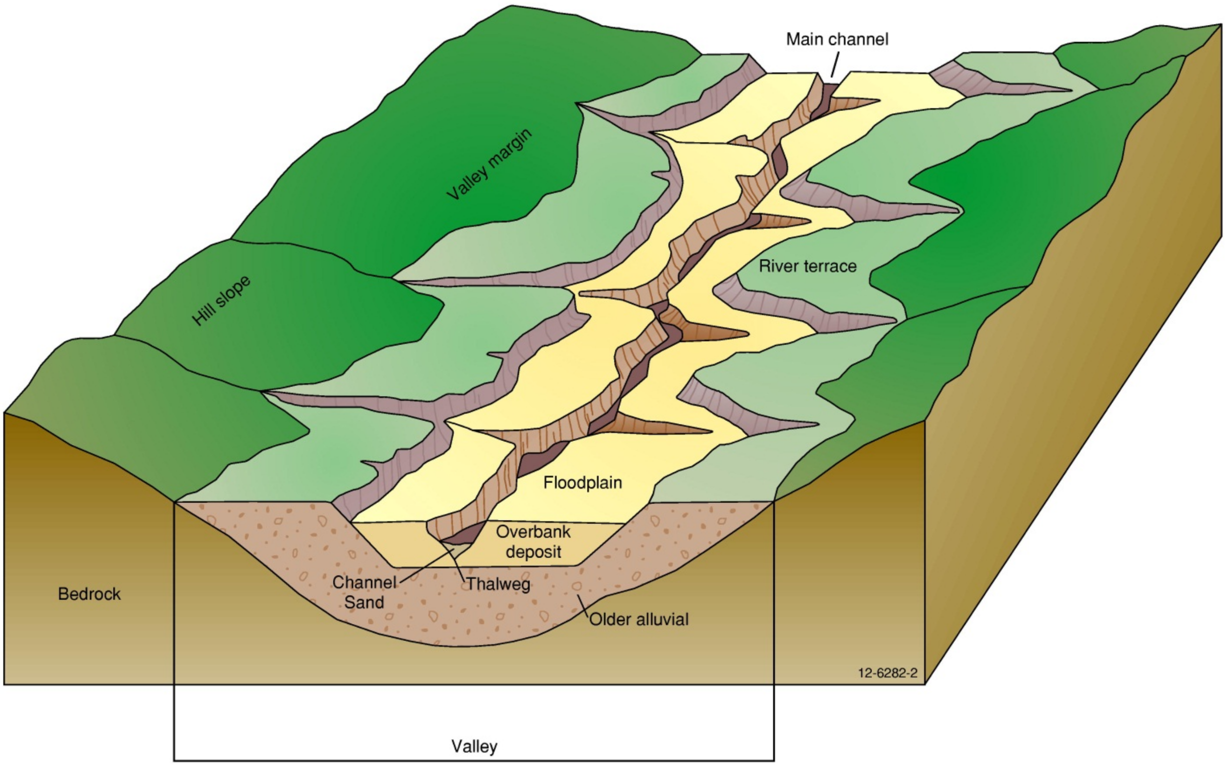


Figure 17: *Block diagram illustrating valley and channel landforms and terminology (adapted from Magee, 2009).*

The remainder of this chapter provides further details about the palaeovalleys that occur in the Gawler–Eucla region, as well as existing knowledge of the groundwater resources. There is particular emphasis on the Kingoonya Palaeovalley as this has been the main focus of field operations for the *Palaeovalley Groundwater Project*. Chapter 5 focuses on the new work program conducted in the Gawler–Eucla region, with new groundwater data, analyses and interpretations presented in Chapter 6.

3.2. The Gawler–Eucla palaeodrainage network

The Gawler–Eucla palaeodrainage network is widespread, interconnected and relatively well defined. From south-east to north-west the major palaeovalley systems in this region, which ring the adjacent Eucla Basin and originally flowed south-west as active surface water bodies into the Cenozoic Eucla sea (Figure 18), include the:

- **Yaninee–Narlaby** Palaeovalley;

- **Kingoonya** Palaeovalley (and the downstream Malbooma and Tolmer trunk systems with influence of estuarine environments);
- **Wynbring** Palaeovalley;
- **Anthony** Palaeovalley;
- **Garford** Palaeovalley; and the
- **Tallaringa** Palaeovalley (and the downstream branching trunks of the Woldra, Karari, Wilkinson systems).

Additionally, minor downstream sections of both the Immarna and Merramangye palaeovalleys occur in the extreme north-western corner of the Gawler–Eucla study site. However, both of these palaeovalleys rise in the Musgrave Province–Officer Basin region further to the north and are thus not considered further in this chapter.

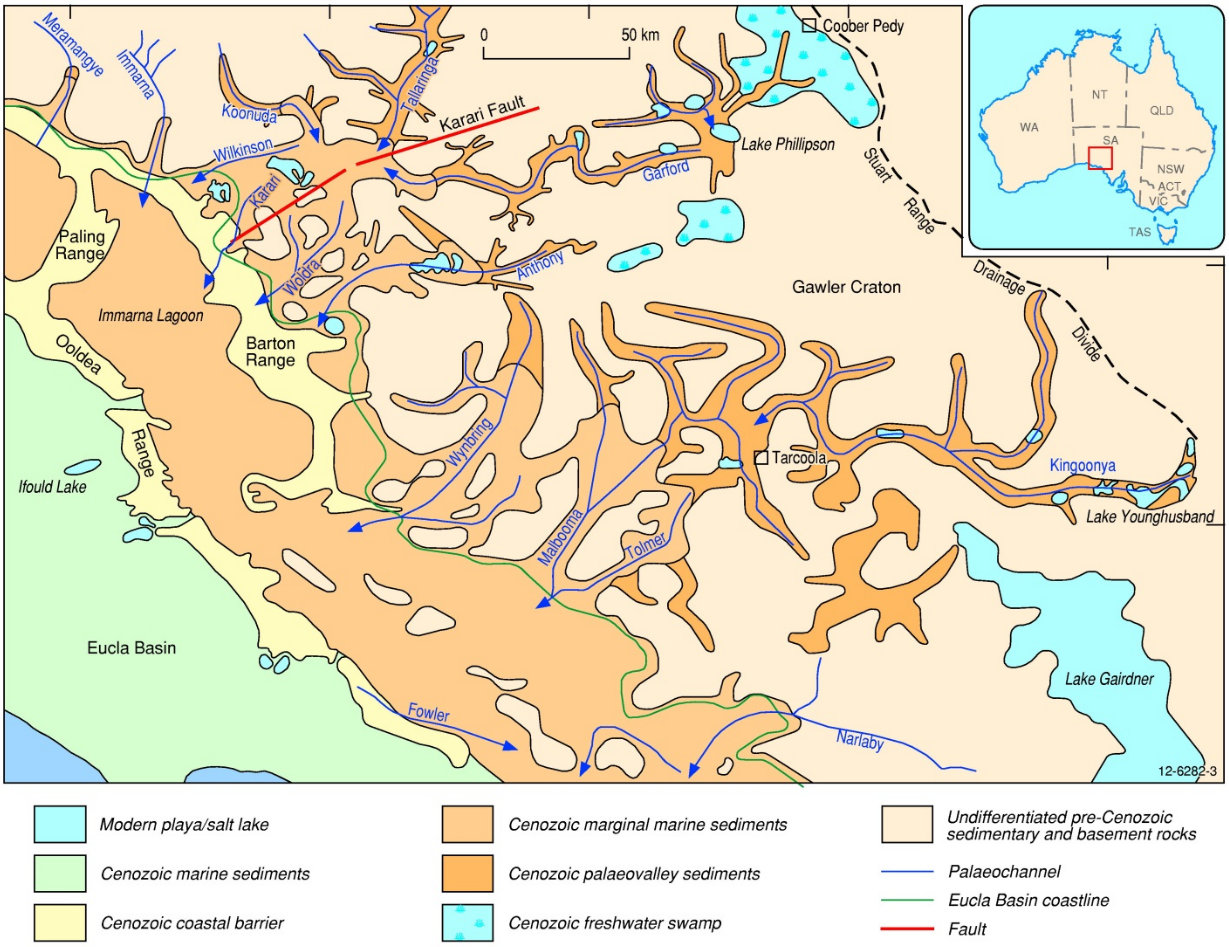


Figure 18: *Palaeogeographic reconstruction during the Eocene of the present-day north-west Gawler Craton and eastern Eucla Basin margin. The interconnected network of palaeovalleys developed on the Gawler Craton flows mostly west and south-westwards towards the Eucla Basin. The ancient Eucla shoreline was considerably further inland than its present-day location, reflecting significant marine transgressions during the Middle to Late Eocene (figure modified after Hou et al., 2001).*

Previous work has shown that the Gawler–Eucla palaeovalleys were mostly incised into the deeply weathered bedrock of the pre-Cenozoic landscape (mainly the various rock units of the Gawler

Craton), although some partly coincide with antecedent Mesozoic systems (Hou et al., 2003a). Detailed evaluation of major structural features in the Gawler Craton using regional airborne magnetic data (1st vertical derivative) indicates strong coincidence between some palaeovalley systems and ancient basement structures, e.g., parts of the Kingoonya Palaeovalley (Figure 19). This coincidence suggests that major basement structures in the Gawler Craton, which probably date to at least the Mesoproterozoic, have influenced the origin and evolution of the regional Cenozoic palaeovalleys.

Similar to other arid zone palaeovalley systems in the NT and WA, the palaeovalleys of the Gawler–Eucla region were subsequently infilled during the Cenozoic Era with a variable assemblage of fluvial, estuarine, deltaic and marine sediments which developed over several major depositional cycles. These episodes mainly occurred during the:

1. Paleocene to Early Eocene,
2. Middle to Late Eocene,
3. Oligocene to Early Miocene, and
4. Middle Miocene to Pliocene.

Consequently, the nature and composition of sediment packages within Gawler–Eucla palaeovalleys depends largely on location relative to the ancient coastline (Magee, 2009). During the Quaternary, most of the region has been blanketed by aeolian sands to form the present-day landscape (Hou et al., 2003b).

The dimensions of the Gawler–Eucla palaeovalleys vary greatly, ranging from <100 metres wide for tributary sections, to more than 20 kilometres wide for the main valley trunks (Figure 20). The valley floor of some larger trunk systems may be over 100 metres below the present land surface (Hou et al., 2003a). The lower palaeovalley reaches are characterised by estuarine sediment deposits which interacted with Cenozoic lagoons and sand barriers, e.g., now preserved in the extensive sand deposits of the Ooldea, Barton and Paling Ranges. Compared with the Yilgarn Craton, the Gawler–Eucla palaeovalleys contain relatively few playas and the palaeovalleys are less apparent at surface (i.e., mappable) using standard mapping techniques (Magee, 2009). This is mainly due to widespread surficial cover and deep weathering of the palaeovalley sediment sequences.

3.2.1. Yaninee and Narlaby Palaeovalleys

The Yaninee and Narlaby palaeovalleys originated in the Gawler Craton west of Lake Gairdner and flowed westerly towards the south-east margin of the Eucla Basin (Figure 18). Mapped segments of these buried valleys trend mainly westwards 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, both the Yaninee and Narlaby palaeovalleys have probably been affected by marine or estuarine conditions associated with eustatic transgressions from Eocene to Pliocene times (Magee, 2009).

The Narlaby Palaeovalley has been extensively explored for secondary uranium deposits. Sporadic mineralisation is associated with redox fronts developed near the contact between carbonaceous sediments of the variably oxidised Pidinga Formation, and overlying oxidised sands of the Garford and Narlaby Formations (Drexel and Preiss, 1995). The quality and quantity of groundwater resources in both palaeovalleys is largely unknown.

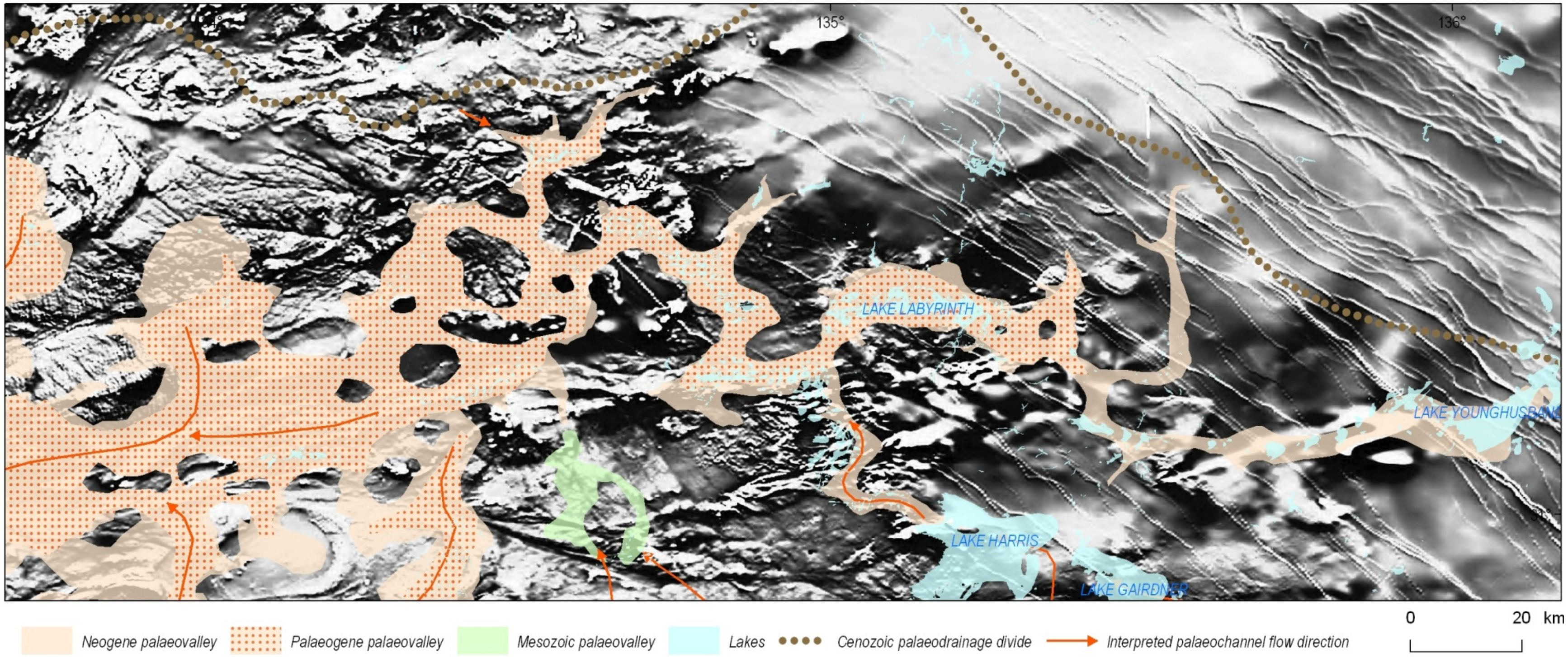


Figure 19: *Kingoonya Palaeovalley overlain on 1st vertical derivative airborne magnetic data, highlighting coincident orientation (at least in part) of major basement structures in the Gawler Craton and Cenozoic palaeovalleys (western part of this image). Despite the major time gap this coincidence suggests that much of the modern landscape may be influenced (at least in part) by ancient geological features.*

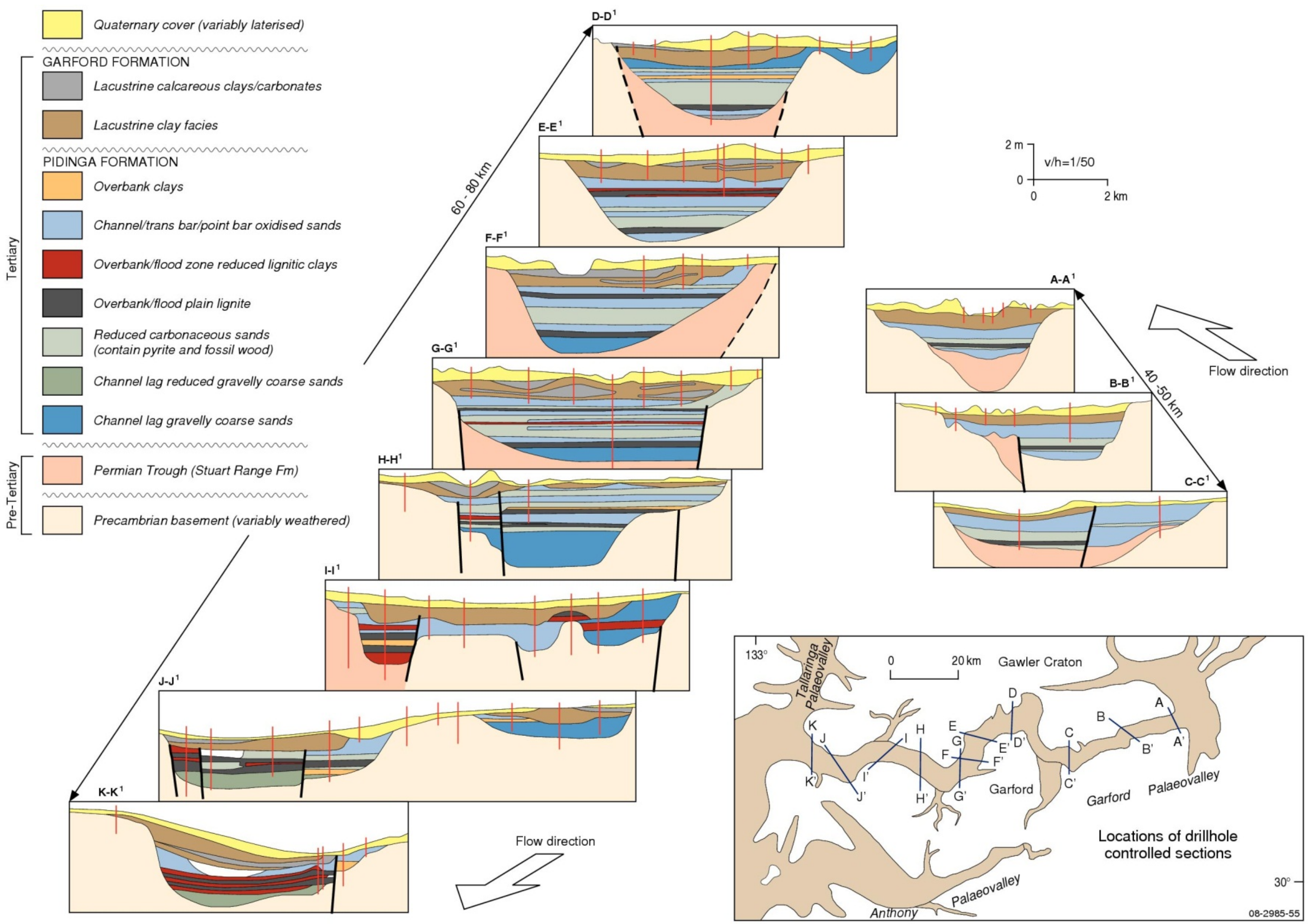


Figure 20: *Sequence of stratigraphic cross-sections along the length of the Garford Palaeovalley, highlighting variations in channel morphology and sediment packages at different segments of the ancient drainage network. The eleven cross-sections shown are based on detailed drilling transects (locations shown on the inset map) undertaken by the Geological Survey of South Australia (figure modified from Hou et al., 2001).*

3.2.2. Kingoonya Palaeovalley

The Kingoonya Palaeovalley is one of the larger and more complex palaeovalley systems on the Gawler Craton (Figure 18). Previous investigations of the Kingoonya Palaeovalley led by the Geological Survey of South Australia have elucidated considerable detail about its geological structure, composition and evolution (Figure 21) (Hou et al., 2003a; Hou, 2004).

Quaternary regolith is widespread in much of the Gawler–Eucla region and completely obscures the modern-day surface expression of the Kingoonya Palaeovalley. However, the work of Hou (2004) showed that an extensive tributary network occurs in the upper and middle reaches of the now-buried valley system, covering over several thousand square kilometres of the arid interior of South Australia.

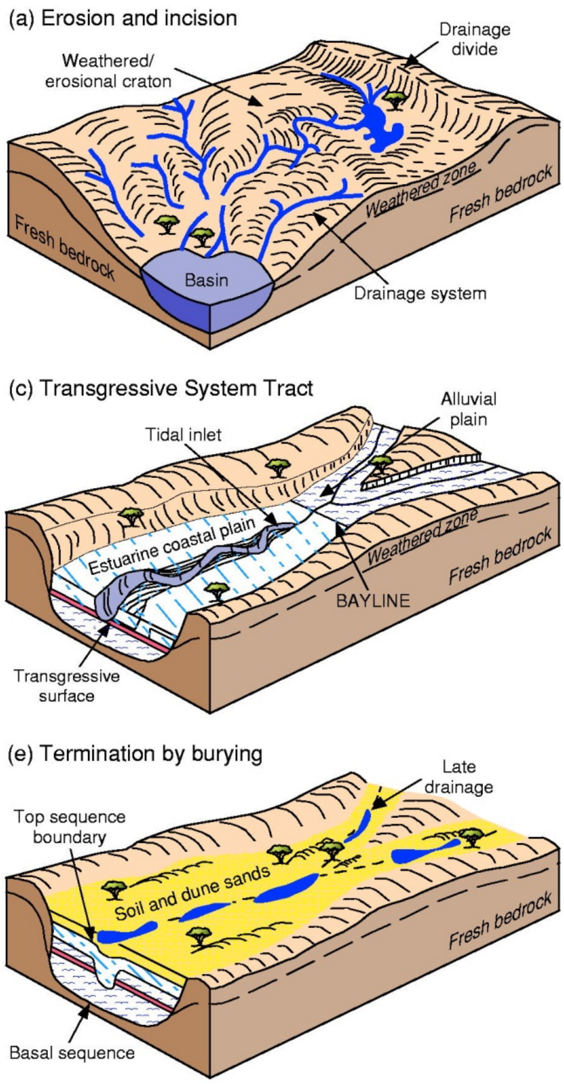


Figure 21: *Genetic model for main stages involved in the evolution of the Kingoonya Palaeovalley. The lowstand, transgressive and highstand system tracts correspond to particular lithofacies which occur in the now-buried valley – see Table 1 (modified after Hou, 2004).*

The main trunk of the Kingoonya Palaeovalley trends predominantly westwards from the Stuart Range drainage divide, passing just north of Lake Gairdner and flowing towards the remote township of Tarcoola, situated on the Trans-Australian Railway Line (Figure 18). In these upper reaches, chains of playas are relatively abundant. Downstream past Tarcoola, the Kingoonya Palaeovalley originally formed a complex series of distributary channels near the eastern Barton and Ooldea Ranges. In the lower reaches of the Kingoonya system these estuarine-influenced palaeochannels include the Wynbring, Malbooma and Tolmer systems (Hou, 2004).

The Kingoonya Palaeovalley is infilled with a complex and varied sequence of Cenozoic sediments of dominantly terrestrial origin (fluvial channels and lacustrine deposits), although marginal marine sediments occur commonly in the lower reaches, e.g., estuarine and tidal flat deposits (Hou, 2004). Detailed geological investigation of the Kingoonya Palaeovalley (Hou, 2004) was based on ~15 drilling transects and >90 drillholes (Figure 22). This work helped to develop well-constrained geological cross-sections and to interpret about10 major lithofacies in the infill sequence (Table 1).

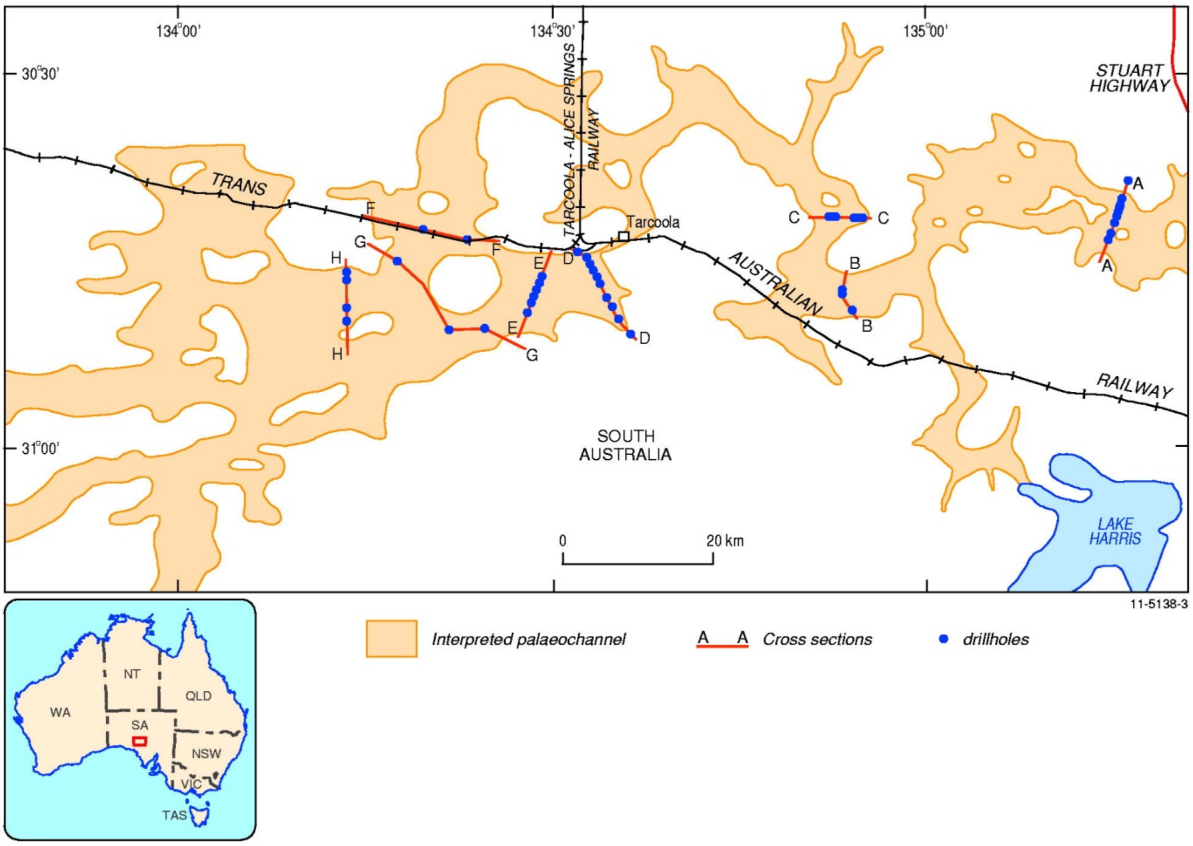


Figure 22: *Location map of geological cross-sections for the Kingoonya Palaeovalley in the Tarcoola region, developed from detailed drilling conducted by the Geological Survey of South Australia. The interpreted cross-sections for Lines D, E, F, G and H are shown in Figures 24-26 (modified after Hou, 2004).*

The palaeovalley infill sequences of the Kingoonya Palaeovalley are dominated by sediments of the Eocene Pidinga Formation in the lower section, and are overlain by the Kingoonya Member of the Miocene age Garford Formation (Figure 23). Facies relationships are complex, with sediment types commonly varying both along and across the incised valley profile. Some of the facies associations and stratigraphic relationships are highlighted in the series of cross-sections shown as Figures 24–26.

Thin basal channel sand and gravel units occur in some places, and these represent the main palaeochannel aquifer associated with the trunk palaeovalley. For example, the cross-section for Line E (upper section in Figure 25) shows two separate palaeochannels with different sedimentary infill sequences. In this figure, the southern channel contains a basal gravelly sand deposit (thalweg sediments), whereas the northern channel does not have the same coarser-grained sediments overlying the basement rocks. In general, the infill sediments within most of the Kingoonya Palaeovalley are predominantly massive clays, silts and fine sands with minor lignite beds. These typically form the main confining units for groundwater contained in the basal sand/gravel aquifer.

Table 1: *Main facies types of the Kingoonya Palaeovalley (modified after Hou, 2004). The lithofacies are depicted on the geological cross-sections in Figures 24-26.*

Facies code	Lithologic features	Structures and fossils	Interpretation and occurrence
Q	Fine sands and regolith	Minor cross bedding	Quaternary regolith and aeolian sand cover
Gm	Gravel, clast-supported, laterally discontinuous	Massive or crude bedding, poorly sorted, sub-angular	(Longitudinal) bedforms, lag deposits; Eocene channel
Ss	Sand, fine to coarse, minor granule and pebble, possibly lignitic	Broad, shallow scours	Scour fill, Eocene and Miocene channels
Sm	Sand, fine to coarse, possibly lignitic	Massive, or weakly laminated	Gravity flow deposits, Miocene channel dominantly
Sh	Sand, fine to very coarse, gravely, possibly lignitic	Horizontal, poorly sorted, sub-angular, sub-rounded	Channel, transverse/point bars; Eocene and Miocene channels
Sl	Sand, fine to medium with silt, clayey, possibly lignitic	Weakly laminated, well-moderately sorted	Tidal flat, estuarine; Eocene and Miocene channels
Cc	Gritty-sandy-silty clay, possibly lignitic	Crude lamination	Basal channel, Miocene channel dominantly
Cm	(Sandy-silty) clay, very fine sand, silt, possibly lignitic	Massive, weakly laminated	Overbank and/or waning flood deposit; Eocene and Miocene channels
Cp	(Sandy-silty) clay, possibly dolomitic, calcareous	Plastic, massive	Lacustrine; Miocene channel
Lp	Lignite with plant fossils, possibly sandy and/or clayey	Plants, mud films	Vegetated (estuarine) swamp deposits, marsh/overbank, flood deposit; Eocene and Miocene channels
Ag	Gypsum, clayey, silty, sandy	Arid features, crystalline grains, filaments on top	Lacustrine chemical precipitation, Miocene channel

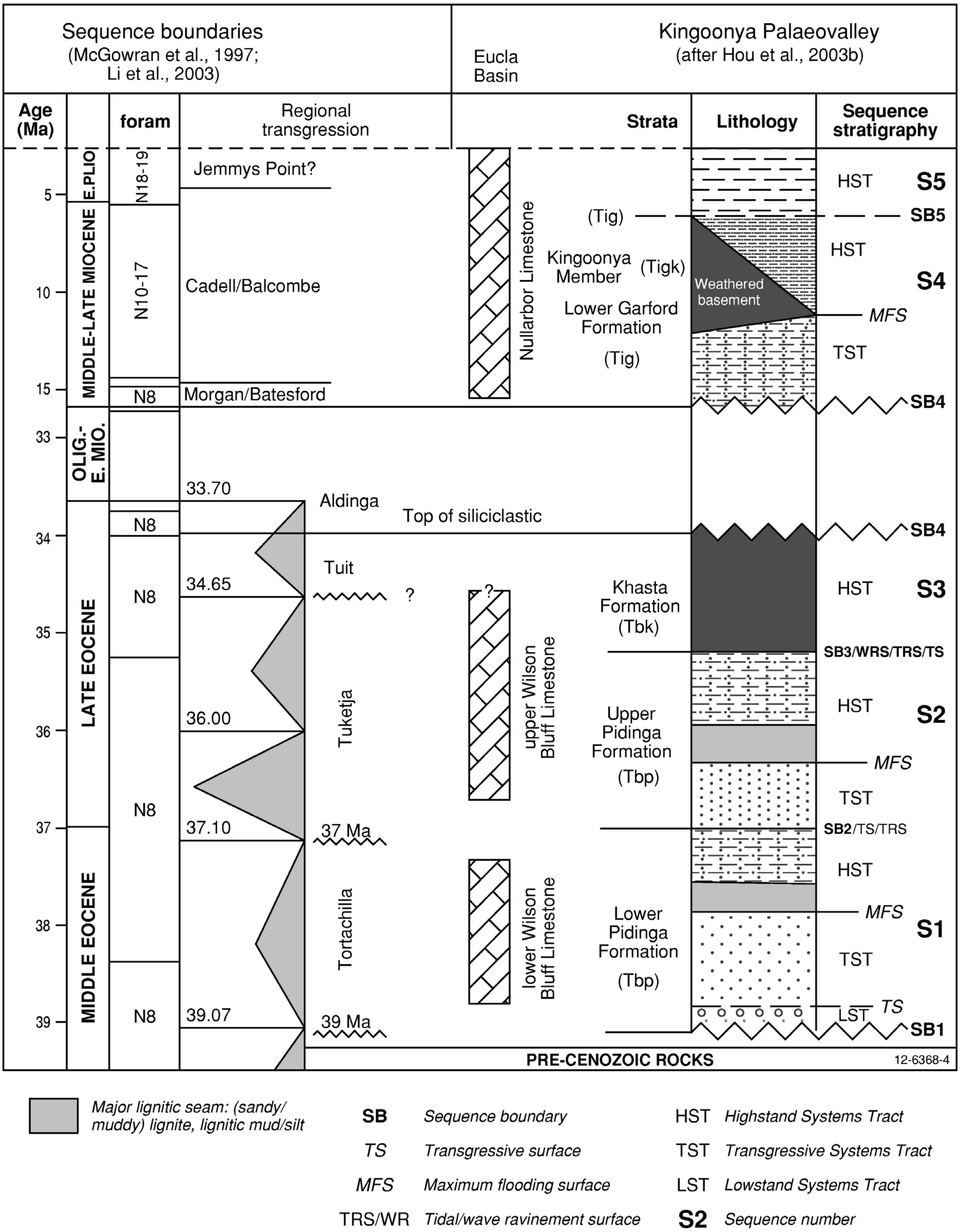


Figure 23: *Lithostratigraphic and sequence stratigraphic correlation chart for channel sediments of the Kingoonya Palaeovalley (modified after Hou, 2004).*

3.2.3. Anthony Palaeovalley

The Anthony Palaeovalley largely trends towards the west and south-west and is relatively short with few tributaries (Figure 18). Compared with most Gawler–Eucla palaeovalleys the Anthony system is poorly understood due to lack of drillhole data, and it was not specifically targeted as part of previous DMITRE drilling programs. Thin and poorly sorted, silicified gravel-bearing sand lenses are common in the upper reaches and may reflect the relatively higher altitude (uplifted ranges) of the sediment source rocks (Hou et al., 2003). Alkaline lake deposits of the Garford Formation are not recognised in the Anthony Palaeovalley, suggesting localised variation of sediment sequences among the larger Gawler palaeovalleys (Magee, 2009). The Challenger gold mine currently uses groundwater sourced from the Challenger Palaeovalley, a small tributary of the Anthony Palaeovalley, to supply water for ore processing and use around the camp (Section 3.3.1).

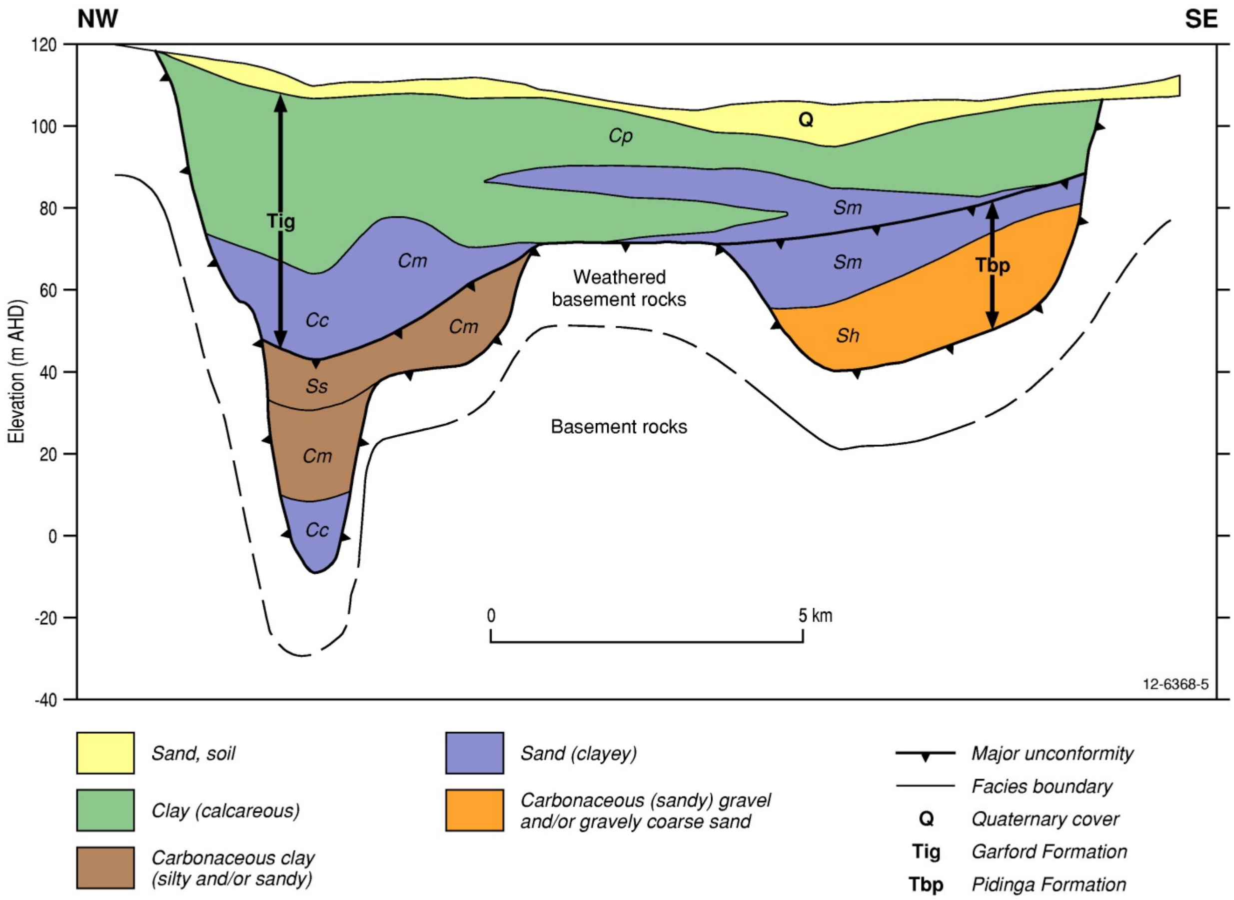


Figure 24: *Interpreted geological cross-section for* ***Line D*** *drilled across the Kingoonya Palaeovalley (see Figure 22 for line location). This section shows lithofacies associations and spatial relationships of the palaeovalley infill sequences determined from detailed analysis of drilling samples (bores not shown). Figure modified after Hou, 2004.*

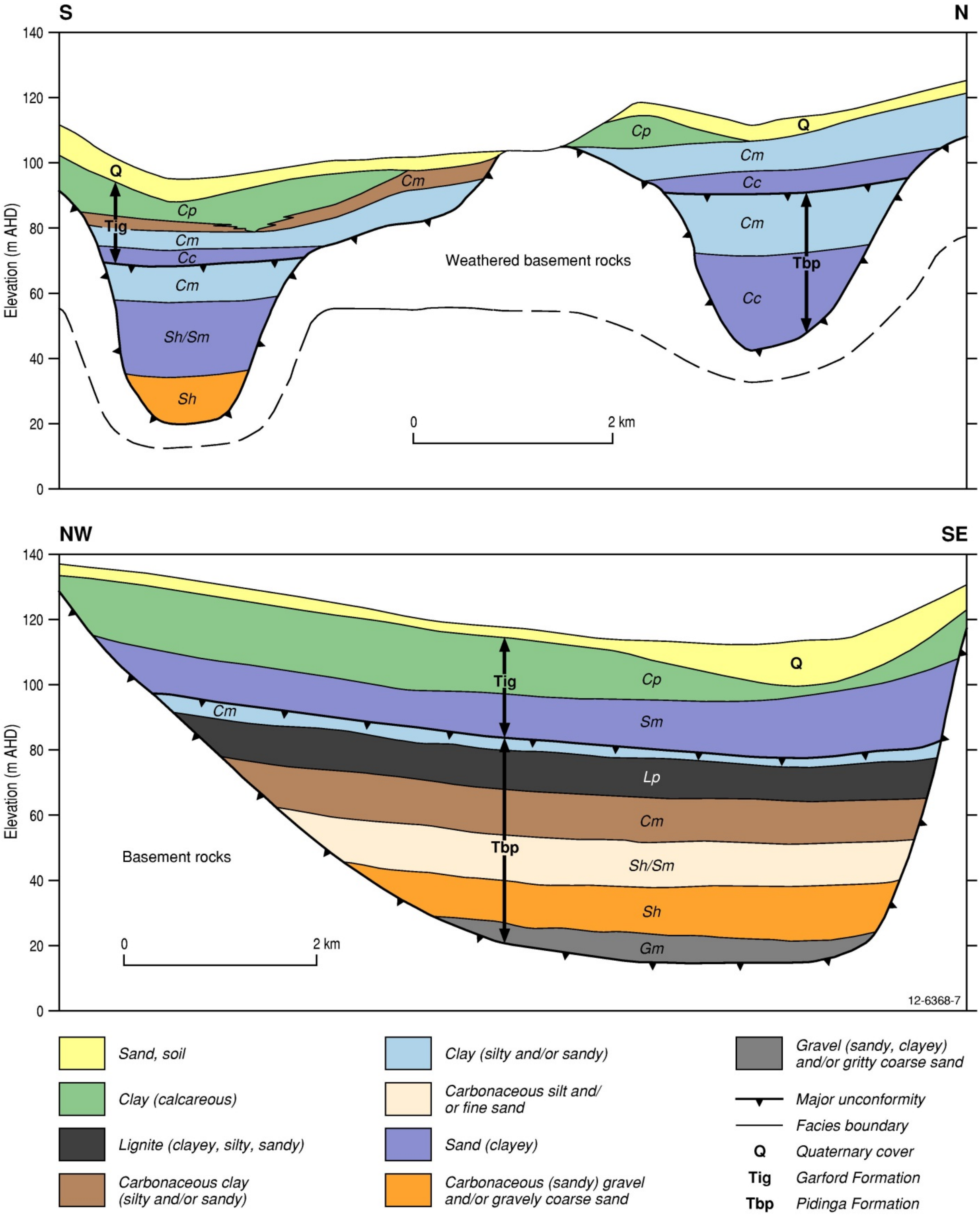


Figure 25: *Interpreted geological cross-sections for* ***Line E*** *(upper section) and* ***Line F*** *(lower section) across the Kingoonya Palaeovalley (refer to Figure 22 for line locations). These geological sections show lithofacies associations and spatial relationships of the palaeovalley infill sequences, as determined from detailed drilling operations undertaken by DMITRE. Figure modified after Hou, 2004.*

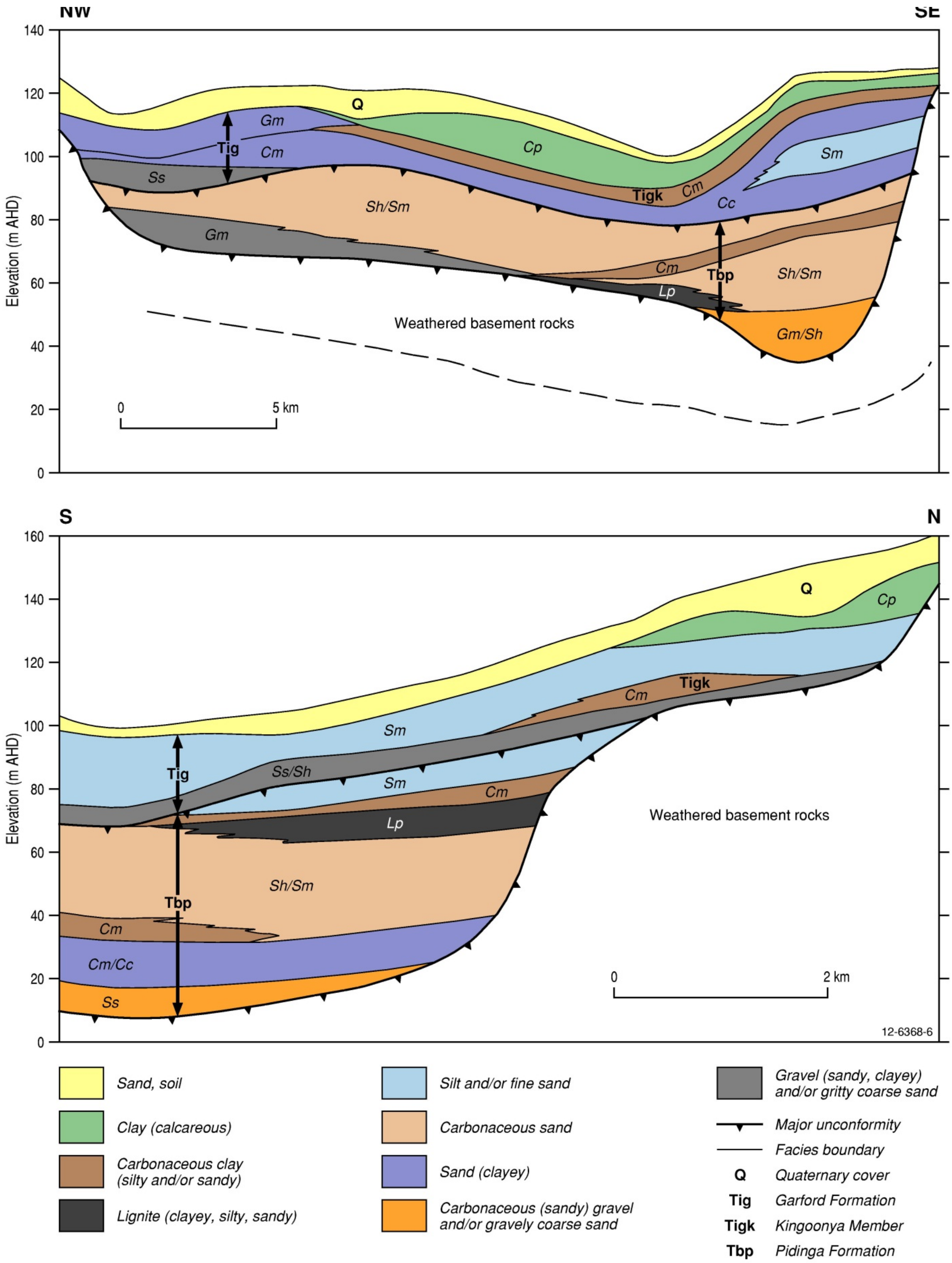


***Figure 26:** Interpreted geological sections for **Line G** (upper section) and **Line H** (lower section) across the Kingoonya Palaeovalley (refer to Figure 22 for line locations). These geological sections show lithofacies associations and spatial relationships of the palaeovalley infill sequences, as determined from detailed drilling operations undertaken by DMITRE (figure modified after Hou, 2004).*

3.2.4. Garford Palaeovalley

The Garford Palaeovalley has an extensive tributary network that trends west-south-west in the upper reaches, but is oriented more south-westerly on the downstream side of its junction with the Tallaringa Palaeovalley (Figure 20). A complex valley mouth with multiple distributor channels (including the Woldra, Rarari and Wilkinson systems) interacts in the estuarine zone with the mouth of the Immarna Palaeovalley to the north and the Anthony Palaeovalley to the south (Figure 18). The estuarine sequences are locally thickened by the presence of the Karari Fault. The stratigraphic architecture of the Garford Palaeovalley is relatively well constrained by eleven drilling transects (Figure 20) and multiple geophysical cross-sections (Hou et al., 2003a, b). Alkaline lake deposits of the Garford Formation commonly infill erosional depressions in the underlying carbonaceous sands of the Eocene Pidinga Formation (Figure 23). Bedrock depths are approximately 80 metres AHD in the lower reaches of the palaeovalley, deepening to approximately 120 metres AHD in the middle reaches. This represents a gradient of about 0.1% (Magee, 2009). Depth to basement is uncertain in the upper reaches. Negative gradients in parts of the lower reaches imply post-Eocene tectonic disruption and indicate that detailed drilling control and tectonic reconstructions are essential to accurately determine valley morphology and sedimentary architecture of the Gawler–Eucla palaeovalleys (Hou et al., 2003a,b).

3.2.5. Tallaringa Palaeovalley

The ancient headwaters of the Tallaringa Palaeovalley are incised into the northern margins of the Gawler Craton (Figure 18). The palaeovalley trends south-south-west from the Stuart Range divide to link with the Garford Palaeovalley near its former outlet into the Eucla Basin. 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 imagery and geophysical datasets but the sedimentary infill sequence and channel morphology is poorly constrained as no detailed drilling program was undertaken as part of the DMITRE investigation (Hou et al., 2003a, 2003b). However, the Garford Formation is known to unconformably overlie the Pidinga Formation in the Tallaringa Palaeovalley, similar to facies relationships in the Garford Palaeovalley. This suggests that the main sedimentary associations in the Gawler–Eucla region are broadly consistent across most palaeovalleys.

3.3. Previous groundwater studies in the Gawler–Eucla

Groundwater resources within palaeovalleys of the Gawler Craton are relatively poorly understood or documented, even for the Garford and Kingoonya systems which have been extensively drilled (Hou et al., 2003a,b; Hou, 2004). Magee (2009) considered this fundamental lack of knowledge of regional groundwater resources surprising, especially as perennial surface water resources are rare and there are significant water supply needs for the many pastoral stations and mining operations in the region. As mentioned in Chapter 2, prior to this present investigation, the most detailed hydrogeological studies of palaeovalley groundwater resources in the Gawler–Eucla region were small-scale and localised assessments for the Challenger gold mine and the Jacinth–Ambrosia heavy mineral sands deposit. These studies were completed by hydrogeological consultants to assess water supply options for the mining operations. Specific details of these previous investigations are outlined below to provide context for data and interpretations presented in Chapters 5–6.

At the regional scale, Martin (1998) and Magee (2009) suggested that groundwater resources in the palaeovalleys of the Gawler Craton are crucially important to the mining industry. In particular, both authors noted that these groundwater systems have significant potential to provide water supplies for ore processing, camp supplies and other mining operations (depending on water quality). Drilling in the Garford Palaeochannel indicated a 10–15 metre thick palaeochannel sand aquifer (thalweg) which potentially contains up to 300 x 10^6 m^3 of saline groundwater in storage (Martin, 1998). From comparison to the Garford Palaeovalley, the larger Tallaringa system on the north-western margin of the Gawler Craton is estimated to contain more extensive sand aquifers with up to 900 x 10^6 m^3 of saline groundwater (Martin, 1998). No individual resource estimates have yet been made for other Gawler Craton palaeovalleys in their entirety, but most are expected to contain similar quantities of groundwater (Magee, 2009). A first-order estimate of the total groundwater resources of the combined palaeodrainage network throughout the region indicated that up to ten times the total of the Garford and Tallaringa palaeovalleys may be available, i.e., ~12,000 x 10^6 m^3 of groundwater (Martin 1998). Water quality (salinity) generally ranges from about 5,000–70,000 mg/L but scant detailed information on regional bore yields and aquifer characteristics has ever been compiled. Martin (1998) cited anecdotal reports suggesting that some palaeovalley groundwater systems in the Gawler Craton may be artesian. Magee (2009) mounted a strong case around the pressing need for further detailed studies of palaeovalley groundwater resources in the Gawler–Eucla region.

Most of the Gawler–Eucla demonstration site for the *Palaeovalley Groundwater Project* occurs in the designated groundwater provinces of the Gawler Craton and the Eucla Basin. There is minor overlap with marginal parts of the Officer Basin in the north-west, and the south-west margin of the Eromanga Basin (part of the GAB). However, the GAB in this area is not widely used for groundwater supplies. The palaeovalleys of the Officer Basin have been specifically investigated via remote studies (in this project) for the Musgrave Demonstration Site. Other palaeovalleys that may overlie the GAB were specifically excluded from the scope of this project and are not discussed further in this report.

3.3.1. Challenger gold mine

The Challenger gold mine is in the northern Gawler Craton (Figure 9). Lode gold mineralisation is mined from cordierite-bearing metasedimentary rocks of the Archean Christie Gneiss. During development of Challenger, which mined its first ore in 2002, several groundwater investigations were carried-out to assess the available water resources and determine the most suitable supply options for the on-site ore processing facilities, infrastructure development, and camp water requirements, e.g., URS, 2001; REM, 2002. These investigations identified the main hydrostratigraphic units in the Challenger area as:

1. Neogene sediments, underlain by carbonaceous clayey sediments. This shallow sandy aquifer (watertable depth usually <20 metres below ground level) contains the freshest groundwater in the area and supplies stockwater at several pastoral bores. Total dissolved solids (TDS) in the perched aquifer groundwater typically range from 2,600–7,800 mg/L;
2. Regional watertable aquifer developed in weathered and fractured crystalline Archean to Lower Proterozoic basement rocks of the Mulgathing Complex. Groundwater in this aquifer is saline (~ seawater salinity) and is currently used to supply potable water for the Challenger mining camp (via on-site reverse osmosis plant); and
3. Deeper confined palaeochannel aquifer (known as the Challenger Palaeochannel) which drains the regional groundwater system in the local area. The Challenger Palaeochannel is a southerly-trending tributary of the larger Anthony Palaeovalley. The local groundwater gradient

for the Challenger Palaeochannel indicates subsurface flow from north to south, i.e., towards the Anthony Palaeovalley, with pre-development flow rates (estimated based on hydraulic gradients derived from a steady state groundwater numerical model and the measured aquifer properties) estimated at 5 metres-per-year (SKM, 2009). The palaeochannel aquifer comprises of basal sands and is confined by a significant thickness (tens of metres) of carbonaceous clay which overlies the thalweg sands. The stratigraphic profile in the Challenger Palaeochannel is probably similar to the layered sand and clay sequences of the nearby Garford Palaeovalley which are well-defined from extensive DMITRE drilling (see lines G-G’ and H-H’ in Figure 20 for comparable sections). The confining clay layer also forms the base to the local perched watertable aquifer used for stock bores.

The conceptual hydrogeological model for the Challenger gold mine area is shown in Figure 27.

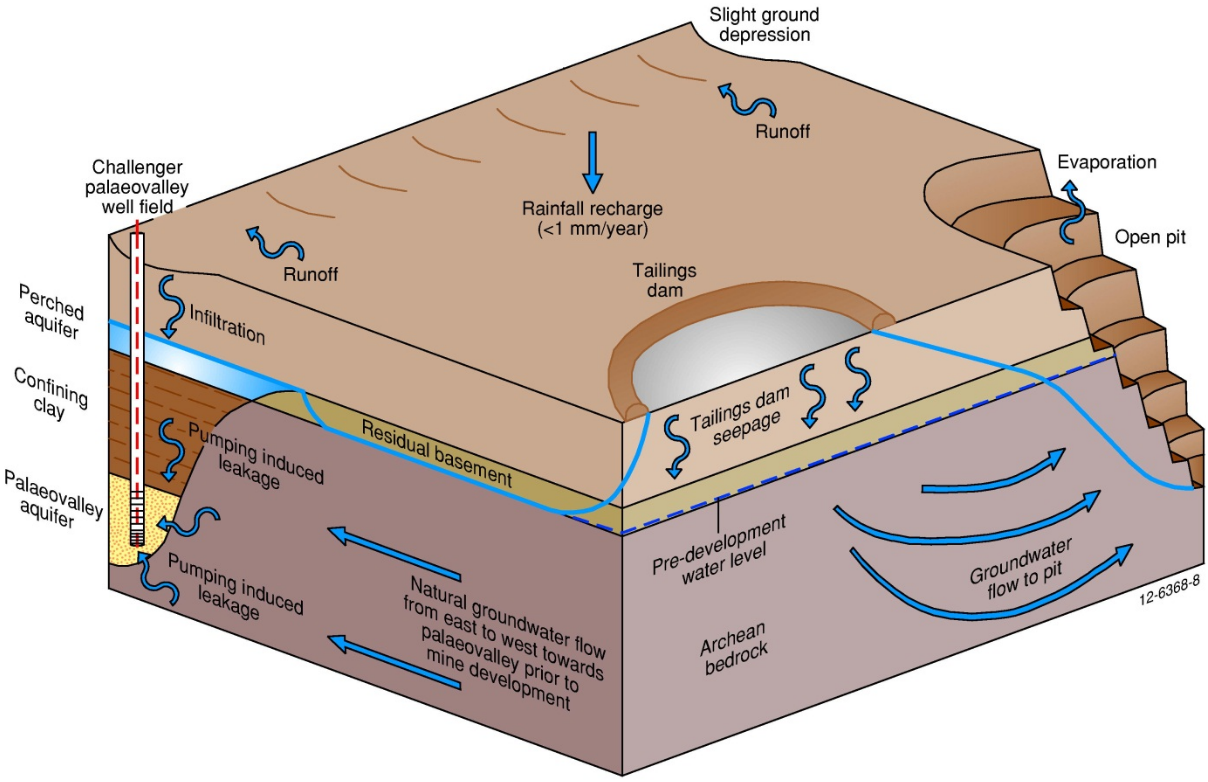


***Figure 27:** Conceptual hydrogeological model developed for the Challenger gold mine area (modified after SKM, 2009).*

Groundwater monitoring data indicates that there is very poor hydraulic connection between the upper perched watertable aquifer and either the regional fractured bedrock aquifer or the confined palaeochannel aquifer (SKM, 2010). The depth to the standing water level for the palaeochannel aquifer varies from about 120–160 metres below ground level (depending on which monitoring bore is measured), and long-term monitoring indicates that the water level is relatively stable.

Following initial hydrogeological studies the Challenger Palaeochannel was targeted as the main water supply source for ore processing at the Challenger gold mine. Four production wells (with adjacent monitoring bores) were drilled into the palaeochannel aquifer to access groundwater and average annual extraction rates now amount to ~500 ML (SKM, 2010). Two of these production wells have been operational since mining began, the third production well was commissioned in September 2007 and the fourth well started pumping in July 2009. Groundwater quality has been monitored regularly in the production wells since operations began (SKM, 2010), and can be summarised as:

1. Highly saline groundwater, with total dissolved solids (TDS) commonly 30,000–50,000 mg/L, ranging up to 130,000 mg/L (hypersaline);
2. Dominantly sodium chloride (Na-Cl) type groundwater, with lesser sulfate;
3. pH range of neutral to slightly alkaline; and
4. Relatively consistent and largely unremarkable major ion concentrations.

Prior to this present study, the groundwater resources of the Challenger gold mine were probably the best-studied palaeovalley groundwater systems on the Gawler Craton. Initial hydrogeological assessments and ongoing annual monitoring programs have provided reliable baseline data on the quality and sustainability of this palaeovalley aquifer since mining operations began in 2002 (Table 2). However, the scope of work on the Challenger Palaeochannel has been spatially restricted to the near-mine area, and the previous hydrogeological studies (and ongoing work) focused exclusively on the water supply requirements of the Challenger gold mine. Consequently, broader regional-scale perspective is notably absent from available consultancy reports. Despite these shortcomings, the available information provides a useful dataset to compare with the findings obtained from this investigation.

3.3.2. Jacinth–Ambrosia heavy mineral sand mine

The Jacinth-Ambrosia heavy mineral sand mine is in the South Australian Eucla Basin about 180 km north-west of Ceduna (Figure 3). The sand deposits, which are owned and operated by Iluka Resources Ltd, contain in excess of 200 million tonnes of zircon-dominated heavy mineral ore. These heavy mineral deposits were formed along the palaeo-shoreline of the Eucla Basin, within an extensive coastal barrier sand system that ringed much of the basin during the Cenozoic (Hou et al., 2011).

Previous groundwater investigations were carried-out by various hydrogeological consultants to determine the most viable and sustainable water resource to support operations at Jacinth-Ambrosia, e.g., Parsons Brinckerhoff, 2005; SKM, 2006. These studies identified a previously unknown palaeovalley system (here termed the Iluka Palaeovalley) situated ~30 km south-west of the deposits as the preferred groundwater supply option for the mine. Aquifer delineation and characterisation were subsequently completed (using integrated airborne electro-magnetic survey data – AEM, drilling, pump tests and numerical modelling) to better understand the palaeochannel groundwater resource and to provide a volumetric estimate of extractable water for the mine. Given this extensive hydrogeological investigation, the Iluka Palaeovalley is the best studied palaeovalley system in the Eucla Basin.

On the basis of detailed AEM data and multiple drilling transects the Iluka Palaeovalley is interpreted as a major SSW-trending system of variable width (1.5–5 km wide) which runs along-strike for at least 50 kilometres (Parsons Brinckerhoff, 2007). The palaeovalley is incised into weathered Precambrian basement rocks (saprolite and weathered granite or gneiss of the Gawler Craton) and the main aquifer is developed at the base of the infill sequence, consisting of fluvial-derived sands and basal gravels of the Eocene Pidinga Formation. The sand deposits are overlain by finer-grained silts and clays which likely represent marginal marine and estuarine facies sediments (10–20 metres thick). These are capped by up to 25 metres of pale Nullarbor Limestone of Miocene age (Figure 28). The palaeovalley stratigraphic profile is indicative of a transitional depositional sequence ranging from terrestrial to estuarine and marginal marine environments, typical of marine transgression and extensive flooding of the original valley.

Table 2: *Average groundwater compositions obtained from production bores CPW1 and CPW2 in the Challenger Palaeochannel near Challenger Gold Mine. Data collected at approximate 6 monthly intervals since July 2002 (although not all analytes were measured at each sampling period). Elements below detection (bd) are not shown.*

Analyte	Symbol	Units	CPW1	CPW2
Barium	Ba	mg/L	0.03	0.03
Beryllium	Be	mg/L	0.01	bd
Bicarbonate	as $CaCO_3$	mg/L		262
Boron	B	mg/L	31.97	5.66
Bromide	Br	mg/L	24	40
Calcium	Ca	mg/L	925	892
Chloride	Cl	mg/L	26,182	25,400
Chromium	Cr	mg/L	0.02	0.01
Copper	Cu	mg/L	0.02	0.02
Electrical Conductivity	EC	μS/cm	46,816	45,631
Fluoride	F	mg/L	<0.5	8.60
Iron	Fe	mg/L	5.43	5.46
Lead	Pb	mg/L	bd	0.01
Magnesium	Mg	mg/L	1,687	1,626
Manganese	Mn	mg/L	0.92	1.10
Molybdenum	Mo	mg/L	0.01	bd
Nickel	Ni	mg/L	0.01	0.02
Nitrate	NO_3	mg/L	0.76	0.40
Nitrite	NO_2	mg/L	0.43	0.40
pH	pH		7.32	7.22
Phosphorous	P	mg/L	0.12	0.15
Potassium	K	mg/L	203	230
Selenium	Se	mg/L	0.10	0.10
Sodium	Na	mg/L	12,936	11,949
Strontium	Sr	mg/L	12.03	13.72
Sulfate	SO_4	mg/L	4,662	6,486
Total Dissolved Solids	TDS	mg/L	44,789	42,359
Zinc	Zn	mg/L	0.08	0.06

The palaeovalley aquifer is unconfined and the aquifer sediments (saturated zone at least 40 metres thick) commonly occur at 45–50 metres depth below surface. Groundwater flow is extremely slow, moving southwards in the direction of the coastline (SKM, 2006. The aquifer receives only minimal recharge. Evaluation of the groundwater contained within the main palaeovalley aquifer (Table 3) shows that it is:

1. Highly saline to hypersaline, with total dissolved solids (TDS) from 40,000–70,000 mg/L, and groundwater salinity commonly increases with increasing aquifer depth (Figure 28);
2. Acidic, with pH 4–6;
3. NaCl-dominated groundwater system with significant levels of $MgSO_4$ but low alkalinity; and
4. Contains high levels of dissolved iron in solution.

Table 3: *Groundwater compositions from test production wells WB1 and WB2 in the Iluka Palaeovalley aquifer (modified from SKM, 2006).*

	Units	Well WB1	Well WB2
Total Dissolved Solids	mg/L	50,100	45,600
Electrical Conductivity	µS/cm	76,800	72,700
Calcium	mg/L	338	395
Magnesium	mg/L	1,660	1,760
Sodium	mg/L	15,700	14,400
Potassium	mg/L	455	455
Chloride	mg/L	26,500	27,100
Sulfate	mg/L	5,450	5,540
Alkalinity	mg/L	<1	<1
Iron	mg/L	54.6	47
Manganese	mg/L	3.4	2.3

Aquifer testing and characterisation was conducted at multiple locations along the palaeovalley (Parsons Brinckerhoff, 2007). For example, a pump test conducted at Well WB1 operated at 15 litres-per-second for 48 hours, and another pump test at Well WB2 ran at 17.8 L/s for 33 hours. These tests showed that the main palaeovalley aquifer is relatively transmissive, with results ranging from 500–1,400 m^2/day, and has an unconfined storage coefficient of 20–30%. Key features of the palaeovalley aquifer derived from the pumping tests (after SKM, 2006) include:

- The Iluka Palaeovalley aquifer is hydrogeologically stratified, with the basal sands and gravels being the most transmissive units;
- Delayed yield (i.e., leakage) from the less transmissive upper units is an important feature of the palaeovalley system; and
- Vertical hydraulic conductivities are 3-10 times less than the horizontal hydraulic conductivities, due mainly to the thinly interbedded nature of various sediment horizons.

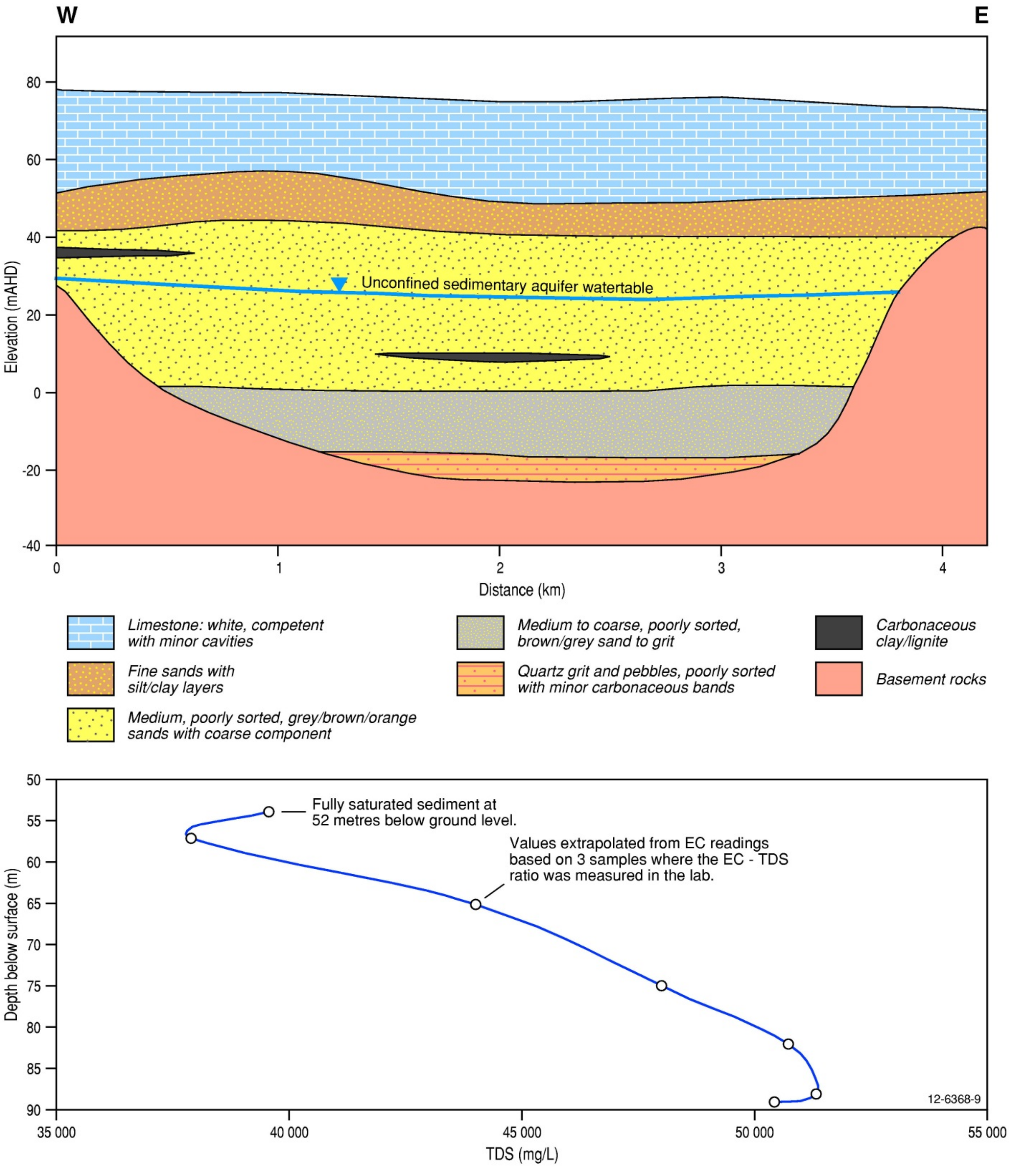


Figure 28: *Upper diagram shows interpreted cross-section for the Iluka Palaeovalley (modified from SKM, 2006). Lower diagram shows profile of TDS (mg/L) variation with depth below surface for the Iluka Palaeovalley, highlighting the general increase in salinity with depth.*

Numerical modelling of the Iluka Palaeovalley based on the aquifer parameters determined from pump testing indicated that the system is capable of providing sufficient groundwater to support Jacinth–Ambrosia mining operations. Modelling suggested that a single borefield with 10 production bores could extract at least 300 L/s of saline groundwater over a 10-year operating period. This would produce ~95 GL of water, which would equate to about 7% of the total water in storage within a 30-km long aquifer system (Parsons Brinckerhoff, 2007). The modelling suggested that drawdown of the watertable would largely be restricted to the confines of the palaeovalley aquifer, and that the watertable would recover to <5 metres below original levels 60 years after pumping ceased.

In summary, several local (but detailed) hydrogeological investigations have been completed to assess the quality and quantity of groundwater stored in the Iluka Palaeovalley. This work has provided (feasible) estimates of the amount of groundwater stored in the main palaeovalley aquifer, and shows that a significant saline groundwater resource exists. This could be used to supply the mining operations at the nearby Jacinth–Ambrosia heavy mineral sand mine.

3.4. Summary

1. Extensive inter-connected palaeodrainage networks, which were active surface water systems at various times during the Cenozoic, occur widely across the western Gawler Craton. Although they are no longer active surface drainages, significant groundwater resources occur within the saturated palaeovalley aquifers, typically hosted in fluvial-derived coarse sands and basal gravel deposits above weathered bedrock.
2. These palaeovalley systems are generally oriented west-south-west to south-west, coincident with the dominant structural trend of bedrock terranes in the Gawler Craton. The direction of groundwater flow largely corresponds with this trend, i.e., flowing towards the palaeo-shoreline of the ancient Eucla Sea.
3. Major sedimentary facies associations are broadly consistent across individual palaeovalleys on the Gawler Craton, reflecting similar sediment provenance and depositional history.
4. The interconnected network of tributary and trunk palaeovalleys stores large quantities of groundwater. However, groundwater quality is typically saline to hypersaline and dominated by sodium chloride (NaCl) compositions.

Previous regional-scale work conducted by DMITRE has provided a detailed understanding on the architecture, evolution and stratigraphy of the Gawler–Eucla palaeovalley networks. However, the groundwater resources of these palaeovalleys are poorly understood at the regional-scale, as past efforts have largely been driven by localised studies to characterise palaeovalley groundwater systems at isolated mining operations such as Challenger and Jacinth–Ambrosia. Consequently, the focus of investigations conducted as part of the *Palaeovalley Groundwater Project* has been to improve regional understanding of palaeovalley groundwater systems across the Gawler–Eucla study site. As outlined in the following chapters, this work has largely involved new field studies to generate baseline hydrogeochemical data for one of the region's largest palaeovalley systems, the **Kingoonya Palaeovalley**.

4. Elucidating Gawler–Eucla palaeovalleys with regional topographic and geophysical data

4.1. Introduction

To complement existing palaeovalley mapping in South Australia (Hou et al., 2007) several regional investigative techniques were evaluated for the Gawler–Eucla site using national-scale topographic and geophysical datasets:

- The Multi-resolution Valley Bottom Flatness Index (or MrVBF);
- Synthetic stream networks generated with ArcHydro software; and
- Regional mapping of depth to magnetic basement, using national-scale airborne magnetic data.

This work aimed to determine the suitability and effectiveness of these three methods in mapping the regional Gawler–Eucla palaeodrainage networks. In particular, this study evaluated the relative potential of the different techniques to further refine the original South Australian palaeovalley map (Hou et al., 2007) for the Gawler–Eucla. These efforts were also applied to other demonstration sites for the Palaeovalley Groundwater Project (refer to other GA Records listed in Chapter 1) so that their overall utility could be assessed for different geological provinces and physiographic regions across the arid and semi-arid zones of Australia.

4.2. The Multi-resolution Valley Bottom Flatness (MrVBF) Index

Gallant and Dowling (2003) noted that zones of sediment deposition play an important role in hydrology because of their ability to absorb and store water. They developed an automatic mapping algorithm for delineating such areas from digital elevation data, known as the Multi-resolution Valley Bottom Flatness (MrVBF) index. This algorithm identifies relatively flat and low-lying areas in the landscape at a range of scales from digital elevation model (DEM) grids, using slope to derive flatness and ranking of elevations within a circular context to derive local low points (Gallant and Dowling, 2003). The DEM is smoothed and coarsened in multiple steps and the algorithm is applied at each resolution. The results at different resolutions are then combined to produce a single multi-resolution index. The index separates upland terrain dominated by erosional processes from lowland depositional terrain, and further divides the depositional areas into different classes based on slope and areal extent, e.g., larger values correspond to broader and flatter valley bottoms. Larger values generally correspond to greater sediment thicknesses in the depositional environment.

Across the Gawler–Eucla demonstration site the MrVBF index has been applied to the 1-arc second Shuttle Radar Topographic Mission (SRTM) DEM grid (Figure 29). Our previous research efforts with the MrVBF algorithm at other sites (e.g., the Paterson Province in WA; English et al., 2012) have shown that both the final derived product and several of the intermediate product levels (particularly Levels 5 to 7) can assist in identifying and mapping segments of palaeovalley trunks and tributaries. Intermediate level imagery proved better able to discriminate subtle landform features that may be related to buried valleys. For example, many of the MrVBF outputs correlate closely with surface features such as salt lakes (low and flat) and raised coastal barrier dune systems. In the Gawler–Eucla region our work recognised that the MrVBF Level 6 output provides enhanced definition and greater resolution of palaeovalley features compared with other MrVBF levels. However, most of the intermediate stage outputs are more useful for defining palaeovalley features than the final MrVBF image, which tends to lack the finer resolution needed to identify smaller tributaries (Figure 30).

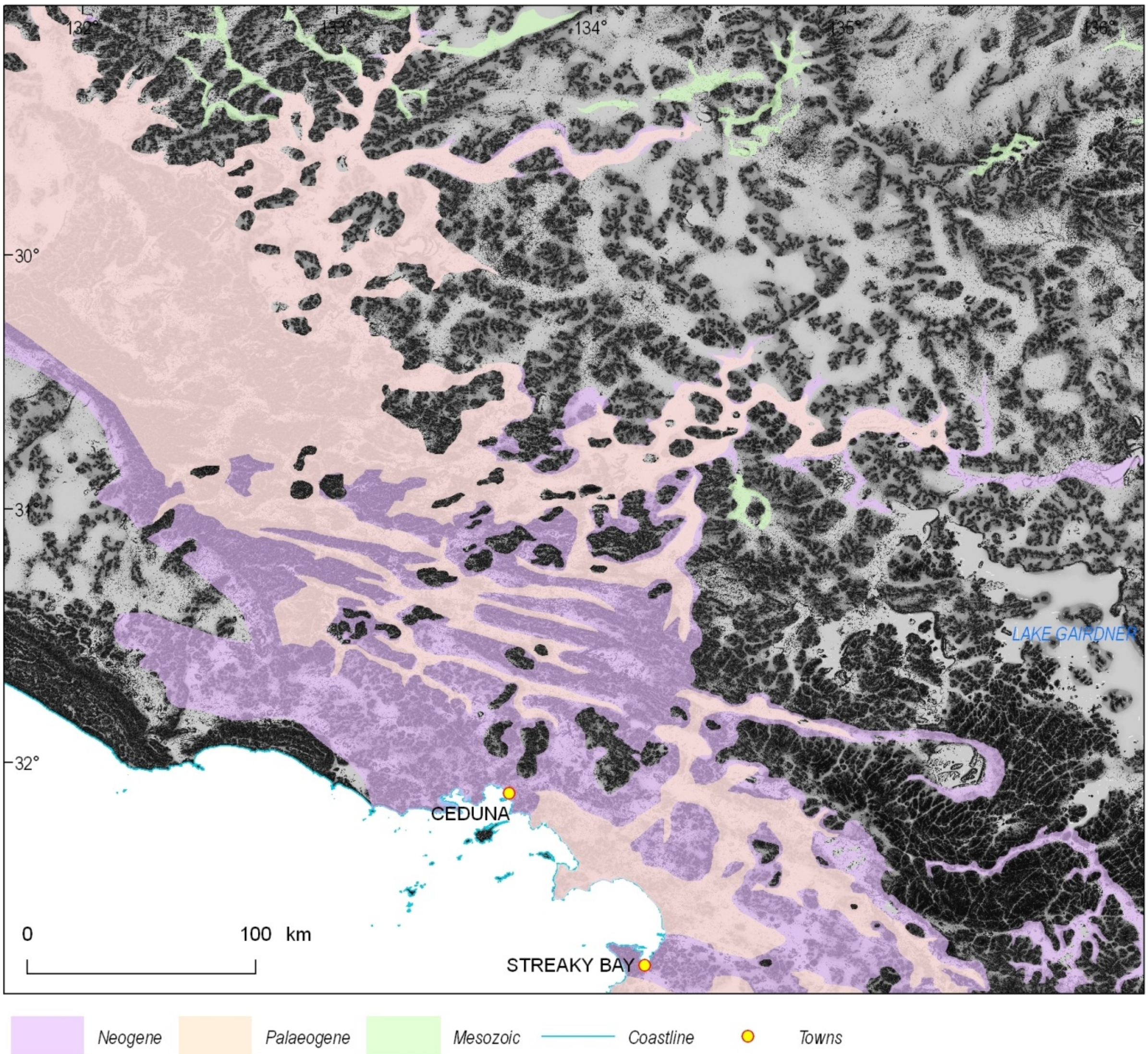
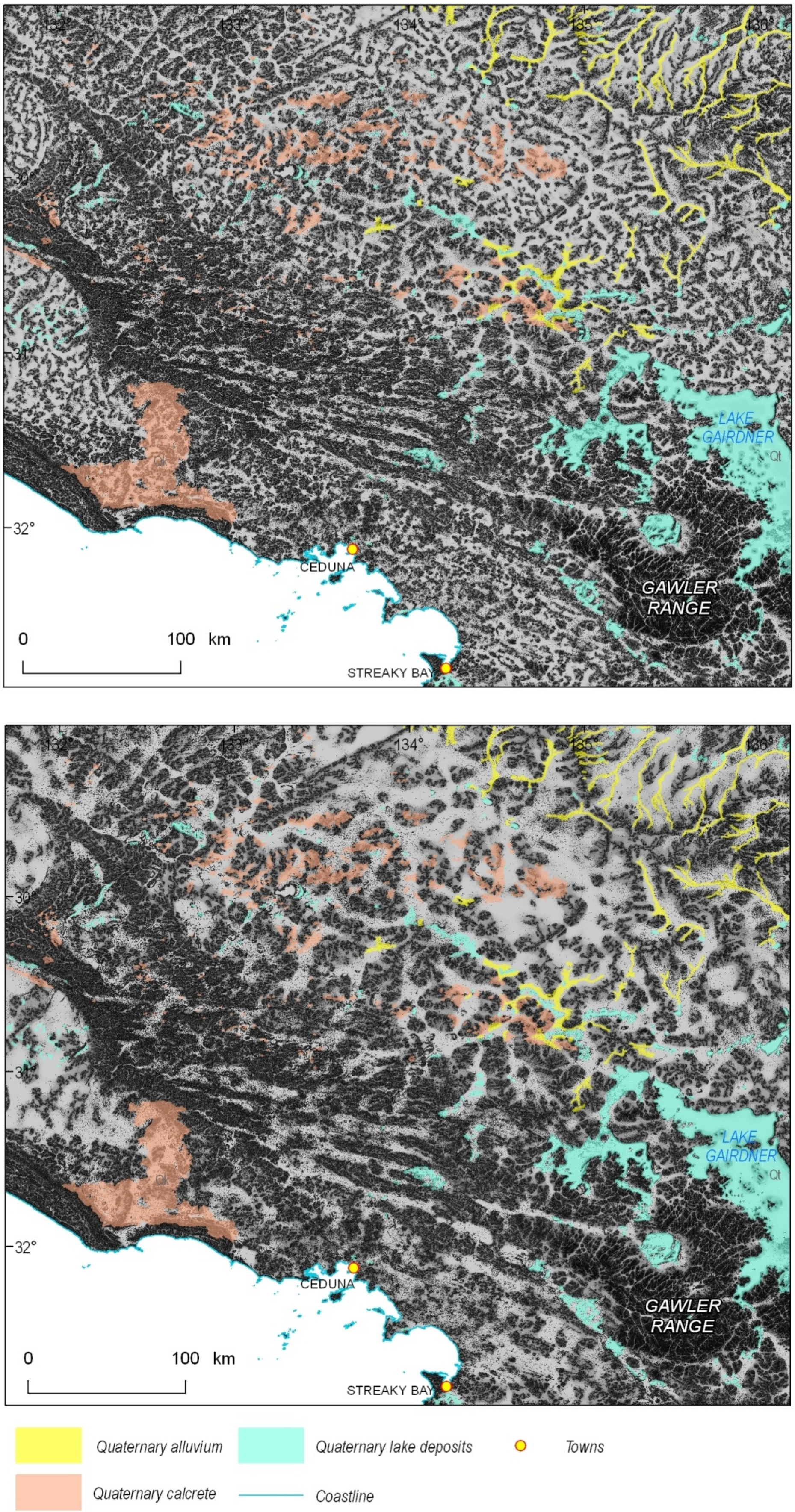


Figure 29: *The MrVBF Level 6 image of the Gawler–Eucla region with South Australian palaeovalley polygon layers overlain (partly transparent). The low and flat areas of the topographic surface are shown as white, whereas relatively higher and steeper areas are black. At these regional scales major systems such as the Kingoonya, Garford and Tallaringa palaeovalleys correspond closely with low and flat-lying areas of the landscape, highlighting the usefulness of the MrVBF image as a regional-scale reconnaissance tool for detecting palaeovalley systems. The spatial distribution of palaeovalleys (of Neogene, Palaeogene and Mesozoic age) is modified from the work of Hou et al., 2007.*

Figure 30:*(overleaf) Comparison of MrVBF Level 5 (upper) and Level 6 (lower) for the Gawler–Eucla. Quaternary alluvium and calcrete are spatially associated with the Kingoonya Palaeovalley.*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STREAKY BAY
Quaternary alluvium
Quaternary lake deposits
Towns
Quaternary calcrete
Coastline

4.3. Applying synthetic streams using ArcHydro software

The scope and scale of regional palaeovalley assessments makes geographic information systems (GIS) a powerful tool for analysing extensive datasets and evaluating spatial data relationships. At the regional scale, palaeovalley mapping depends on using many related data sources to assess geologic and physiographic features. The application of GIS plays a significant role in this process, providing consistent methods for palaeodrainage delineation using digital elevation models (DEM). The ArcHydro software application has been developed as a useful add-on to the standard ArcGIS environment and has the required tools to enable detailed terrain analysis for palaeovalley mapping (Maidment, 2002).

The ArcHydro toolset was applied to the Gawler–Eucla regional DEM as part of our efforts to assess the utility of regional data in mapping palaeovalleys. ArcHydro tools consist of two modules, with one developed for surface water applications by the *ESRI*, and the other developed for groundwater investigations by *Aquaveo* (Appendix 2). One particularly useful feature of the ArcHydro toolset is the ability to generate and define synthetic drainage patterns based on DEM data, e.g., the SRTM dataset. As the shape of the land surface directs the drainage of water through the landscape, the erosive power of water slowly reshapes the physical features of the surface. Digital elevation models (DEM) have thus been used to analyse drainage patterns of surface terrain, and drainage areas can be mapped according to physical rules. This feature is particularly useful in arid zones where perennial streams are rare, as the synthetic stream output provides visual clues to better understand the spatial arrangement of relict (and commonly buried) drainage patterns.

The Gawler–Eucla demonstration site occurs in an arid region of South Australia and there are no active perennial surface water bodies. The ArcHydro toolset has been applied to the regional DEM (Figure 3) to derive a synthetic stream network (Figure 31). Analysis of this stream pattern highlights depressions in the surface topography (relative low points in the landscape) that may reflect part of the ancient surface drainage pattern. Many of these topographic lows correspond to existing palaeovalleys mapped at broad-scale, suggesting that there is moderate to strong coincidence of palaeovalleys with the synthetic stream network generated for the Gawler–Eucla region, especially on the broader plains. Our further analysis indicates that the ArcHydro toolset may also assist in defining segments of the higher-order tributary network, which is otherwise difficult to identify. Indeed, this has directly helped us to identify potential upper tributaries connected to broader parts of the Kingoonya Palaeovalley.

4.4. Mapping depth to magnetic basement

The geomagnetic response of sedimentary basins is affected predominantly by the geomagnetic field of the underlying basement rocks. Generally, sedimentary rocks have weak magnetic responses due to the low abundance of magnetic minerals, and the effects of various geological processes such as weathering and oxidation. Thus, the depth to magnetic basement (also known as crystalline basement) can be defined by mapping the distribution of magnetic minerals which occur in the deeper rock mass.

Several techniques have been developed to estimate the depth to crystalline basement rocks from magnetic data, such as the:

1. Naudy method (Naudy, 1971);

2. Euler deconvolution (Thompson, 1982);
3. Werner deconvolution (Werner, 1953; Ku and Sharp, 1983); and
4. Spectral Slope method (Spector and Grant, 1970).

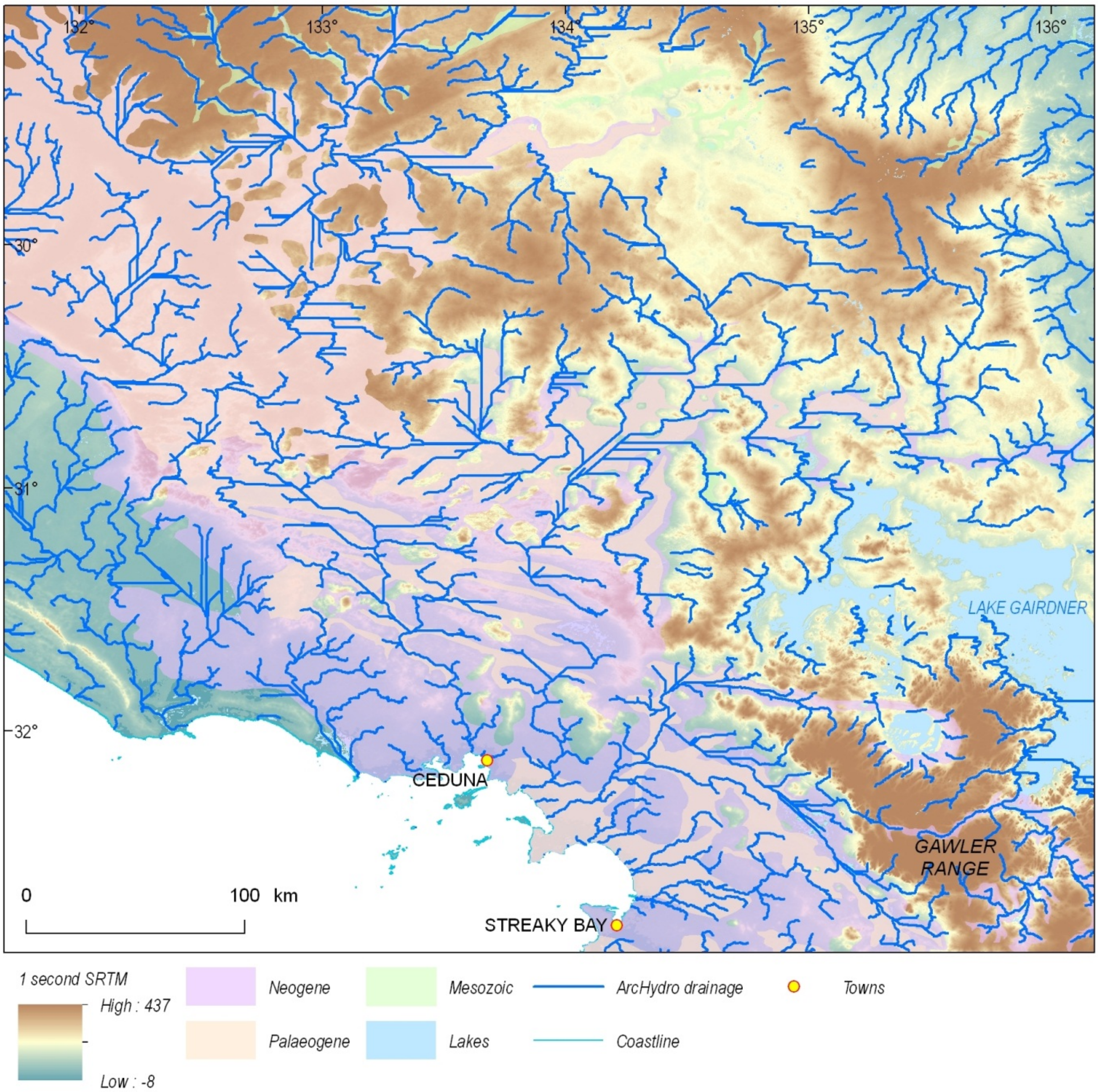


Figure 31: *ArcHydro synthetic streams for Gawler–Eucla region (blue lines) overlain on the 1-arc second SRTM digital elevation model. There is strong coincidence between the mapped palaeovalleys and the artificially derived stream network, indicating that this ArcHydro application provides useful information to identify and delineate regional palaeovalleys.*

For this study, the total magnetic intensity (TMI) data from the national aeromagnetic grid of Australia was sampled for the Gawler–Eucla demonstration site (Figure 32). Geoscience Australia is custodian of this national geophysical dataset, which is freely available for download via the Geophysical Archive Data Delivery System (GADDS):

http://www.geoscience.gov.au/bin/mapserv36?map=/public/http/www/geoportal/gadds/gadds.map&mode=browse.

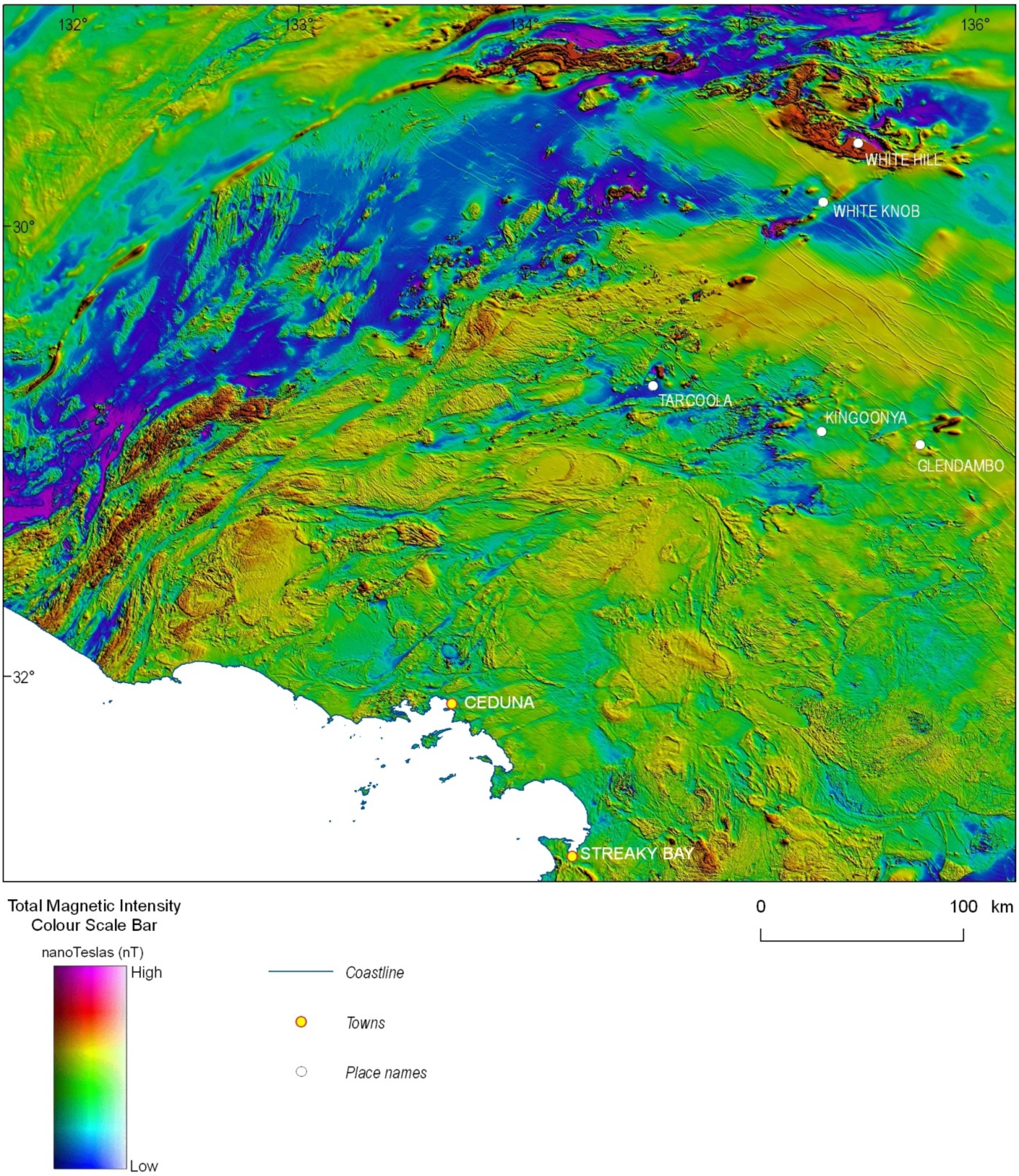


Figure 32: *Total Magnetic Intensity image (from aeromagnetic grid data) of the Gawler–Eucla study site. The TMI data were accessed through Geoscience Australia's internal data systems, and can also be freely accessed via GADDS.*

4.4.1. Processing methodology

The Spectral Slope method of Spector and Grant (1970) provides an estimate of the depth to crystalline (magnetic) basement rocks based on the analysis of the power spectrum of aeromagnetic data. The method was applied to the total magnetic intensity (TMI) data for the Gawler–Eucla region (40 metre grid cell size), which is stored in the National Airborne Geophysical database at Geoscience Australia. The TMI grid was then reduced to the pole to normalize the effect of induced magnetisation and dipole effects of magnetic bodies using *Intrepid* processing software. The grid was subsequently divided into sub-domains of 20 x 20 kilometres with 50% overlap and radial power spectra were generated for each sub-domain with *Intrepid* software (Figure 33).

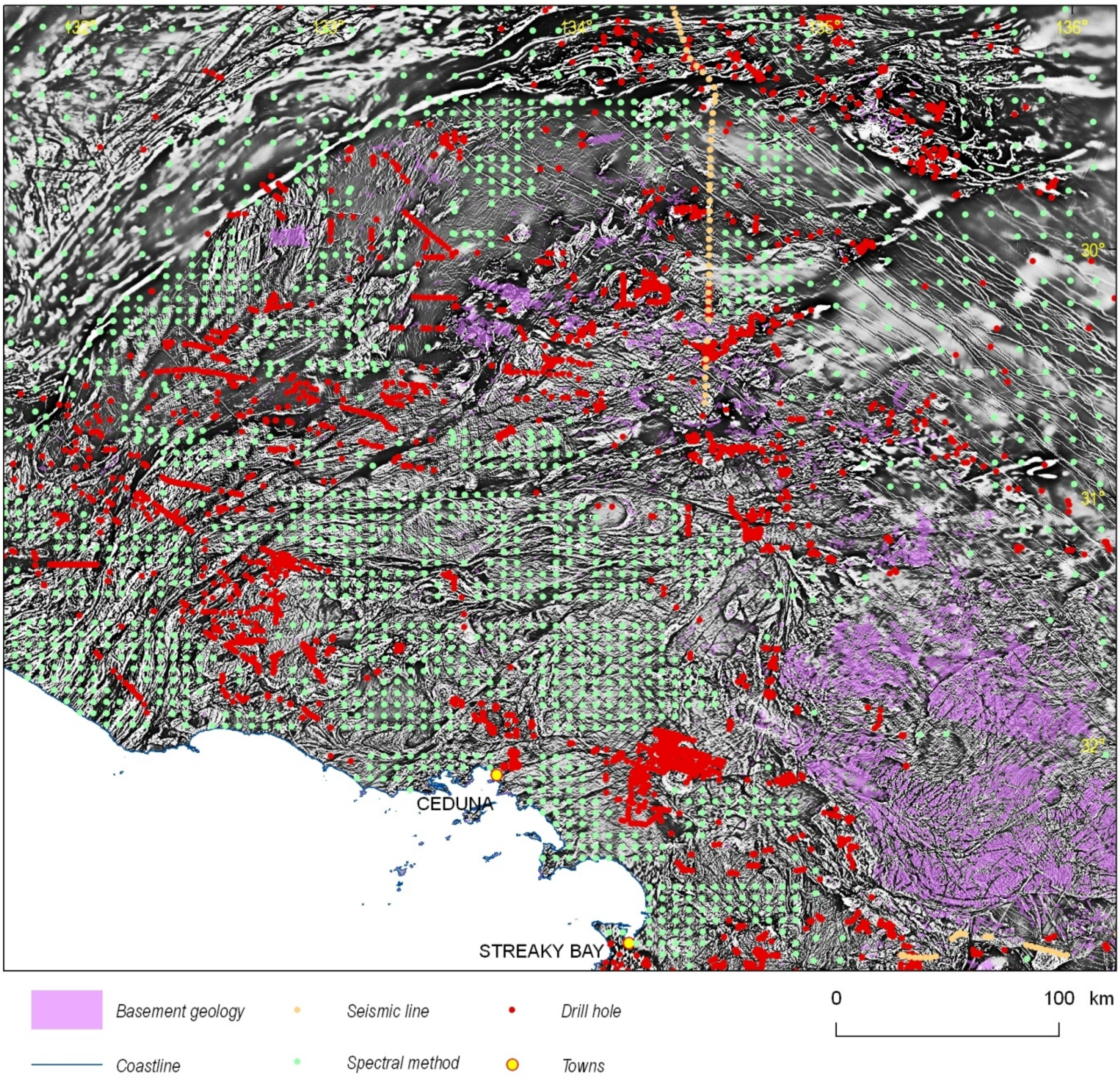


Figure 33: *1st vertical derivative map of the total magnetic intensity (TMI) field with the location of basement outcrop, drill holes and centre point for each spectral sub-domain used for depth estimation.*

Each radial spectrum was examined using Geoscience Australia in-house Matlab scripts to determine the slope, and hence calculate the mean depth to the top of the crystalline basement within the selected sub-domain. Testing has shown good correlation between the magnetic estimated depths and the actual basement depths, where it can be confidently determined from drilling and seismic data (Figure 33).

Using this dataset, the Spectral Slope method (Spector and Grant, 1970) was then used to compute the depth to magnetic basement across the entire Gawler–Eucla study site. The purpose of this approach was to determine if depth to magnetic basement mapping could be usefully applied to define the location and depth of arid zone palaeovalleys at the regional scale. A computer programming routine was developed to semi-automate the process of calculating depth to the magnetic basement, which could then be analysed for potential palaeovalley signatures.

4.4.2. Results and discussion

The grid of depth to basement estimates obtained using the spectral method, combined with borehole data and seismic interpretation for the Gawler–Eucla site (Figure 34), shows that two main factors control the nature of the final mapping output, namely: the original survey parameters such as flight-line spacing and nominal altitude, and the intensity of magnetisation of the crystalline basement.

In areas with closer flight-line spacing there are more accurate estimates and improved definition of the basement depth and structure, e.g., in the central west and south-eastern regions of the Gawler–Eucla site. However, even though reduced flight line spacing (≤250 metres) provides good resolution of basement depths at sub-basin scale, this scale of resolution is unable to resolve palaeovalley features as they typically have much smaller wavelengths. Highly detailed magnetic surveys with line spacing of ≤100 metres could potentially define larger palaeovalley systems (e.g., major valley trunks), but the acquisition of such closely-spaced data would prove costly. Consequently, there were no high-resolution aeromagnetic data used for the depth to magnetic basement mapping for this study.

The second major factor relating to the magnetisation of the basement is also vital. The Spectral Slope method will pick the depth to the first highly magnetic layer below surface. Thus, in areas where consolidated basement has low magnetisation (e.g., due to weathering), the method will fail to yield an accurate result for depth to basement. Further details on this technique were presented at the Australian Society of Exploration Geophysicists (ASEG) conference in Sydney (August 2010) (Meixner et al., 2010: Appendix 3).

In conclusion, although the application of the Spectral Slope method using the available regional airborne magnetic data was successful, our analysis of the results shows that the resolution of these data is too coarse to permit detailed delineation of palaeovalley features in the Gawler–Eucla. Consequently, there was no further development or application of the depth to magnetic basement work as part of this study.

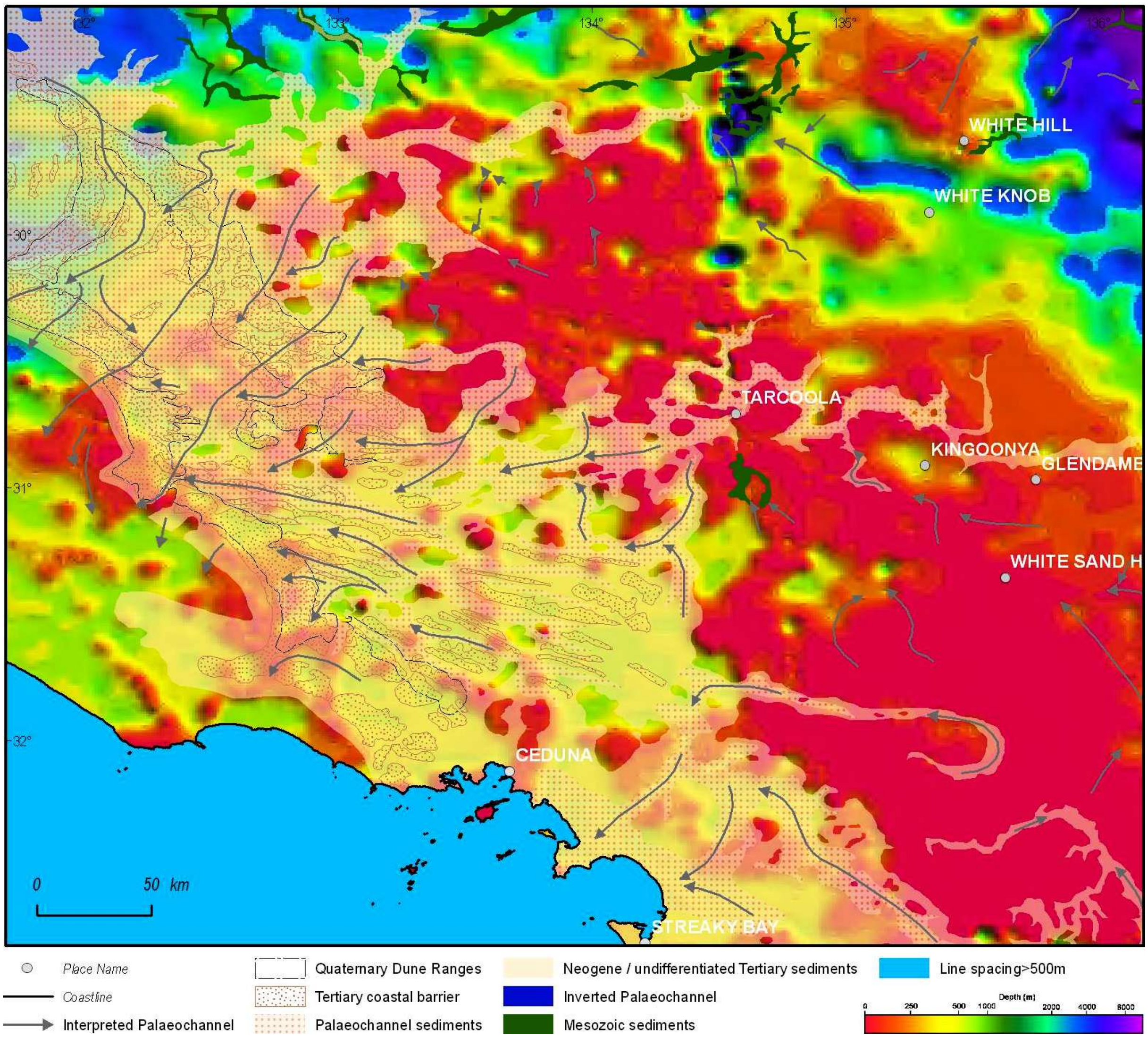


Figure 34: *Colour-draped image of the estimated depth to magnetic basement map, overlain with the Palaeodrainage and Tertiary Coastal Barriers of South Australia; 1:2M scale map (Hou et al., 2007).*

4.5. Conclusions on regional mapping techniques

As part of our approach to investigate the palaeovalleys of the Gawler–Eucla region we applied three regional mapping techniques using readily available national datasets, namely the 1-arc second SRTM DEM and the Australian aeromagnetic grid. Based on this work, the following conclusions are made:

4.5.1. MrVBF

The Multi-resolution Valley Bottom Flatness (MrVBF) algorithm provides a robust and effective terrain analysis tool that is relatively easy to apply to regional topographic data in the GIS operating environment. Application of the MrVBF method to the Gawler–Eucla site showed that several of the intermediate stage outputs (rather than the final derived product) provide better definition of palaeovalley features and are more likely to show evidence of smaller tributary branches. There is good overall agreement between several of the MrVBF outputs and the existing South Australian palaeochannel map (Hou et al., 2007), even though the MrVBF tool was not used to generate the original SA map. The MrVBF output clearly provides enhanced definition and mapping power compared to stand-alone visual inspection of aerial photography, satellite imagery and DEM. Consequently, its application is highly recommended as one of the initial steps involved in delineating palaeovalley systems (as well as other landscape features) during regional reconnaissance mapping.

4.5.2. ArcHydro streams

Synthetic stream networks of varying scale can be generated over regional DEM using ArcHydro tools. When applied to arid environments the stream output from ArcHydro software forms an artificial surface drainage pattern that could potentially develop if sufficient precipitation was available to the local hydrologic system. Based on the topographic variations that naturally occur in the landscape the ArcHydro software uses predetermined rules to mimic the flow of water. This can assist in mapping palaeodrainage networks due to the commonality of palaeovalleys and topographic lows. In particular, our research has shown that finer aspects of otherwise undetectable tributaries can be determined by generating synthetic streams. However, we caution against applying this method in isolation, as it is critical to regard the model outputs as artefacts of the topographic data and not true representations of palaeovalley systems. Despite this limitation, ArcHydro tools can provide another useful application to aid mapping efforts, especially when used in conjunction with other regional analysis techniques such as the MrVBF index.

4.5.3. Depth to magnetic basement mapping

The use of depth to magnetic basement mapping is of limited value for detailed palaeodrainage mapping. The derived basement map for the Gawler–Eucla site generated from this research failed to identify any regional palaeovalleys. A key limiting factor in the application of this technique is the line spacing of the input data; at the typical 400 metre spacing of Australia’s national airborne magnetic coverage the magnetic basement maps are simply too coarse to define even relatively large palaeovalleys. For most arid zone regions this essentially limits the use of depth to magnetic basement studies to the much larger scale of sedimentary basins, where it may provide a useful first-order estimate of the depth of sedimentary cover overlying crystalline basement. The method is potentially useful for palaeovalley exploration in areas of high-resolution data coverage (<100 metres line spacing), but unless already acquired for other purposes (such as mineral exploration) the high cost of obtaining such detailed data would make the technique prohibitively expensive for most water resource studies.

5. Investigating palaeovalley groundwater systems in the Gawler–Eucla region

5.1. Introduction

Prior to developing the Gawler–Eucla field work program our initial review of previous hydrogeological studies showed distinct lack of data and information to characterise regional palaeovalley groundwater systems. As outlined in Chapter 3, existing detailed work on mine water supply and environmental monitoring programs was localised to near-site areas around the Challenger and Jacinth–Ambrosia deposits. Consequently, the broader regional perspective on groundwater systems was lacking from these reports. To address this fundamental gap in existing knowledge of the Gawler–Eucla palaeovalley aquifers a new field investigation was considered a critical task for the *Palaeovalley Groundwater Project*.

Following several workshop consultations among the project Technical Advisory Group (TAG) (with meetings held at Glen Helen in October 2008, Ceduna in May 2009 and Kalgoorlie in 2010), there was widespread consensus to focus on improving regional understanding of palaeovalley groundwater systems from the Gawler–Eucla site, with particular emphasis on acquiring and interpreting baseline hydrogeochemistry data. Further consultation among project staff at Geoscience Australia and the Geological Survey of South Australia (GSSA) identified the **Kingoonya Palaeovalley** as the main regional target for this new work program. This decision was based on recognition that:

- It is one of the longer and deeper arid zone palaeovalleys in South Australia, and its spatial extent is relatively well constrained due to previous integrated mapping and detailed drilling (Hou, 2004; Hou et al., 2007);
- The geological composition, stratigraphic architecture and palaeogeographic evolution of the buried valley are well understood from recent investigations, which have focused mainly on the upper and middle reaches of the palaeovalley system (Hou, 2004);
- The region has relatively more groundwater bores and wells across the length of the system than other palaeovalleys in the Gawler–Eucla region;
- The groundwater system in the Kingoonya Palaeovalley is poorly characterised, with basic information such as total dissolved solids and electrical conductivity data lacking for most bores listed in the South Australian government groundwater database;
- The area is currently being targeted by mineral exploration companies for a variety of commodities (such as uranium and gold), and any future mining operations that may occur (if successful mineral deposit discoveries are made) would almost certainly seek to use palaeovalley aquifers as a main source of water; and
- The area is serviced by several small outback communities (Kingoonya, Tarcoola and Glendambo) and potential sampling sites are relatively easy to access via existing roads or pastoral station tracks.

5.2. Key research objectives

The main objectives of our new field program for the Gawler–Eucla demonstration site were to:

1. Characterise the hydrogeochemical composition of groundwater from the Kingoonya Palaeovalley, including standard physical parameters such as pH, Eh and temperature, major and minor (trace) ionic species, stable isotopes (oxygen and deuterium), and radiogenic isotopes (carbon-14 and radon-222);
2. Evaluate the spatial distribution and variability of hydrogeochemical data from the Kingoonya Palaeovalley, relating observed data patterns or trends to the geological composition of the basement rocks or palaeovalley sediments;
3. Determine the dominant physical and chemical processes that affect the groundwater system in the Kingoonya Palaeovalley;
4. Compare the new compositional data with the existing (though limited) hydrogeochemical data available for localised mine-scale studies at Challenger and Jacinth–Ambrosia, in order to evaluate variations in the hydrogeochemistry of different palaeovalleys in the Gawler–Eucla region; and
5. Interpret the evolution and temporal development of the Kingoonya Palaeovalley aquifer, including radiocarbon dating of groundwater, and provide recommendations about the viability and sustainability of the overall groundwater resource.

5.3. Groundwater sampling in the Kingoonya Palaeovalley

Preliminary hydrostratigraphic interpretation conducted for this project identified several prospective aquifers in the Kingoonya Palaeovalley. In particular, the highest groundwater yields are likely to occur in the basal sections of the Eocene infill sequence where coarse-grained sands and some gravel- and pebble-rich horizons occur. These represent remnant sediments of the palaeochannel thalweg and are the units of greatest hydraulic conductivity in the palaeovalley sequence. Although significant quantities of groundwater are expected to occur in the Kingoonya Palaeovalley, water quality is likely brackish to saline given the very low precipitation and subdued rates of flow in the groundwater system. This interpretation is supported by regional groundwater data available from the South Australian Department of Environment, Water and Natural Resources (DEWNR), which shows elevated salinity levels in the shallow aquifer across most of the Kingoonya study region (although the salinity data do not discriminate between groundwater in fractured rocks, palaeovalleys, and near-surface perched aquifers, Figure 35). Depth to watertable for the shallowest aquifer across the region is commonly >10–20 metres (Figure 36).

5.3.1. Pre-fieldwork planning and GIS data analysis

To successfully achieve the objectives of the proposed investigation program sample collection sites were first identified from existing data. Our plans for new groundwater sampling were restricted to existing water bores and wells within the Kingoonya region, as there was no opportunity (due to funding and resource restrictions) for new drilling operations and bore installations. Permanent surface water is also scarce in the region and there are no recorded groundwater springs or seeps, indicating that accessible bores or wells are the only viable source of groundwater for sampling.

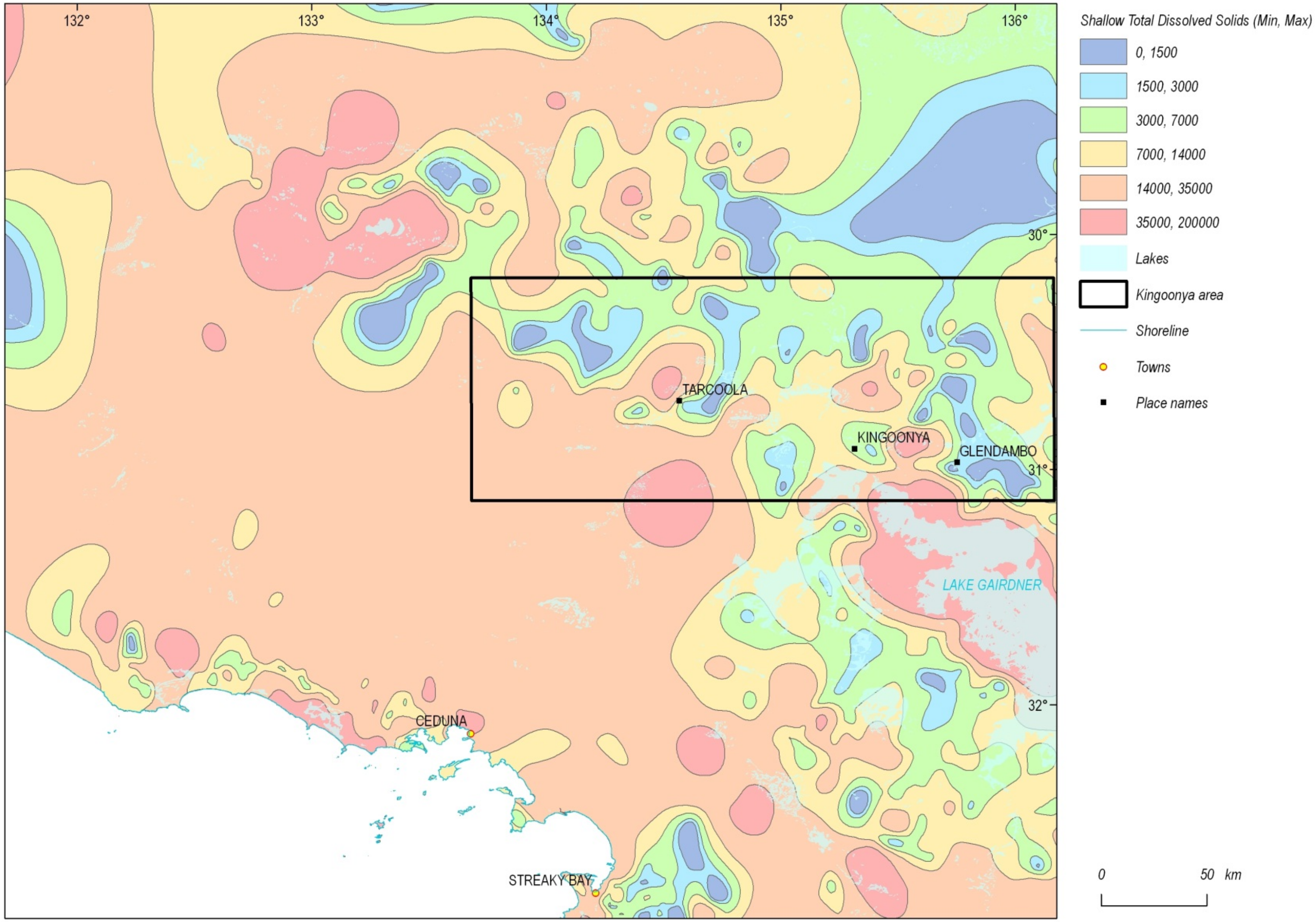


Figure 35: *Regional groundwater salinity data (total dissolved solids, TDS) for the shallowest aquifer across the Gawler–Eucla region (based on data from the South Australian Department of Environment, Water and Natural Resources). Note that this map is based on relatively sparse point-source data, suggesting that the distribution of some water quality zones depicted here is largely an artefact of the contouring method used to develop the map.*

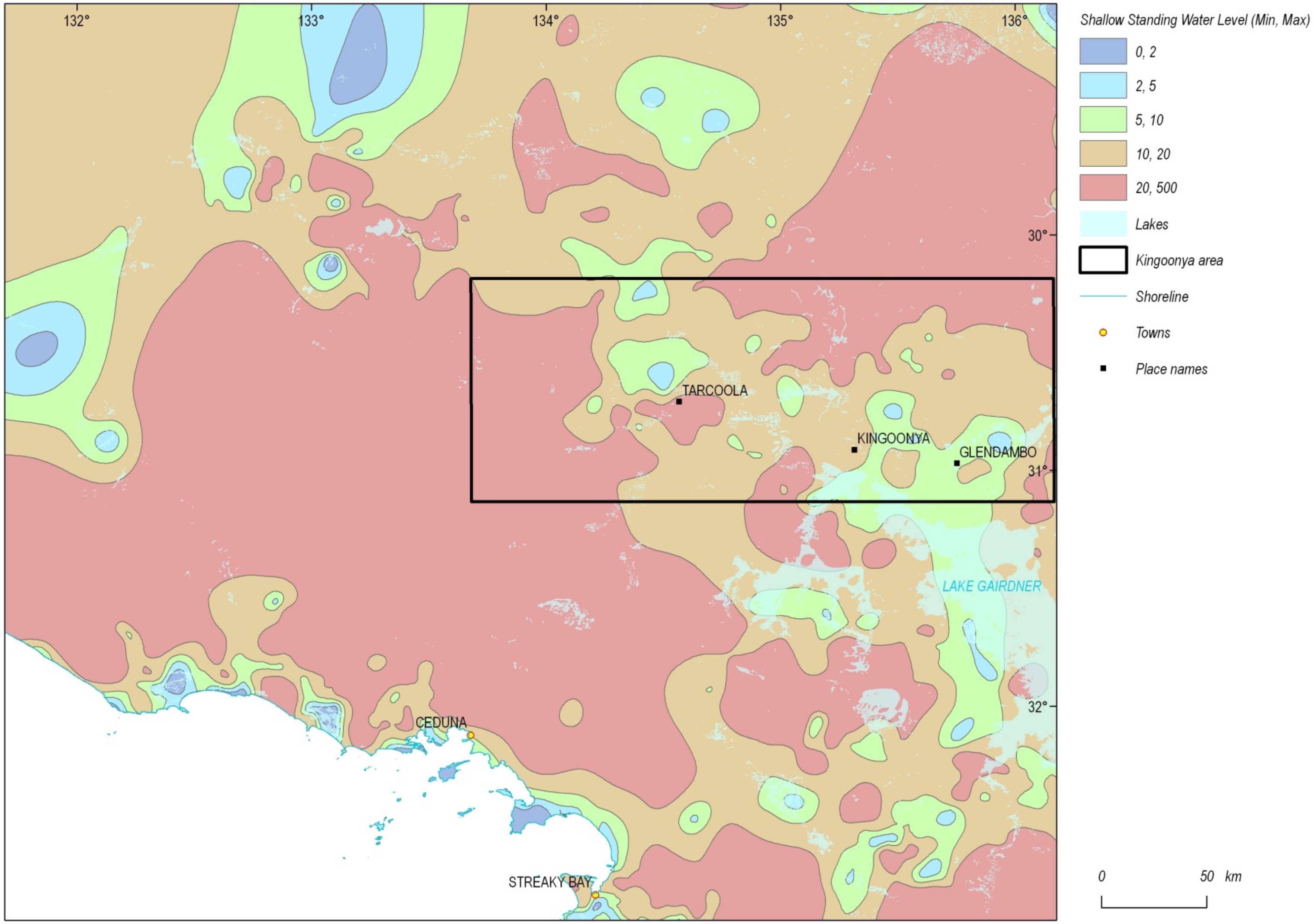


Figure 36: *Regional depth to watertable contour map (in metres below surface) for the shallowest aquifer system across the Gawler–Eucla study site (based on data obtained from the South Australian Department of Environment, Water and Natural Resources). The Kingoonya region study area is shown.*

The initial task in fieldwork planning focused on selecting potential sampling sites. This work was completed by desk-top analysis of existing spatial and borehole data from the South Australian government, for example, freely available borehole data downloaded from the South Australian Resources Information Geoserver, SARIG (http://www.pir.sa.gov.au/minerals/sarig). SARIG is the South Australian government online database that provides the most comprehensive listing of state-wide groundwater bores (among many other resource-related datasets). The database contains basic groundwater information for the entire state including location, yield, salinity, lithology, and drilling data for many wells and bores (note that completed data entries are absent for many bores, such as those that pre-date the development of the database and the implementation of standard reporting requirements – some historic data may also not yet be entered into the database, i.e., it remains stored on microfiche or in hard-copy reports). Following digital download the data were incorporated into the *Palaeovalley Groundwater Project* geodatabase (ArcGIS format) for the Gawler–Eucla region (Figure 37).

During the initial planning phase potential groundwater sampling sites in the Kingoonya Palaeovalley were selected to coincide with palaeovalley reaches which originally formed in palaeo-terrestrial (fluvial and lacustrine) environments. Further downstream of Tarcoola (>20 km) palaeogeographic reconstructions indicate that the Kingoonya Palaeovalley was variably influenced by marginal marine conditions throughout the Cenozoic, especially during major marine transgressions that flooded the estuaries further inland (Hou, 2004). Consequently, no wells were selected for sampling within the downstream estuarine-dominated parts of the Kingoonya Palaeovalley (note that there are no wells or bores drilled into this part of the palaeovalley, probably because there is no agricultural activity carried-out in this region).

Potential sampling locations were initially selected using a simple GIS query in the ArcGIS operating environment. This query highlighted bores from the SA state database that coincided with the mapped extent of the Kingoonya Palaeovalley (based on the map of Hou et al., 2007). A 2-kilometre wide boundary filter was applied to the palaeovalley polygon so that proximal bores (which may intersect palaeovalley sediments or parts of adjacent aquifers such as fractured or weathered basement rocks) would also be included in the short-list.

Upon running the initial GIS query ~210 bores within the pre-defined Kingoonya Palaeovalley survey area were selected. As part of our internal data quality assurance and control (QA/QC) process detailed analysis of the information in SARIG available for this subset of bores indicated that, of the total number of positive matches, only about 60 bores were likely to be suitable for groundwater sampling (Figure 38). The remainder of the bores/wells were deemed unsuitable due to:

- Boreholes being incorrectly attributed in SARIG as water wells when it was clear from analysis of the more detailed information in the database that they were originally drilled as mineral exploration holes, and thus cannot be sampled for groundwater due to improper development as water wells (e.g., uncased holes or holes were back-filled);
- Bores labelled as abandoned or not-open as of their last status update;
- Bores not completed to sufficient depth to intersect the watertable;
- Bores too shallow for groundwater sampling, e.g., the hole was abandoned after only a few metres of drilling; and
- Bores labelled as ‘dry’.

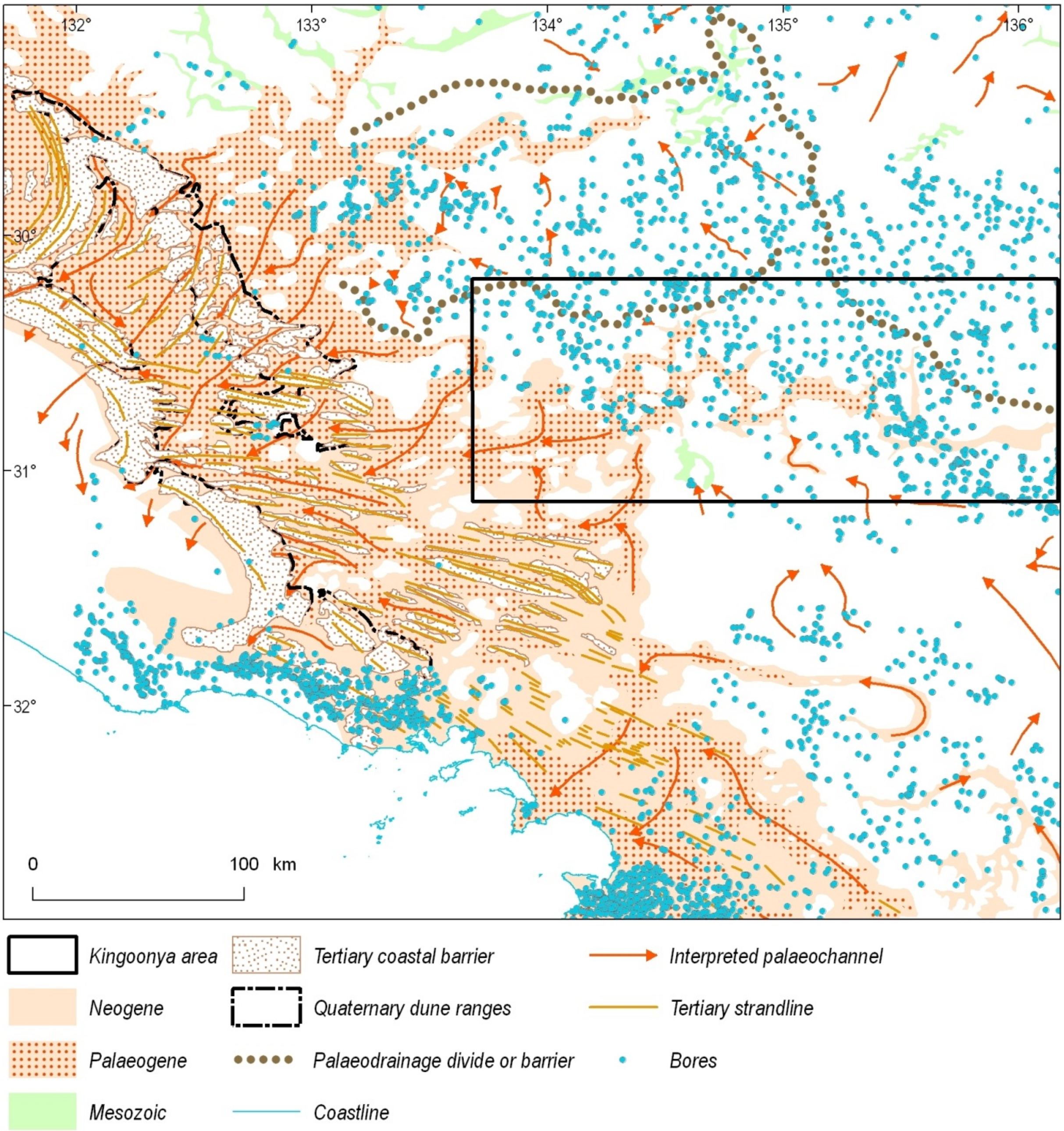


Figure 37: *Existing groundwater bores and wells within the Gawler–Eucla study site, based on the groundwater bore dataset from the South Australian Resources Information Geoserver (SARIG). The main investigation area around the Kingoonya Palaeovalley is also outlined. Note that there are no bores drilled into the more downstream, estuarine-dominated parts of the Kingoonya Palaeovalley, i.e., in the south-west corner of the outlined study area.*

Further database analysis of the ~60 boreholes selected for sampling indicated sparse available information on groundwater and lithological characteristics. Although SARIG is capable of storing significant amounts of data for each bore or well, most of the selected bores from the Kingoonya region lacked detailed information. Typically, the location (X, Y coordinates), construction date, type of drillhole and drilling depth are the only completed data fields. There are also standing water levels (SWL) for many holes (although readings may be decades old), and rare electrical conductivity and bore yield data. More detailed information relating to the downhole lithologic sequence and other characteristics of the groundwater system were either never recorded during construction or have subsequently been lost or misplaced. This effectively means that the only way to now determine the actual geological sequence which has been intersected by each bore is to re-drill adjacent holes. Consequently, this high level of hydrogeological uncertainty means that some boreholes which appear (from the existing SA palaeochannel map) to be situated in the Kingoonya Palaeovalley may actually intersect other geological formations, such as fractured rock aquifers of the surrounding basement sequence. Our method for handling this geological uncertainty in the data analysis phase is discussed further in Section 6.3.1.

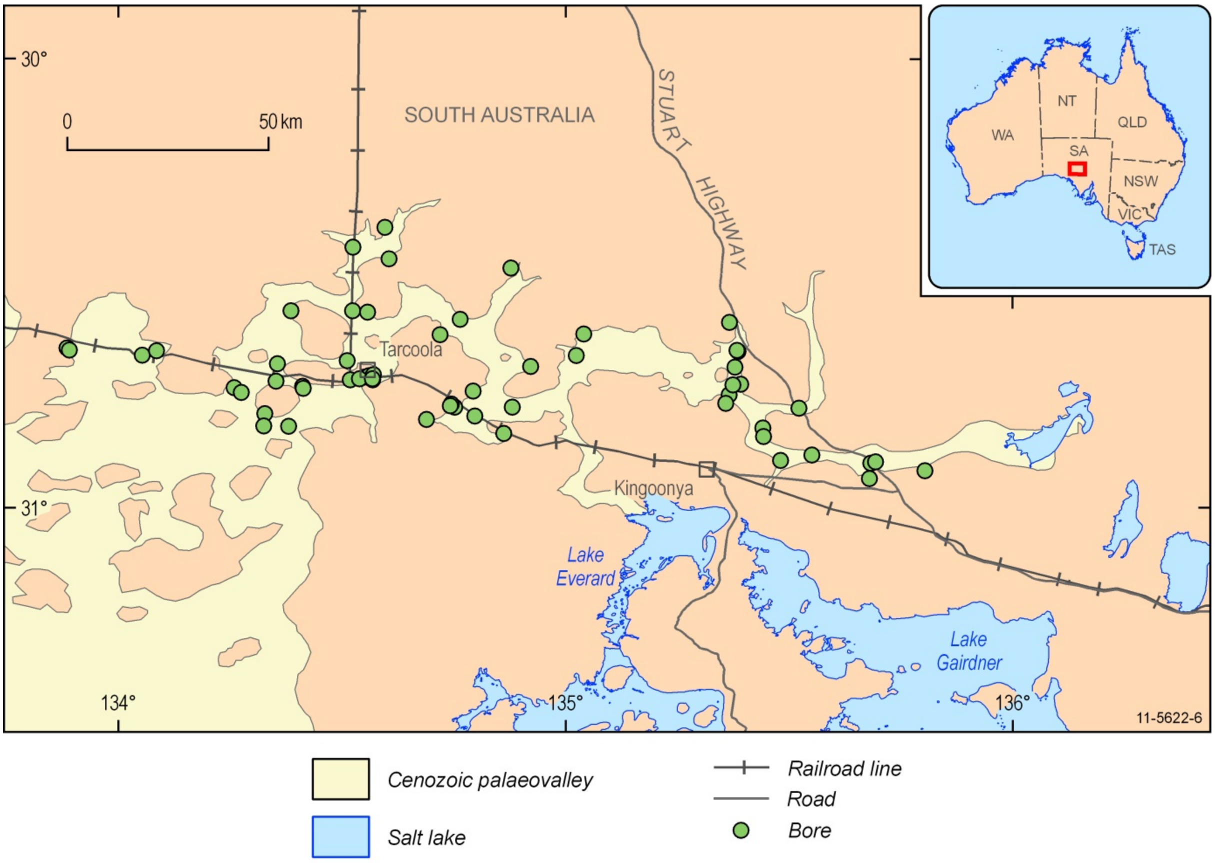


Figure 38: *Bores and wells in the Kingoonya Palaeovalley area selected for sampling from GIS analysis of South Australian Department of Environment, Water and Natural Resources borehole data.*

Despite the lack of detailed information available from SARIG, GIS manipulation of the SA waterbore data provided the most effective way to select potential groundwater sampling sites. Based upon the outcome of the GIS analysis two fieldtrips were undertaken to complete sampling of the selected 60 groundwater bores. The initial trip (July 2010) focused on the western and central areas of the study region (around Tarcoola), and the second trip (November 2010) encompassed eastern parts of the Kingoonya Palaeovalley (Figure 38).

Other important tasks required prior to fieldwork included:

- Contacting relevant landholders, informing them of the intended workplan, and gaining approvals to visit proposed sites and collect the groundwater samples;

- Ensuring that all required sampling equipment and consumables (probes and sampling bottles etc.) were available and in good working order (this was mostly done by the field team from the Geological Survey of South Australia); and
- Arranging fieldtrip logistics such as site accommodation, vehicles, supplies, and travel plans.

5.3.2. Fieldwork program

Geoscience Australia staff involved in the collection of groundwater samples from the Kingoonya Palaeovalley were kindly assisted in the field by the Geological Survey of South Australia (GSSA). This collaboration arose during the 3rd Technical Advisory Group (TAG) workshop of the *Palaeovalley Groundwater Project* held in Kalgoorlie (March, 2010). The GSSA were then in the early stages of a larger regional-scale hydrogeochemical sampling program to help promote mineral exploration opportunities across South Australia (this is a state-wide collaborative project between the South Australian government and the CSIRO to expand the regional-scale hydrogeochemical dataset across the state and help promote further mineral exploration). Consequently, a dedicated and well-equipped hydrogeochemical sampling team had already been assembled for this purpose.

Following discussions at the TAG 3 workshop the GSSA agreed to collaborate with GA and assist with the detailed sampling program in the Kingoonya Palaeovalley as part of their in-kind contribution towards the Palaeovalley Groundwater Project. The GSSA provided the necessary sample collection equipment and consumables for the fieldwork as well as a 2-person sampling team and a well-equipped field vehicle to accompany GA staff. Additionally, they liaised with local land-holders and arranged all necessary approvals for land access and sampling work. All members of the GA team involved in the Kingoonya Palaeovalley sampling program are extremely grateful for the generosity and assistance shown by colleagues in the GSSA (see Acknowledgement section for details).

Initial groundwater sampling in the Kingoonya region was conducted in early-mid July 2010, with follow-up work completed in November 2010. The groundwater sampling program was carried-out using the techniques successfully employed by the GSSA as part of their regional groundwater sampling project. The methodology is similar to that outlined by Noble and Gray (2010) for collection of hydrogeochemical samples for mineral exploration in Western Australia (with some modifications based on Cook et al. (1999) and Love et al. (2002) to suit local conditions and specific sampling interests). For the purposes of our investigation the field methods and sampling protocols proved highly effective and maximised productivity in the field (further discussed in Section 5.3.2.1).

During the fieldwork program the initial (and sometimes the most difficult and time-consuming) stage in the sample collection process involved driving to the selected site (via pre-loaded GPS waypoints) and locating the actual ground position of the water bore or well (Figures 39–40). Frequently, this proved a difficult task, and some of the proposed sites were found to have no obvious markers to identify the borehole stem or wellsite. At several localities the search for the expected borehole proved elusive and consequently no sample was collected. At other sites, samples could not be collected due to inoperable bore infrastructure or inaccessible watertables.

Likely reasons to explain the discrepancy between expected bore coordinates (as listed in SARIG) and the actual ground locations include:

- The wellsite is now completely covered or obscured, e.g., by vegetation regrowth or regolith;

- The coordinates entered in the SARIG database are incorrect, or were recorded using an unknown reference datum or a technique with a large amount of positional error, such as an estimated position from a topographic map; or
- The original wellsite infrastructure has subsequently been removed or destroyed.

Figure 39: *Typical groundwater sampling site at a pastoral station windmill in the Kingoonya Palaeovalley area (photo by Evgeniy Bastrakov, November 2010).*

5.3.2.1. Groundwater sample collection process

Once the selected site was located the sample collection process followed a consistent routine to ensure standard procedures were followed and potential sources of sampling error were minimised, e.g., sample contamination and duplication. The key steps involved in the collection of the Kingoonya region groundwater samples were:

1. Investigation and description of the sampling site. This was an important initial step with detailed notes recorded about the location of the site (e.g., physiography, vegetation, geology), the characteristics of the borehole casing or wellsite infrastructure, the type of sample to be collected (pumped or bailed), and the potential for any groundwater contamination. The main features of interest at each site were also photographed.
2. Measurement of the depth to the watertable – this was achieved using a handheld downhole depth probe, and the information recorded to confirm the presence of groundwater and determine the sampling depth. Groundwater samples were generally collected 5–15 metres below the watertable, although this was not always possible, e.g., in cases where depth was <5 metres between watertable and bottom of the borehole.

3. Preparation and calibration of the field analytical equipment (usually on a daily basis). The GSSA sampling team used the YSI® 556 multiprobe system (MPS) and measured on-site field parameters such as: temperature, redox potential (Eh), pH, electrical conductivity (EC) and dissolved oxygen (DO) of groundwater. These measurements were made continuously via a flow-through cell until readings were stabilised (Figure 41). The pH and EC probes were calibrated with known standards prior to use. Calibration of redox potential was achieved using Zobell's Solution.
4. Preparation and labelling of sample collection bottles with site identification numbers and details of the required laboratory analyses. Depending upon the analytical process to be conducted in the laboratory (Table 4) the groundwater samples were collected using either Teflon-coated plastic vials, glass McCartney bottles or high density polyethylene (HDPE) bottles of varying size.
5. Set-up of the submersible downhole water pump to begin purging the bore in preparation for sampling. During the initial fieldtrip in July 2010 a stainless steel *Grundfos* MP-1 pump (on-loan from the South Australian Department for Environment, Water and Natural Resources) was used to pump the groundwater samples. This pump was operated using portable petrol-powered generators (Figure 42). For the November 2010 trip, samples were collected using a plastic Monsoon pump powered by the field vehicle battery. Field experience showed that the MP-1 pump has greater capacity, but the Monsoon pump is easier to set-up and operate (Roger Fidler, pers. comm., 2011). As a back-up system a simple hand-bailer device was also available to collect samples in case of pump problems, and where bores or wells proved unsuitable for pumping, e.g., due to low yields or highly turbid groundwater.

Figure 40: *A hand-dug well lined with timber in the Kingoonya Palaeovalley area (photo by Evgeniy Bastrakov, November 2010).*

Figure 41: *The YSI® 556 MPS used for field measurement of groundwater sampled from sites in the Kingoonya region (photo by Ashraf Hanna, July 2010).*

6. Pumping groundwater from the bore/well for sample collection. Ideally the pump was operated continuously to flush ~2–3 well volumes before bottling samples (apart from the initial sample for radon which was required pre-purge), although pumped bore volumes were estimated and not actually determined. For samples collected with a bailer it was not possible to purge the well before sampling (although only one sample was collected using a bailer, from Bulga Well, 5736-15). Pumped groundwater was fed into the flow-through cell and analysed until water conditions stabilised for key variables such as temperature, pH, and electrical conductivity (EC). Once these parameters had stabilised, individual water samples were collected in the various sized bottles and any special samples treatments were also administered.
7. For samples which needed filtering (Table 4), the sample collection process involved pumping a slug of groundwater (~2–3 litres) into a pre-rinsed 5 litre plastic spray pump-pack (rinsed at least 3 times with the initial volume of pumped groundwater prior to sample collection). The pump unit was then pressurised and fed through an in-line 47 mm diameter NUCLEPORE filter (containing 45 micron Millipore filter paper). The sample collected for cation analysis was acidified using nitric acid to 'fix' the cations and avoid any precipitation of salts from solution. Field experience has shown that this pressurised system is quicker and ensures that filters last longer than comparable suction-based methods, although suction may be slightly more efficient (Roger Fidler, pers. comm., 2011).

8. For unfiltered samples, bottles were rinsed 3 times with water from the pump outlet prior to collection (Table 4). Field alkalinities were also determined by titration. The total alkalinity (assumed to be HCO_3^- for the pH range sampled) was measured in the field using a HACH titration kit.
9. Sampling operations at each site took around 30–60 minutes on average. Following collection of the required samples all equipment was cleaned and re-packed in the field vehicles ready for the drive to the next sampling site. The sample bottles were stored in cool containers away from direct sunlight for daily transport back to field operation bases at Kingoonya (July 2010) or Glendambo (November 2010).

Figure 42: *Portable generator system set-up for running the MP-1 pump during groundwater sampling operations in the Kingoonya Palaeovalley during July 2010 (photo courtesy of Tania Wilson, GSSA, July 2010).*

5.3.2.2. Post-fieldwork operations

Following the successful completion of each fieldwork program groundwater samples were transported by road to the Adelaide field operations compound used by the GSSA. During transportation the samples were kept cool and dry. Once in Adelaide the samples were prepared for shipment to the various laboratories selected for analytical work (Table 4). Of the 60 potential sampling sites selected from initial planning in the office (Section 5.3.1), 44 field sites were visited during the combined trips of July and November 2010. A total of 27 groundwater samples were collected from the designated sites. It was not possible to collect samples from the 17 other site locations visited due to various reasons, such as the inability to locate bores/wells, inaccessibility to the site or to access the watertable, or an insufficient amount of groundwater available for collection.

Presentation and analysis of these data are outlined and discussed further in Chapter 6.

Table 4: *List of sample types, treatments and analytical laboratories for groundwater samples collected from the Kingoonya Palaeovalley.*

Sample Purpose	Treatment	Laboratory	Container
Radon (pre-purge sample)		CSIRO Land & Water Laboratory, Adelaide	22 ml Teflon-coated plastic vial with pre-weighed volume of scintillant
Alkalinity	Unfiltered for laboratory	CSIRO Exploration & Mining Laboratory, Perth	125 ml HDPE plastic bottle
Anions	Filtered	CSIRO Land & Water Laboratory, Adelaide	125 ml HDPE plastic bottle
Cations	Filtered and fixed to pH<2 with HNO_3	CSIRO Land & Water Laboratory, Adelaide	125 ml HDPE plastic bottle
Stable isotopes – ^{18}O and D	Unfiltered	CSIRO Land & Water Laboratory, Adelaide	Glass McCartney bottle
Stable isotopes – ^{34}S	Unfiltered	Stable Isotope Laboratory, GNS, New Zealand	5 litre HDPE plastic bottle (sub-set of radiocarbon sample)
Radiocarbon	Unfiltered	CSIRO Land & Water, Adelaide and the ANU SSAMS (July, 2010); Rafter Radiocarbon Laboratory, GNS, New Zealand (Nov 2010)	5 litre HDPE plastic bottle
Radon (post-purge sample)		CSIRO Land & Water Laboratory, Adelaide	22 ml Teflon-coated plastic vial with pre-weighed volume of scintillant
Au/PGE	Unfiltered, treated with carbon sachet	CSIRO Exploration & Mining Laboratory, Perth	1 litre HDPE plastic
Archive 1	Untreated	Stored at GSSA, Adelaide	1 litre HDPE plastic
Archive 2	Filtered and acidified	Stored at GSSA, Adelaide	500 ml HDPE plastic

1. Note: For the July 2010 radiocarbon samples initial laboratory analysis was performed at CSIRO Land & Water (Adelaide), with radiocarbon determinations made on the Single Stage Accelerator Mass Spectrometer (SSAMS) at the Australian National University (Canberra).

6. Hydrogeochemistry of groundwater in the Kingoonya Palaeovalley

6.1. Introduction

The acquisition of new hydrogeochemical data for the Gawler–Eucla demonstration site involved the collection of 27 groundwater samples from existing bores within the Kingoonya Palaeovalley region (Chapter 5). These samples were collected to characterise the ionic and isotopic signatures of groundwater in the aquifer, and provide a baseline hydrogeochemical dataset for this arid zone palaeovalley. This work represents the most comprehensive regional study of palaeovalley groundwater compositions and natural tracers in the Gawler–Eucla region to date. The purpose of this chapter is to present the analytical results of the groundwater sampling program and provide preliminary evaluation of the dataset. Further interpretation and discussion of the implications of these data are outlined in Chapter 7.

6.2. Hydrogeochemical methods and data presentation

Field parameters were measured on-site for each groundwater sample using the methods previously outlined in Chapter 5. Laboratory analyses for cations and anions, stable isotopes ($\delta^{18}O$ and δD) and radon-222 were undertaken by the CSIRO. The CSIRO Land and Water Laboratory in Adelaide performed most of the analyses, although the gold and platinum group elements (Au/PGE) and alkalinity determinations were completed at the CSIRO Exploration and Mining Laboratory in Perth. The CSIRO Land and Water Laboratory (Adelaide) also handled and prepared the set of July 2010 samples collected for radiocarbon analysis, with measurements performed on the Single Stage Accelerator Mass Spectrometer (SSAMS) at the Australian National University in Canberra. Radiocarbon analyses for the November 2010 samples were performed at the Rafter Radiocarbon Laboratory in New Zealand (a division of the National Isotope Centre operated by GNS Science), and the sulfur isotope analyses were undertaken at the GNS Stable Isotope Facility on a sub-set of the radiocarbon samples.

6.2.1. Physical and chemical field parameters

Field-based measurements were acquired at the time of sampling from each bore using the *YSI*® 556 MPS provided by the GSSA. This device was used to measure various groundwater parameters such as temperature, pH, electrical conductivity (EC), redox potential (Eh), and dissolved oxygen (DO). Groundwater was pumped continuously through the flow-through cell until key parameter readings had stabilised and could be recorded. Field titrations were also performed to analyse for groundwater alkalinity (Section 5.3.2). Field-based data collected during sampling operations in the Kingoonya region, including watertable depths, sampling depths and the total depth of the bore/well are provided in Appendix 4. Figures 43–46 highlight the spatial distribution and variability of several important groundwater field parameters. Figure 47 shows the relationship between the dissolved oxygen and Eh data, and Figure 48 shows variability of groundwater temperature related to watertable depth.

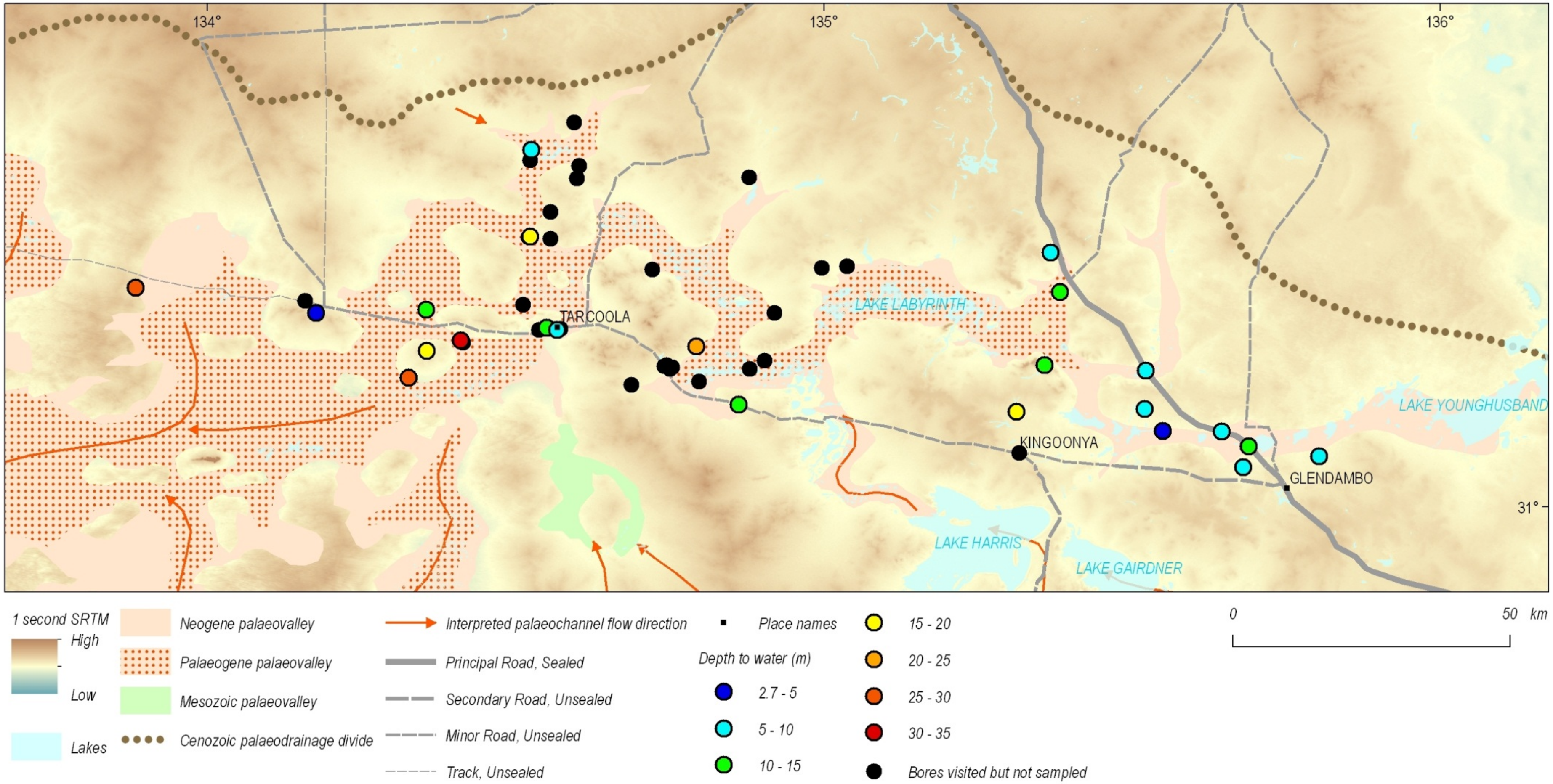


Figure 43: *Spatial distribution of depth to the watertable for sampling sites in the Kingoonya Palaeovalley, during field operations in July and November 2010. The area covered by the sub-region of the Gawler–Eucla demonstration site shown here is presented in Figures 35–37. The palaeovalley spatial extents depicted are derived from the earlier mapping work of Hou et al., 2007.*

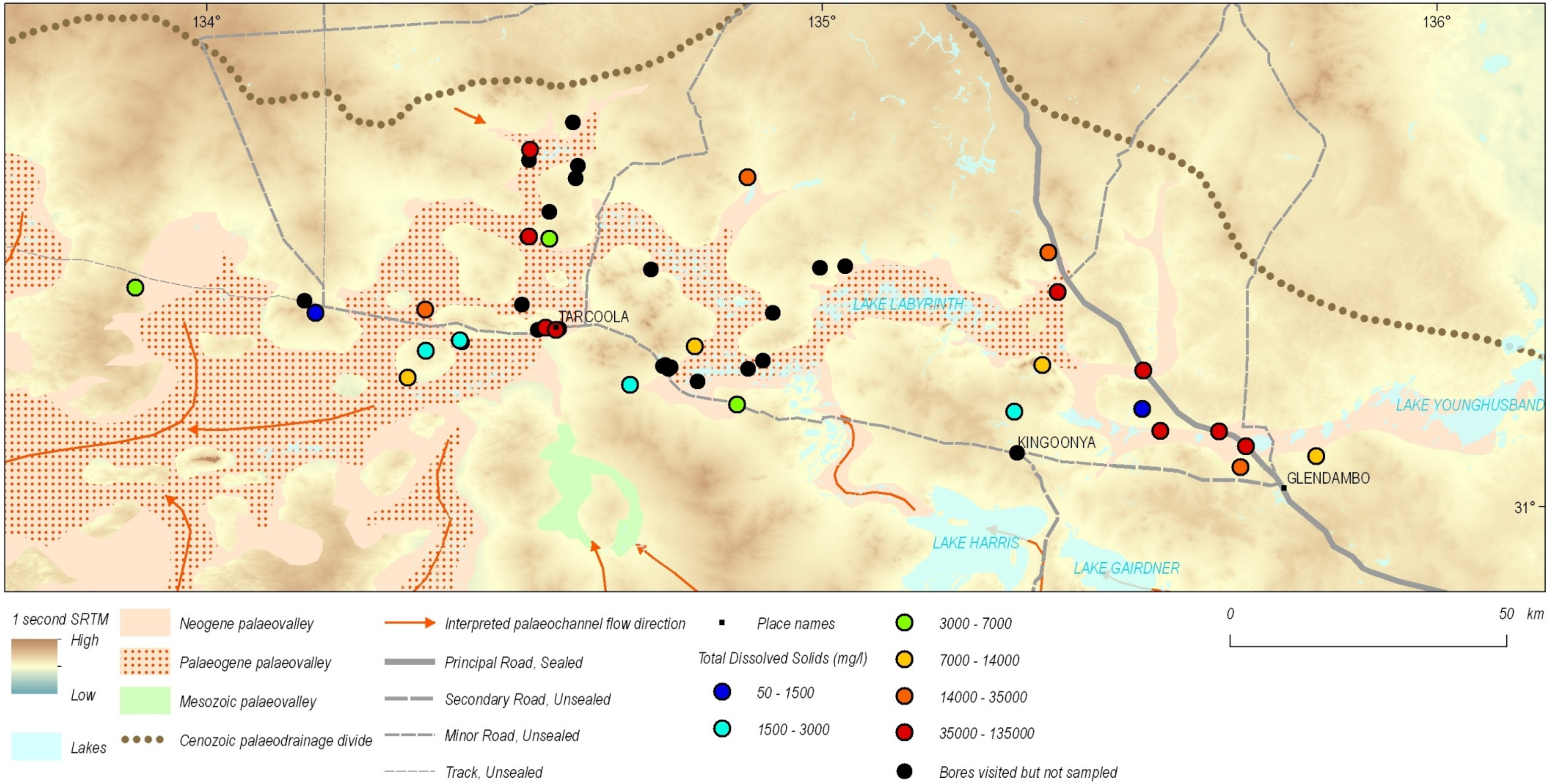


Figure 44: *Spatial distribution of the total dissolved solids (TDS) in groundwater sampled in the Kingoonya Palaeovalley region, during July and November 2010. The area covered by the sub-region of the Gawler–Eucla demonstration site shown here is presented in Figures 35–37. The palaeovalley spatial extents depicted are derived from the earlier mapping work of Hou et al., 2007.*

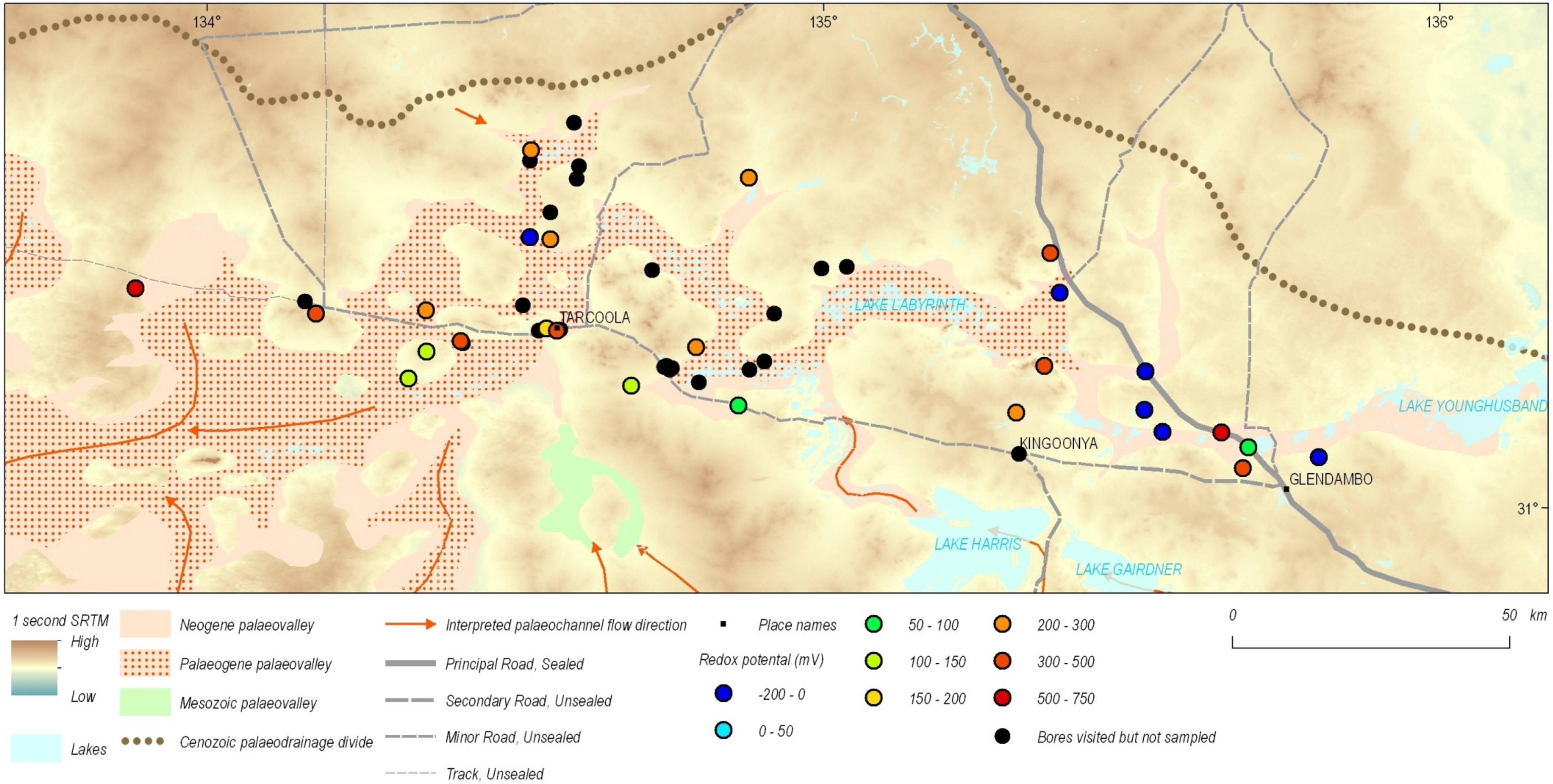


***Figure 45:** Spatial distribution of redox potential (Eh) of groundwater samples measured (in millivolts) during field operations in the Kingoonya Palaeovalley region during July and November 2010. The area covered by the sub-region of the Gawler–Eucla demonstration site shown here is presented in Figures 35–37. The palaeovalley spatial extents depicted are derived from the earlier mapping work of Hou et al., 2007.*

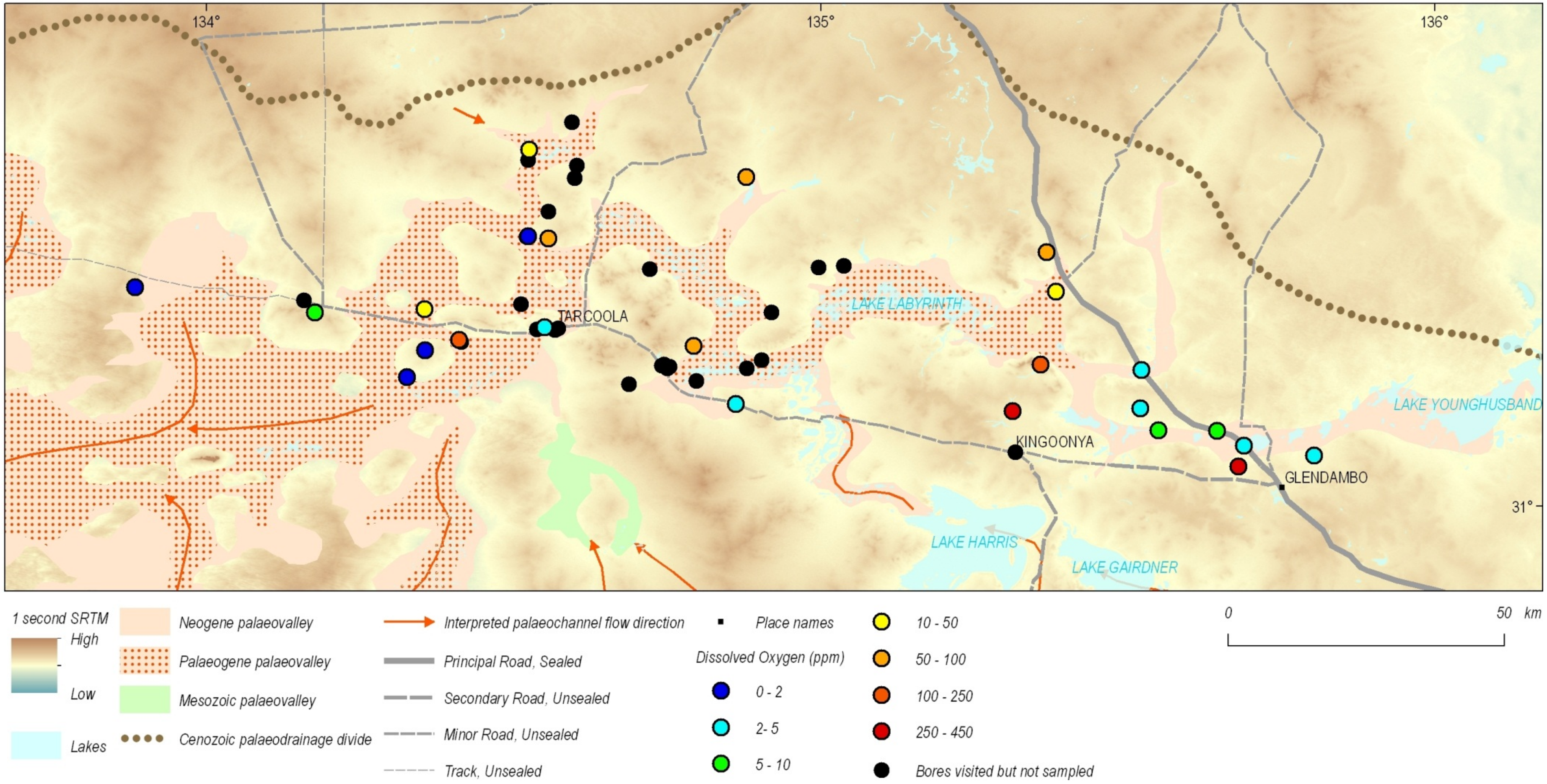


Figure 46: *Spatial distribution of dissolved oxygen abundance (ppm) for groundwater sampled in the Kingoonya Palaeovalley region during field operations in July and November 2010. The area covered by the sub-region of the Gawler–Eucla demonstration site shown here is presented in Figures 35–37. The palaeovalley spatial extents depicted are derived from the earlier mapping work of Hou et al., 2007.*

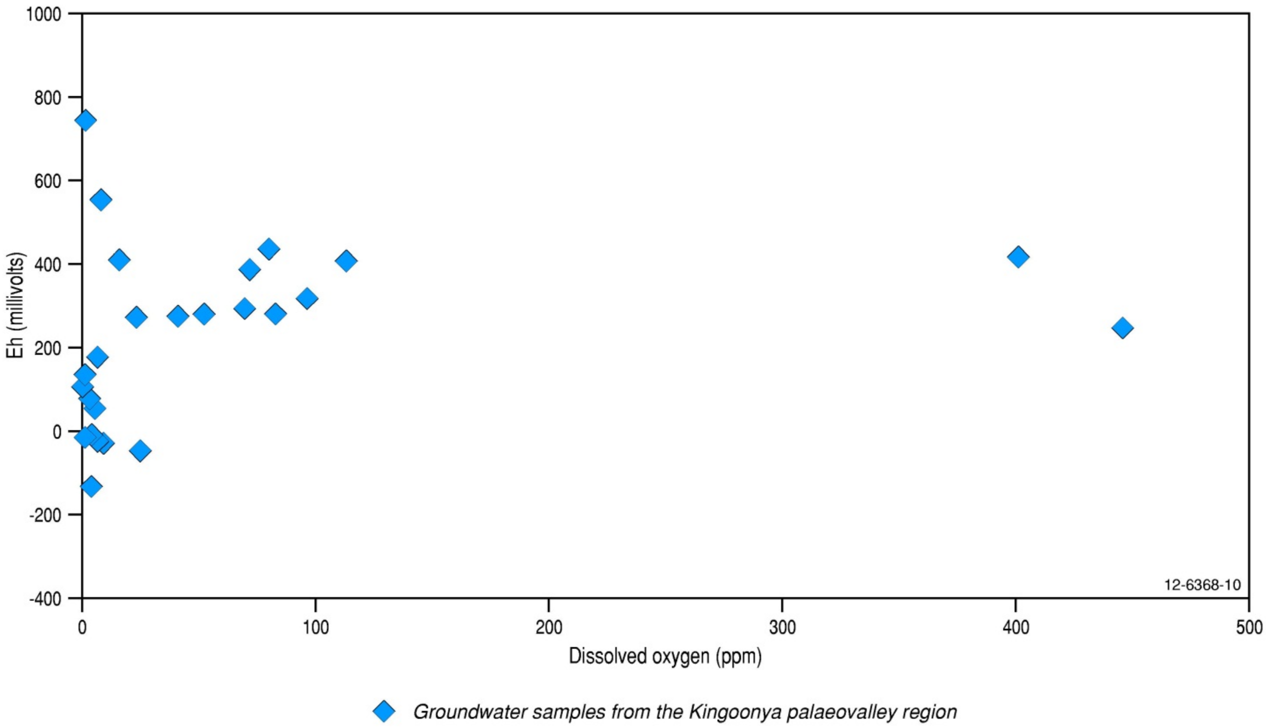


Figure 47: *Dissolved oxygen and redox potential for Kingoonya region groundwater samples.*

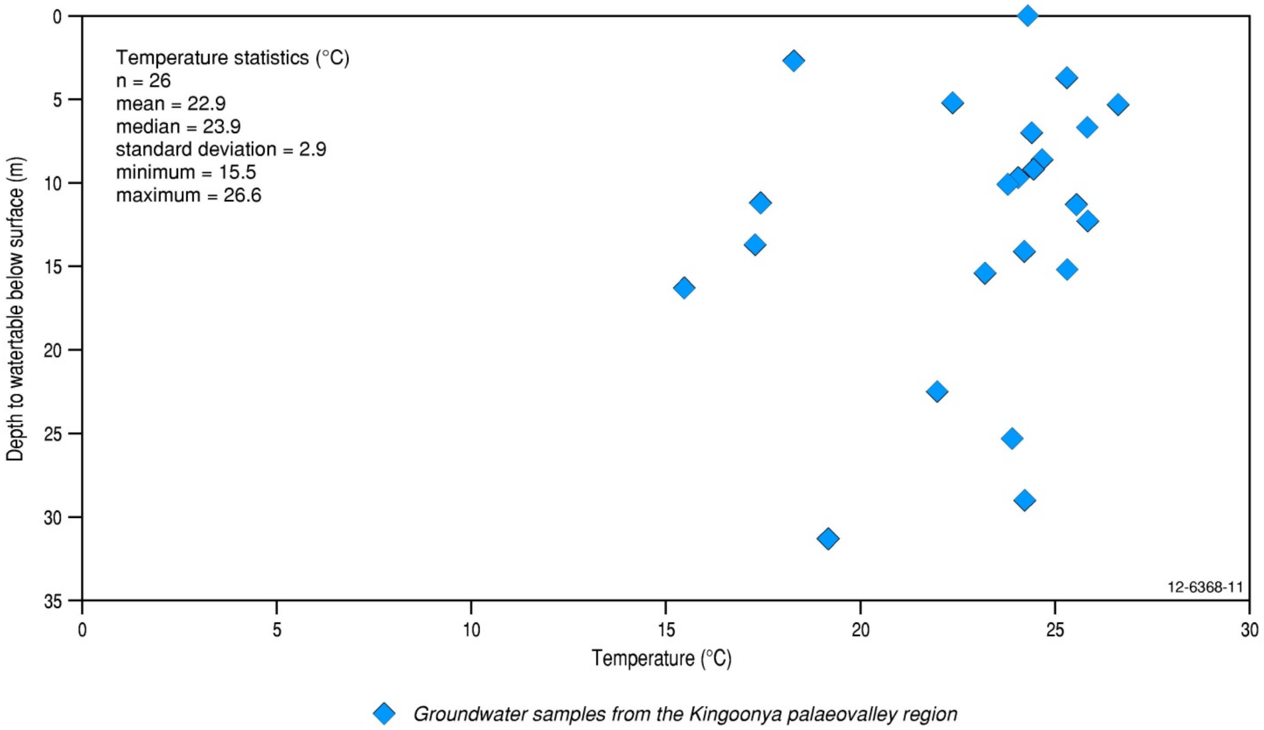


Figure 48: *Variation of groundwater temperature from the Kingoonya Palaeovalley region with depth to the watertable for each bore.*

6.2.2. Cations

The major cations (Ca, K, Mg, and Na) in the Kingoonya groundwater samples were analysed by Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) at the CSIRO Land and Water Laboratory in Adelaide. The ICP-OES method was also used to analyse for a suite of minor cations: Al, As, B, Cd, Co, Cr, Cu, Fe, Mn, Mo, Ni, P, Pb, S, Sb, Se, Si, Sr and Zn. The detection limits for the cations analysed using ICP-OES vary depending on the salinity of the sample, with greater dilution factors needed for higher salinity samples (which also increased the minimum detection limit). The ICP-OES analytical results for the major cations (and selected minor cations), reported at the parts per million (ppm) level, are provided in Table 5.

Trace elements were measured using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) at the CSIRO Land and Water Laboratory in Adelaide. Trace cations analysed using ICP-MS were: Li, Sc, V, Cr, Mn, Co, Ni, Cu, Zn, Ga, As, Rb, Y, Zr, Nb, Mo, Ag, Cd, Sn, Sb, Ba, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Hf, Ta, W, Pb, Th, and U. The complete dataset for the ICP-MS analyses is provided in Appendix 5. Many of the trace cations (especially rare earth elements) are below detection limits for most samples. However, data for several trace element-enriched samples are shown in Table 6: Bore 5636 (354 Mile Siding), Bore 5836-86 (Tarcoola Gold TW2); Bore 5836-27 (RL33), Bore 6036-119 (Highways Well B19) and Bore 6036-127 (Highways Well B27).

Groundwater sampled from Bore 6036-127 (Highways Well B27) was the most chemically unusual sample collected during this field investigation as it contained relatively elevated concentrations for many trace cations (most rare earth elements, platinum group elements, gold, and silver) as well as very low pH. This is an anomalously acidic and metal-enriched groundwater sample (Table 6).

To aid in the low-level (parts per trillion or ppt range) detection of Au, Ag, and platinum group elements (Pd and Pt) a specialised carbon sachet technique was used. The sachets consist of 1 gram of activated carbon in a nylon mesh (manufactured by CSIRO Exploration and Mining) placed in a 1 litre sample bottle (Noble and Gray, 2010). Following field operations the bottles were placed on a roller for at least 4 days to agitate the sample. The water volume was then measured and the carbon sachet removed, rinsed and dried before being dispatched for ICP-MS analysis at a commercial laboratory, UltraTrace in Perth (Gray et al., 2009). The results for positive samples with above detection limit readings for one or more of Au, Ag, Pd, and Pt are presented in Table 7.

6.2.3. Anions

The major anions (Cl, SO_4, Br, F and NO_3) from the filtered Kingoonya groundwater samples were analysed at the CSIRO Land and Water Laboratory (Adelaide) using Ion Chromatography (IC). The other major anions (HCO_3 – also known as alkalinity - and PO_4) were analysed by laboratory titration at CSIRO. Samples collected during fieldwork in July 2010 were also analysed for alkalinity separately at the Geoscience Australia Laboratory in Canberra (to evaluate analytical precision between different laboratories). Field-based titrations were performed for the groundwater samples collected during November 2010 field operations (although, for logistical reasons, field titrations were not conducted for the samples collected in July 2010). The major anion data is shown in Table 8 with the preferred laboratory alkalinity results.

Table 5: *Major cation (and selected minor cation) data for groundwater samples from the Kingoonya Palaeovalley region, analysed using ICP-OES.*

Bore no.	Ca	K	Mg	Na	S	Si	B	Fe	Mn	Sr
	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
5736-08	231	76.8	271	1,670	278	11.8	3.3	<0.5	<0.25	3.6
5736-07	4.5	0.5	0.9	3.6	0.6	3.2	<0.1	<0.1	<0.05	<0.05
5636-23	304	40.4	156	1,010	86	14.6	0.6	75.7	1.26	3.29
5736-20	167	48.1	220	2,600	155	14	1.7	<0.5	<0.25	3.2
5736-17	97.6	19.3	21.7	455	29.7	30.1	1.4	<0.5	<0.25	0.6
5736-15	1,740	232	733	8,460	819	14.1	<5	<5	<2.5	6.1
5736-41	137	24.9	86.4	1,280	182	13.9	2.45	<0.5	<0.25	1.8
5836-86	740	616	5120	41,700	3,920	<5	<10	15	7.61	14.6
5836-126	547	262	1,380	13,500	1,730	7.2	9.05	<5	<2.5	10.7
5836-27	1,240	232	1,620	10,100	1,140	<5	7.33	1,480	18.6	26.1
5837-84	984	190	964	8,870	1,490	6.8	13.6	<5	<2.5	19.6
5836-687	84.7	16.2	47.2	294	50.7	8.5	0.624	<0.5	<0.25	0.9
5837-64	464	74.8	365	1,990	509	9.5	2.83	<1	<0.5	7.2
5836-16	178	26.6	155	1,670	143	18.7	1.09	<1	<0.5	2.0
5836-20	358	27	162	1,460	0.967	15.9	1.7	9.28	2.37	4.1
5836-42	120	30.7	77.1	574	2.74	40.6	<0.1	<0.1	0.402	1.1
5936-35	1,320	124	544	3570	875	27.2	5.12	<0.5	<0.25	15.7
5936-118	59.1	347	981	15,500	1,330	<2.5	4.38	<2.5	<1.25	1.5
5936-13	89.9	17.4	44.6	250	33	37.5	0.622	<0.05	<0.05	1.0
5936-49	564	59	293	3400	214	19.9	3.75	<0.5	<0.25	7.9
6036-119	461	718	3,720	30,300	3,410	<5.0	2.62	89.2	3.49	15.7
6036-135	866	947	5,590	45,300	4,930	1.26	2.52	<5.0	<2.5	14.8
6036-18	94.1	22.7	42.6	172	2.14	13.6	0.222	<0.05	2.22	1.09
6036-127	651	1,760	5,810	59,800	4,770	14.6	3.94	<5.0	5.72	14
6036-125	493	884	4,720	42,000	3,860	1.03	3.82	5.04	<2.5	9.0
6036-58	735	78.6	481	3,610	384	37.9	4.02	<0.5	<0.25	13
6036-109	212	92.5	244	2,730	6.4	9.7	2.8	<0.5	0.5	5.4

Table 6: *Selected Kingoonya region bore data with groundwater samples containing anomalous trace elements.*

	Units	354 Mile Siding (5636-23)	Tarcoola Gold TW2 (5836-86)	RL33 (5836-27)	Highways Well B19 (6036-119)	Highways Well B27 (6036-127)
pH		6.68	5.99	6.52	7.26	3.64
TDS	ppm	4,410	133,450	44,089	83,990	120,300
Redox	mV	744	178	-17	-132	555
DO	%	1.6	6.7	1.3	4.0	8.3
Cl	ppm	1,600	87,000	26,000	61,000	110,000
Br	ppm	5.6	140	57	82	140
NO_3	ppm	1.0	<10	8.5	19	92
SO_4	ppm	200	14,000	4,100	12,000	17,000
Ca	ppm	304	740	1,240	427	573
K	ppm	40.4	616	232	528	1,420
Mg	ppm	156	5,120	1,620	3,700	5,530
Na	ppm	1,010	41,700	10,100	29,700	55,865
S	ppm	86	3,920	1,140	3,410	4,770
B	ppm	0.584	<10	7.33	2.62	3.94
Fe	ppm	75.7	15	1,480	89.2	<5.0
Si	ppm	14.6	<5	<5	<5.0	14.6
Sr	ppm	3.28	14.6	26.1	15.7	14
Li	ppb	<4	<100	20	320	2010
Mn	ppb	1480	10,100	24,000	5,016	8,855
Co	ppb	5.46	8.4	4.60	16.8	411.6
Ni	ppb	4.0	<10	2	4	196
Zn	ppb	73.6	140	28	2,000	90
Ga	ppb	40.4	10	9	<4	21
As	ppb	1.0	5	<0.9	<20	<20
Rb	ppb	4	<100	60	156	900
Cd	ppb	<0.04	<1	0.2	2	6
Ba	ppb	221	40	56	40	<30
La	ppb	0.06	1.2	0.21	<4	42
Ce	ppb	0.47	1.2	0.60	<1	157.6
Pr	ppb	0.04	<0.1	0.02	<1	24
Nd	ppb	0.13	0.2	0.08	<2	116

	Units	354 Mile Siding (5636-23)	Tarcoola Gold TW2 (5836-86)	RL33 (5836-27)	Highways Well B19 (6036-119)	Highways Well B27 (6036-127)
Sm	ppb	0.05	<0.2	<0.03	<4	21
Gd	ppb	0.06	<0.2	<0.03	<2	29
Dy	ppb	0.06	<0.1	<0.02	<2	28
Ho	ppb	0.02	<0.05	<0.01	<0.6	6.0
Er	ppb	0.03	<0.2	<0.03	<0.6	18.5
Ta	ppb	0.04	0.3	0.25	<0.8	<0.7
W	ppb	<0.2	<5	<1	<40	<30
Pb	ppb	1.28	8	5.2	<20	40
Th	ppb	12.2	6	40	<200	<200
U	ppb	2.8	<4	3.2	<0.6	3.0
Au	ppt	<5	<5	<5	<5	6.8
Pd	ppt	1	<1	<1	4.2	14.4
Pt	ppt	<1	<1	<1	<1	3.9
Ag	ppt	<25	<25	<25	71	312

***Table 7:** Au, Ag and platinum group element data for Kingoonya groundwater samples with at least one element above detection limits (all values in parts per trillion or ppt; samples not shown have values below detection).*

Bore no.	Bore name	Au	Ag	Pd	Pt
5636-23	354 Mile Siding	<5	<25	1	<1
5736-15	Bulga Well	<5	28	1.4	1.4
5836-126	TPH PC1	<5	47	<1	<1
5836-20	Warna Well	<5	60	<1	1.5
5936-35	Scott's Well	<5	31	3.9	2.9
5936-118	PDH BB2	<5	34	6.1	<1
5936-13	North Well	<5	35	3.9	<1
5936-49	Wallabyng Range Well	<5	38	29.7	<1
6036-119	Highways Well B19	<5	71	4.2	<1
6036-135	Highways Well B29	<5	32	5	<1
6036-18	Mulga Well No.2	<5	<25	2.8	<1
6036-127	Highways Well B27	6.8	312	14.4	3.9
6036-125	Highways Well B25	<5	151	6.5	<1
6036-58	Monty's Well	<5	37	3.5	5.2
6036-109	Bulyacobbie Bore	<5	23	3.9	<1

Table 8: *Anion data for Kingoonya region groundwater samples analysed using Ion Chromatography (IC) or laboratory titration (HCO_3 and PO_4).*

Bore no.	Bore name	HCO_3	PO_4	F	Cl	Br	NO_3	SO_4
		(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)
5736-08	Malbooma Swamp	125	0.02	2	2,800	11	50	730
5736-07	Malbooma Outstation	34	0.17	0.4	5.4	<0.05	1.6	3.3
5636-23	354 Mile Siding	476	0.02	<0.5	1,600	5.6	1.0	200
5736-20	Hiern's Well	663	0.08	4.5	4,700	16	3.4	510
5736-17	Clayson's Well	318	0.7	0.4	510	2.1	0.5	72
5736-15	Bulga Well	469	0.6	<5	20,000	27	13	3,000
5736-41	West Pinding Tank	118	0.06	1.0	2,200	7.6	93	600
5836-86	Tarcoola Gold TW2	52	0.04	<10	87,000	140	<10	14,000
5836-126	TPH PC1	170	0.03	<5	26,000	45	44	6,100
5836-27	RL33	nd	0.06	<5	26,000	57	8.5	4,100
5837-84	Commrailways A37-10	168	0.02	<5	18,000	49	52	5,300
5836-687	Liffy's Bore	228	0.04	2.2	1,600	6	150	410
5837-64	No. 34 Bore	87	0.01	<2	3,100	10	77	1,100
5836-16	Welcome Well	149	0.02	<2	2,200	3.5	110	330
5836-20	Warna Well	658	0.03	<1	3,400	9.2	1.5	3.3
5836-42	Mullina Well	347	0.17	<0.5	1,100	1.1	0.7	6.3
5936-35	Scott's Well	389	0.16	<2	7,800	23	260	3,000
5936-118	PDH BB2	245	0.05	<5	27,000	64	<5	4,400
5936-13	North Well	310	0.13	0.9	420	1.4	70	100
5936-49	Wallabyng Range Well	414	1.0	<2	7,000	16	58	670
6036-119	Highways Well B19	nd	0.01	<10	61,000	82	19	12,000
6036-135	Highways Well B29	121	0.01	<10	89,000	71	<10	17,000
6036-18	Mulga Well No.2	536	0.05	<0.2	240	1.3	0.3	3.9
6036-127	Highways Well B27	nd	0.01	<10	110,000	140	92	17,000
6036-125	Highways Well B25	130	<0.01	<10	82,000	65	<10	13,000
6036-58	Monty's Well	246	0.04	<2	8,400	22	79	1,300
6036-109	Bulyacobbie Bore	846	1.9	<1	5,200	14	<1	15

1. nd = no data

6.2.4. Oxygen-18 and deuterium

Oxygen and deuterium isotope analyses were performed at the CSIRO Land and Water Laboratory in Adelaide. The oxygen isotope analytical method is based on the standard procedure of Epstein and Mayeda (1953) with in-house modification to allow for automated analysis via the water equilibration system (WES). Isotope ratios were measured on a GEO 20–20 dual inlet stable isotope gas ratio mass spectrometer (manufactured by PDZ Europa Ltd. UK). Rigorous quality control procedures ensured consistent and reliable data. Oxygen isotope results are reported as the per mille (‰) deviation from the international Vienna Standard Mean Ocean Water (VSMOW). Analytical uncertainty is ±0.15‰ or 1 standard deviation.

The deuterium isotope compositions for the Kingoonya groundwater samples were also determined using the water equilibration (WES) technique at CSIRO Land and Water Laboratory (Adelaide). This is similar to the oxygen isotope method except that hydrogen atoms in the water molecule are equilibrated with hydrogen gas (rather than oxygen isotopes and gas). A platinum catalyst is used to complete equilibration within 1 hour. The deuterium isotope results are also reported as per mille (‰) deviation from the Vienna Standard Mean Ocean Water (VSMOW) standard. The analytical uncertainty is ±1.0‰ (1 standard deviation).

Oxygen and deuterium isotope data are presented in Table 9 and a comparison plot is shown in Figure 49. Oxygen isotope values range from -5.87‰ to +8.90‰ with mean of -0.86‰. Deuterium isotope values range from -38.7‰ to +28.0‰ with mean -16.9‰. The plotted dataset defines a relatively linear trend away from the Global and Local (Adelaide) Meteoric Water Lines with several values isotopically enriched relative to the SMOW standard (Figure 49). The Local Meteoric Water Line (LMWL) equation for Adelaide (used in Figure 49) has been obtained from the Global Network of Isotopes in Precipitation (GNIP) program coordinated by the International Atomic Energy Agency (IAEA). This is based on a set of monthly stable isotope analyses for local precipitation collected at the GNIP site in Adelaide since the early 1960’s (although the dataset is not continuous for every month).

Table 9: *Oxygen and deuterium isotope data for Kingoonya region groundwater samples.*

Bore	Bore name	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)
5736-08	Malbooma Outstation	-2.78	-15.6
5736-07	Malbooma Swamp	-3.93	-31.5
5736-20	Hiern's Well	-0.16	-12.8
5736-17	Clayson's Well	-1.63	-15.0
5736-15	Bulga Well	3.92	8.2
5736-41	West Pinding Tank	-4.71	-37.8
5836-86	Tarcoola Gold TW2	2.01	-9.6
5836-27	RL33	-1.66	-23.5
5837-84	Commrailways A37-10	-3.11	-32.2
5836-687	Liffy's Bore	-4.79	-38.7
5837-64	No. 34 Bore	-3.12	-31.9

Bore	Bore name	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)
5836-16	Welcome Well	-2.06	-32.1
5836-20	Warna Well	-0.58	-13.4
5836-42	Mullina Well	-3.24	-22.4
5936-35	Scott's Well	1.89	-5.4
5936-118	PDH BB2	-1.63	-10.0
5936-13	North Well	-5.87	-35.9
5936-49	Wallabyng Range Well	2.54	-0.9
6036-119	Highways Well B19	-0.55	-17.8
6036-135	Highways Well B29	0.95	-10.9
6036-18	Mulga Well No.2	-1.80	-14.4
6036-127	Highways Well B27	2.48	-3.2
6036-125	Highways Well B25	0.00	-13.4
6036-58	Monty's Well	-2.67	-29.9
6036-109	Bulyacobbie Bore	8.90	28.0

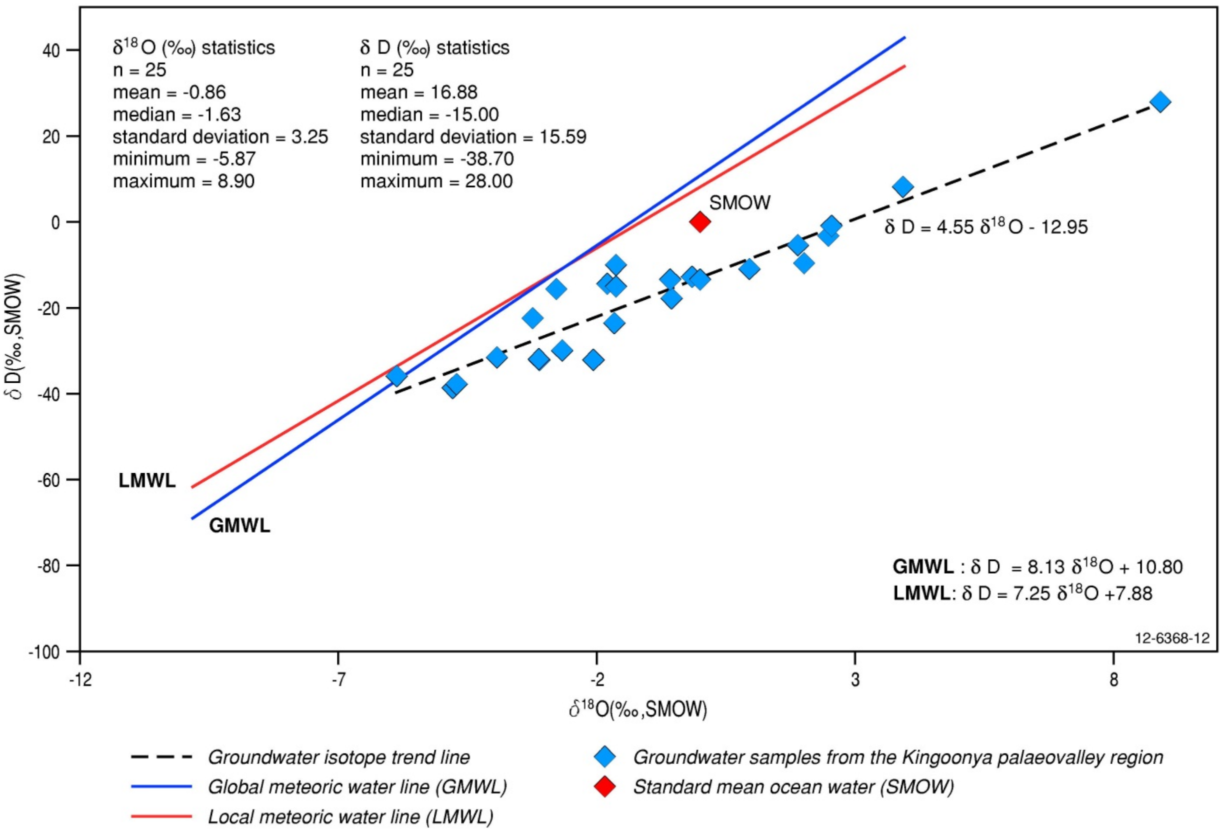


Figure 49: *Stable isotope plot of $\delta^{18}O$ vs. δD for groundwater from the Kingoonya region. The Adelaide Local Meteoric Water Line (LWML) is derived from ~50 years of rainfall data compiled for the Global Network of Isotopes in Precipitation (GNIP) project administered by the International Atomic Energy Agency (IAEA).*

6.2.5. Sulfur-34

Sulfur isotopes ($\delta^{34}S$) were measured at the Stable Isotope Laboratory operated by GNS Science in New Zealand (http://gns.cri.nz/gns/Home/Services/Laboratories-Facilities/Stable-Isotope-Laboratory). The 11 samples collected during field operations in November 2010 were dispatched for analysis, although isotope data could not be acquired for 2 samples due to unspecified analytical problems in the laboratory. The samples were weighed out in duplicate in tin capsules with an equal amount of vanadium oxide (VO_5) and run on a EuroVector Elemental Analyser (EA) connected to a GVI IsoPrime mass spectrometer. All results are averages and standard deviations of duplicates and are reported with respect to the international standard Vienna Cañon Diablo Troilite (VCDT), normalized to the GNS internal standard: R2298 with reported values of 8.6‰ for $\delta^{34}S$ (Table 10, Figure 50). The Vienna Cañon Diablo Troilite (VCDT) standard has an absolute isotope ratio of (44,360 ± 40) x 10^{-6} (MacNamara and Thode, 1950). Sulfur isotope ratios were measured on $BaSO_4$ produced from the supplied water samples during laboratory preparation. The analytical precision for $\delta^{34}S$ on the EA instrument is 0.5‰.

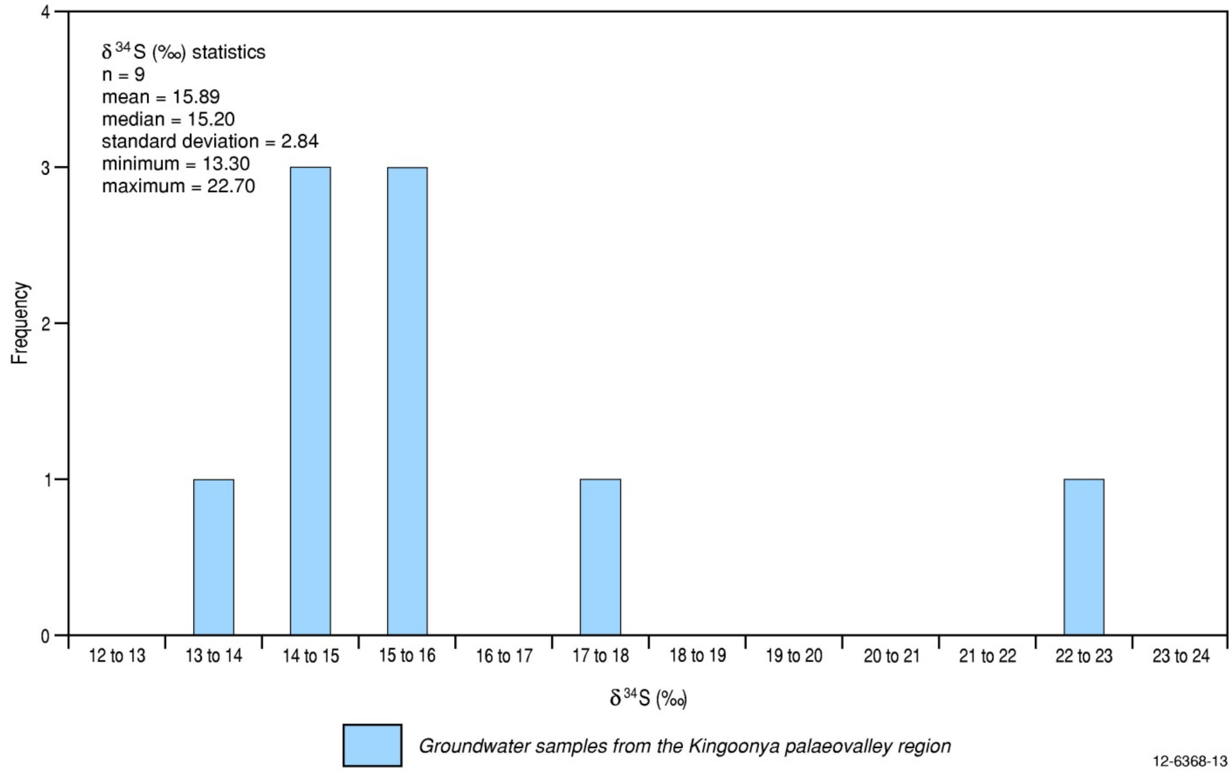


Figure 50: *Frequency histogram of $\delta^{34}S$ isotope data for groundwater systems in the region of the Kingoonya Palaeovalley.*

Table 10: *Sulfur isotope data for groundwater samples from the Kingoonya region.*

Bore No.	Bore name	$\delta^{34}S$ (‰)	std. dev.
5936-35	Scott's Well	13.3	0.0
5936-107	PDH BB2	22.7	0.0
5936-13	North Well	15.4	0.0
5936-49	Wallabyng Range Well	17.9	0.0
6036-119	Highways Well B19	14.3	0.0
6036-135	Highways Well B29	15.2	0.1
6036-127	Highways Well B27	14.6	0.1
6036-125	Highways well B25	14.4	0.0
6036-58	Monty's Well	15.2	0.0

6.2.6. Radiocarbon

Radiocarbon and $\delta^{13}C$ data were obtained from 21 samples to evaluate groundwater residence times (Table 11, Figure 51). The groundwater ages are reported as the conventional radiocarbon age before present using the Libby half-life of 5,568 years (Arnold and Libby, 1949). However, the ages have not been corrected for water–rock interactions (as this was beyond the scope of the present study) and are thus likely to represent the maximum sample age. Further work to evaluate the most applicable radiocarbon correction method (and hence derive more accurate radiocarbon ages) is recommended as part of any further groundwater work in this region. The percent Modern Carbon (pMC) value refers to the absolute percent Modern Carbon (dissolved inorganic carbon) relative to the National Bureau of Standards (NBS) oxalic acid standard (HOxl) corrected for decay since 1950. The radiocarbon data supplied by the laboratories (radiocarbon age, $\Delta^{14}C$, $\delta^{14}C$ and pMC) are as defined by Stuiver and Polach (1977).

The radiocarbon data show a wide spread of uncorrected ages, ranging from typical modern ^{14}C signatures (indicating the added presence of radiocarbon (active) derived from post-1950's nuclear bomb testing) to samples with low pMC and uncorrected ages estimated at >20,000 years. Other groundwater samples have a range of estimated residence times between these upper and lower bounds. The spatial distribution of percent Modern Carbon (pMC) for groundwater samples in the Kingoonya Palaeovalley is highlighted in Figure 52, and the following comments apply:

- The 3 samples with the lowest pMC values and hence the longest residence times (all with pMC <10) occur in the headwaters of the Kingoonya Palaeovalley;
- Other groundwater samples close to those with low pMC have significantly elevated pMC which is typical of modern radiocarbon signatures. However, the location of these samples indicates that they may not be sourced directly from the palaeovalley aquifer, i.e., groundwater may occur in fractured rock aquifers (refer to Section 6.3 for further analysis discussion); and
- Further downstream in the Kingoonya Palaeovalley there are a range of radiocarbon signatures, with values varying from 10–20 pMC to >100 pMC (i.e., 'modern' carbon), and there are no distinctive or consistent spatial patterns.

Table 11: *Radiocarbon data for Kingoonya region groundwater samples.*

Bore	Bore name	δ13C	±	pMC	±	δ14C	±	D14C	±	14C age	±
5736-08	Malbooma Swamp	-7.55	0.2	29.41	0.108			-705.9	1.08	9,830	45
5736-20	Hiern's Well	-9.11	0.2	88.88	0.213			-111.2	2.13	950	35
5736-17	Clayson's Well	-6.44	0.2	103.85	0.29			38.45	2.9	Modern	
5736-41	West Pinding Tank	-7.89	0.2	80.44	0.19			-195.6	1.9	1,750	35
5837-84	Commrailways A37-10	-12.3	1	39.87	0.148			-601.3	1.48	7,385	40
5836-687	Liffy's Bore	-7.91	0.2	64.55	0.161			-354.5	1.61	3,515	40
5836-16	Welcome Well	-8.26	0.2	36.27	0.119			-637.3	1.19	8,145	35
5836-42	Mullina Well	-5.32	0.2	97.53	0.231			-24.68	2.31	200	30
5736-07	Malbooma Outstation	-17.2	2.0	99.92	0.25			-0.77	2.48	Modern	
5636-23	354 Mile Siding	-11.44	0.15	95.7	0.24			-42.96	2.39	350	20
5836-86	Tarcoola Gold Mine TW2	-11.35	2.0	18.61	0.09			-813.9	0.9	13,505	50
5837-64	No.34 Bore	-6.79	0.15	28.09	0.11			-719.1	1.12	10,200	45
5936-35	Scott's Well	0.9		98.67	0.18	19.2	1.9	-13.3	1.8	49	15
5936-118	PDH BB2	-7.6		105.36	0.18	91.4	1.9	53.6	1.8	Modern	
5936-13	North Well	-11.5		111.35	0.19	144.5	1.9	113.5	1.9	Modern	
5936-49	Wallabyng Range Well	-6.2		101.98	0.18	59.4	1.9	19.8	1.8	Modern	
6036-119	Highways Well B19	-3		9.05	0.07	-905.4	0.7	-909.5	0.7	19,243	60
6036-135	Highways Well B29	-6.8		7.03	0.07	-927	0.7	-929.7	0.7	21,266	75
6036-18	Mulga Well No.2	-6.8		104.38	0.18	83.2	1.9	43.8	1.8	Modern	
6036-125	Highways Well B25	-7.2		3.31	0.06	-965.7	0.6	-966.9	0.6	27,310	140
6036-58	Monty's Well	-10.6		97.18	0.18	0.8	1.8	-28.2	1.8	170	15

1. Note: Samples 5736-08 to 5837-64 (12 samples) were analysed for radiocarbon at the ANU SSAMS Laboratory, and samples 5936-35 to 6036-58 (9 samples) were analysed at the Rafter Radiocarbon Laboratory in New Zealand.

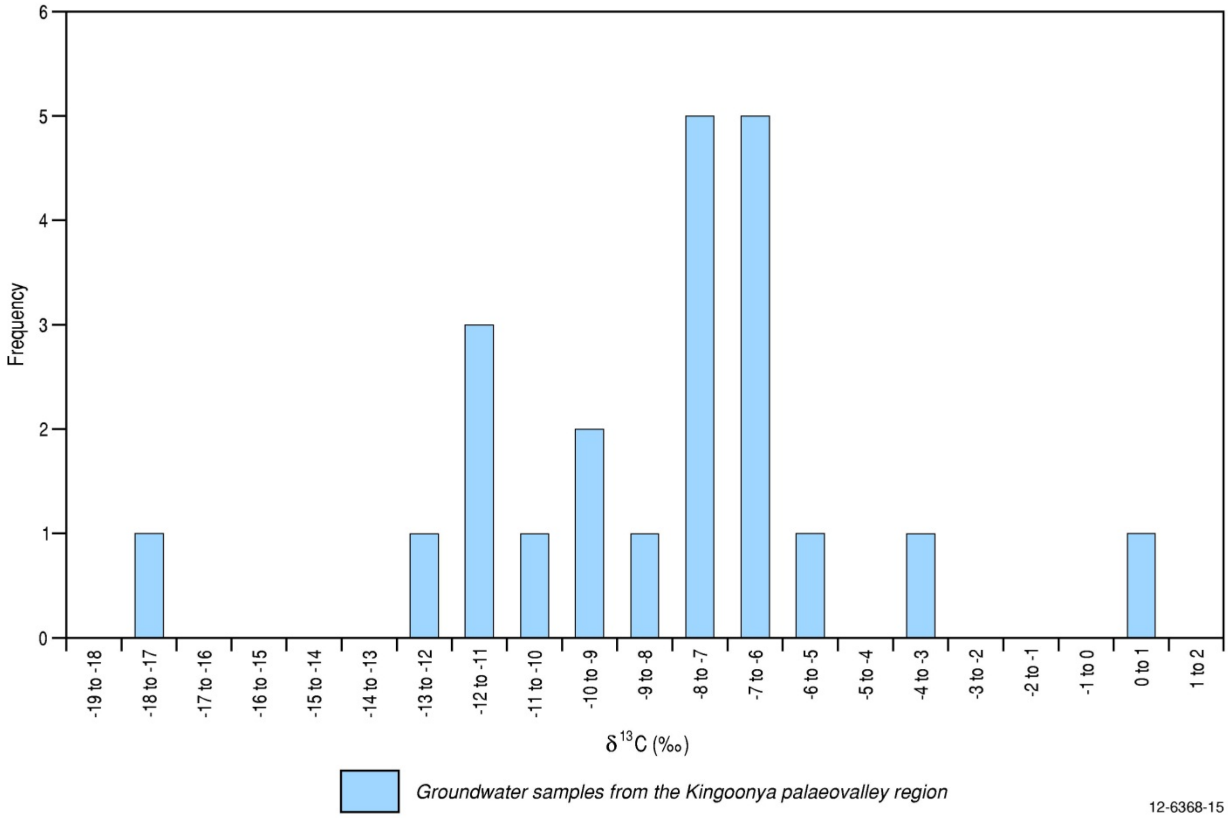


Figure 51: *Frequency histogram of $\delta^{13}C$ in groundwater from the Kingoonya Palaeovalley.*

6.2.7. Radon-222

Radon-222 is a noble gas with a half-life of 3.82 days that has become increasingly used in groundwater studies over the past decade (Cook et al., 2003). The concentration of radon in groundwater reflects the mineral composition of the aquifer (i.e., radon is derived from the radioactive decay of uranium- and thorium-bearing minerals in the aquifer), and also the geometric arrangement of aquifer pore spaces (Love at al., 2002).

Samples from the Kingoonya Palaeovalley were collected for radon analysis at the CSIRO Land and Water Laboratory in Adelaide (Table 12, Figures 53–54).

Care was exercised with the field sampling procedure in the field to ensure that the Kingoonya samples were representative of the radon in the groundwater. Analyses were performed using two distinct methods (direct and PET), which both involve measuring the alpha activity of water with an ultra-low background Quantulus liquid scintillation counter (LSC). This was done after concentrating radon using a mineral oil/scintillant mixture in 22 ml Teflon coated vial (Love et al., 2002).

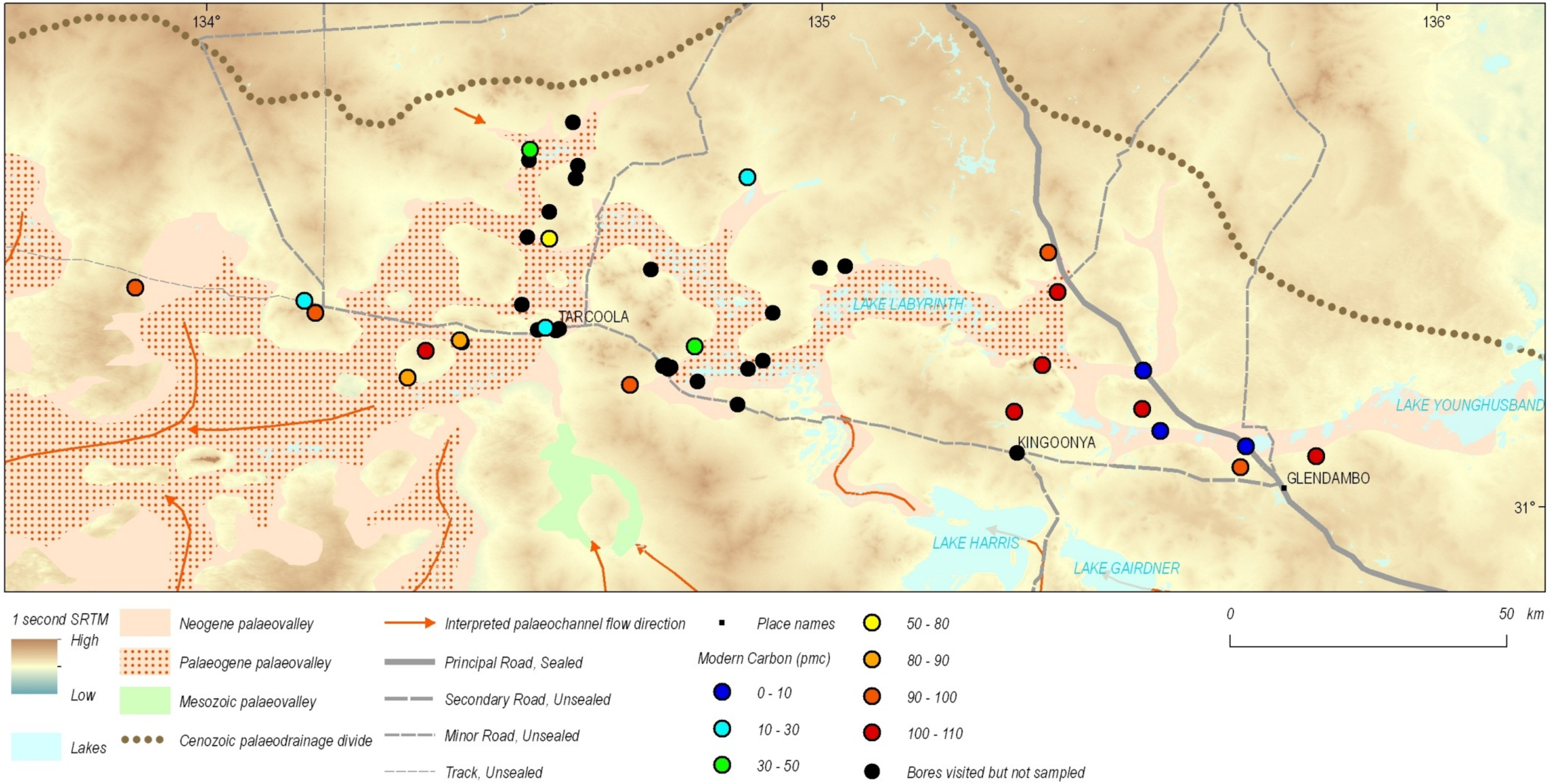


Figure 52: *Spatial distribution of percent Modern Carbon (pMC) for groundwater samples in the Kingoonya Palaeovalley region.*

Variations in the analytical procedure for the two radon sampling methods are:

- **Direct Method** – this is the simpler analytical method, although its use is largely restricted to analysing radon in groundwater (surface water samples generally have much lower levels of radon). The limit of detection is 18 mBq/L (milli Becquerels-per-litre) at a count time of 200 minutes (standard CSIRO laboratory count time). The analytical uncertainty varies from ~0.1-1.0 Bq/L depending on the radon concentration in the sample.
- **PET Method** – this analytical method involves concentrating the radon in the sample from 1.25 L of water into mineral oil in a small vial (22 mL). As this method has a lower detection limit (~5 mBq/L) it can also be used for analysing surface water samples. The analytical uncertainty is significantly better than the Direct method, especially at low initial radon concentrations.

Table 12: *Radon-222 data for Kingoonya region groundwater samples.*

Bore no.	Bore name	Analysis method	Rn pre-purge time	Rn post-purge time	Rn pre-purge (Bq/L)	Rn post-purge (Bq/L)
5736-07	Malbooma Outstation	Direct		14:58		19.40
5636-23	354 Mile Siding	Direct	16:50	17:25	1.44	0.79
5736-20	Hiern's Well	Direct	12:30	13:33	44.3	6.02
5736-17	Clayson's Well	Direct	14:59	15:45	1.23	1.13
5736-41	West Pinding Tank	Direct		14:02		23.10
5836-86	Tarcoola Gold TW2	Direct	16:54	17:19	27.2	69.00
5836-27	RL33	Direct	17:02	17:58	1.57	17.90
5837-84	Commrailways A37-10	Direct	12:56	13:54	20.1	81.70
5837-64	No. 34 Bore	Direct	12:14	13:00	62.4	59.10
5836-16	Welcome Well	Direct		15:02		39.50
5836-42	Mullina Well	Direct	13:46	14:12	0.64	0.37
5936-35	Scott's Well	PET	13:05	13:53	1	0.95
5936-118	PDH BB2	PET	10:10	11:20	0.056	13.90
5936-13	North Well	PET		15:29		1.82
5936-49	Wallabyng Range Well	PET	11:53	12:20	0.284	0.28
6036-119	Highways Well B19	PET	14:57	15:30	1.69	7.73
6036-135	Highways Well B29	PET	10:34	11:37	2.05	18.20
6036-18	Mulga Well No.2	PET		16:58		0.52
6036-127	Highways Well B27	PET	09:59	10:42		4.00
6036-125	Highways Well B25	Direct		16:58		13.00
6036-58	Monty's Well	Direct	14:16	14:43	18.3	18.40
6036-109	Bulyacobbie Bore	Direct		09:38		0.71

Pre-purge samples were not collected at 7 sites due to logistics or equipment problems. Post-purge radon values less than pre-purge values for the same sample suggest that degassing has occurred. Consequently, these samples were not used for flow calculations (as recommended by Love et al., 2002).

At 14 different sites two separate groundwater samples were collected from the bore/well, with one sample collected prior to purging (an undisturbed groundwater sample), and another sample collected after 2–3 well volumes had been pumped (shown in Table 12 as the pre-purge and post-purge values and sampling times, respectively). The reason for this approach was to try and evaluate aquifer flow rates by comparison of radon concentrations in both the unpurged and the purged samples. This method has been successfully applied in previous studies of fractured rock aquifers, e.g., Green et al., 2007. In bores or wells with high horizontal flow rates the concentration of radon in the unpurged sample is similar to that of the purged sample. Conversely, in bores/wells with low horizontal flow rates the concentration of radon in the unpurged sample will be significantly lower, as the radon will decay to background levels as it sits exposed to the atmosphere in the well.

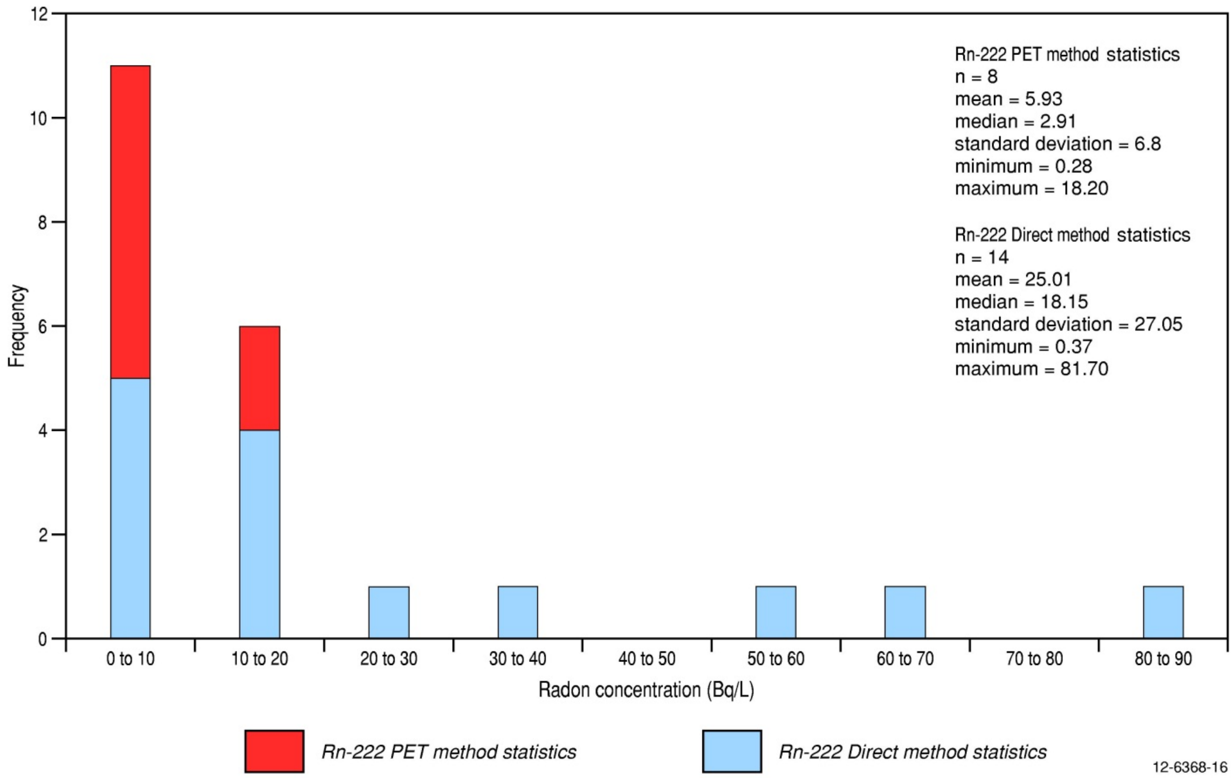


Figure 53: *Histogram of radon concentration data (Bq/L) in groundwater from the Kingoonya region (samples collected post-purge during field operations in July and November 2010).*

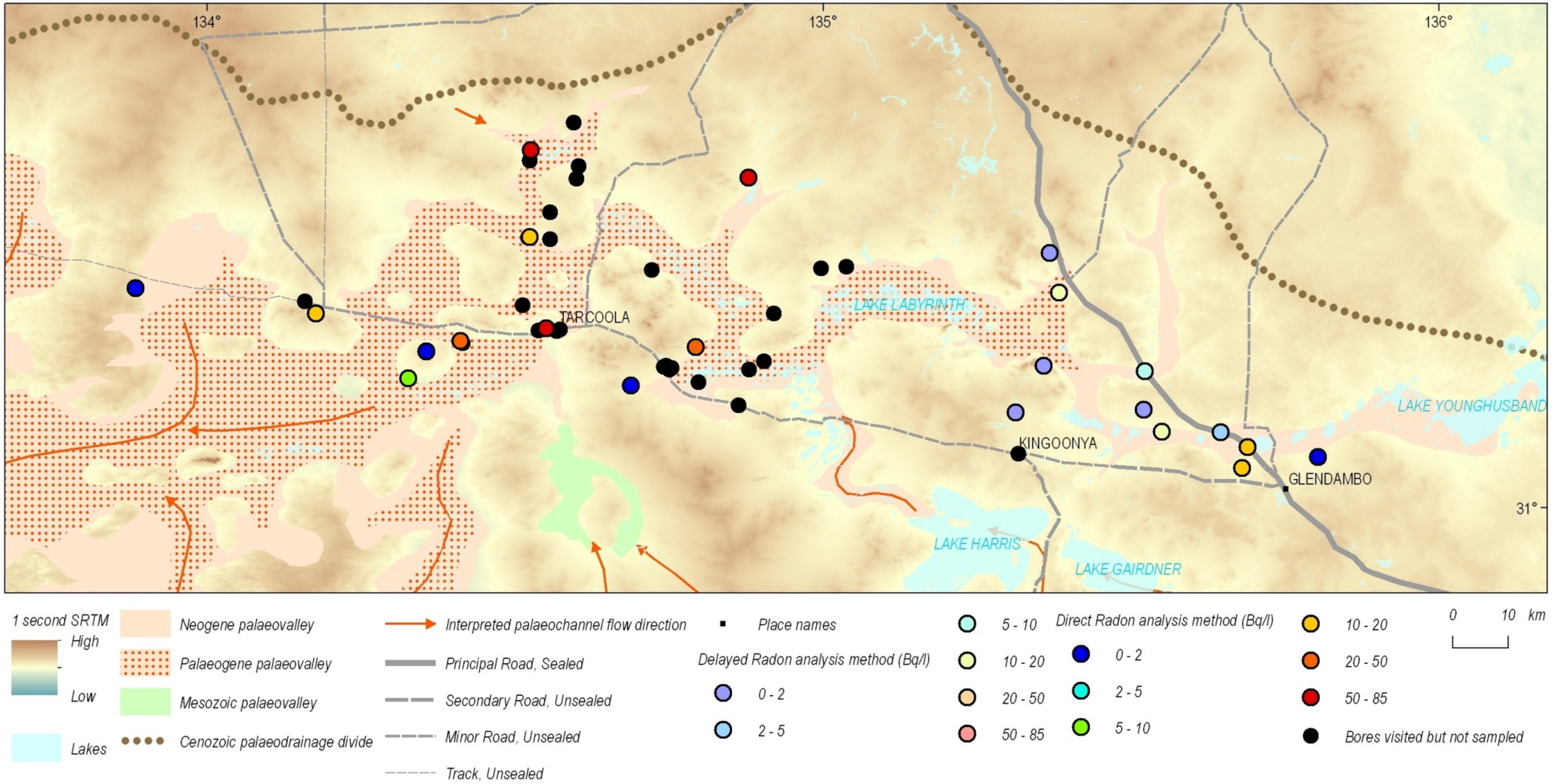


Figure 54: *Spatial distribution of radon-222 concentrations in groundwater sampled in the Kingoonya Palaeovalley region during field operations in July and November, 2010.*

6.3. Analysis and interpretation of hydrogeochemical data

The fundamental nature of any groundwater sample is largely defined by the pH, Eh, and the concentration of the four major cations (Na^+, K^+, Ca^{2+} and Mg^{2+}) and the four major anions (Cl^-, SO_4^{2-}, HCO_3^- and NO_3^-) (MacDonald et al., 2008) [note that the ionic charges for various ions discussed in this section are only shown in the text at the initial mention of each species. For ease of reading, all subsequent references do not include the ionic charge].

The key physico-chemical parameters outlined above reflect the origin of the groundwater (e.g., precipitation, connate water, marine intrusion etc.) and the main processes and reactions that affect groundwater during its evolutionary journey within an aquifer. Consequently, it is critical to understand the common range and variability of these parameters (including outliers) so that baseline hydrogeochemical profiles are well defined for groundwater systems of particular interest. In this section the hydrogeochemical data obtained from the Kingoonya region are analysed and interpreted to better understand the origin and evolution of this arid zone palaeovalley.

6.3.1. Recognising and defining regional aquifer systems in the Kingoonya area

Potential sites for groundwater sampling were initially selected by a GIS query based on coincident groundwater bores and the previously defined extent of the Kingoonya Palaeovalley (after Hou et al., 2007). Additionally, a 2-km wide GIS buffer was included around the margins of the palaeovalley polygon so that nearby bores which may access other aquifers (i.e., non-palaeovalley aquifers such as fractured bedrocks) could also be sampled and compared. Following completion of the fieldwork program we further evaluated the location of all sampled bores/wells and geological logs (only four bore logs available in SARIG), as well as the mapped variations in sediment thickness along the length of the Kingoonya Palaeovalley. These parameters were then cross-referenced with the new hydrogeochemical data to help us develop a semi-quantitative understanding of the most probable aquifer tapped by each bore or well. Based on this analysis, we defined three groundwater classes with varying levels of confidence in their likely affinity with the Kingoonya Palaeovalley aquifer:

- Groundwater is most likely sourced from the palaeovalley aquifer, with a high-level of confidence level (this group is designated as PV-L);
- Groundwater is possibly sourced from the palaeovalley aquifer, with a moderate level of confidence (this group is designated as PV-P); and
- Groundwater is unlikely to be sourced from the palaeovalley aquifer (it is more likely derived from a fractured rock or regolith aquifer), i.e., there is a low-level of confidence that groundwater in this group is derived from a palaeovalley aquifer (this group is designated as PV-U).

Each of the 27 groundwater samples collected for this project was assigned to one of these three categories based on detailed analysis of the available evidence (Table 13). These classes are used as a reference system for the hydrogeochemical data analysis and interpretation in this section.

Table 13: *Classification of groundwater samples from the Kingoonya region based on groundwater affinity.*

Interpreted groundwater affinity	Abbreviated code	Bore/well numbers	Total number of bores/wells
Likely palaeovalley aquifer (high confidence level)	**PV – L** (blue symbols used in data plots)	Bulga Well (5736-15) West Pinding Tank (5736-41) Tarcoola Gold TW2 (5836-86) TPH PC1 (5836-126) RL 33 (5836-27) Commrailways A37-10 (5837-84) Highways Well B19 (6036-119) Highways Well B29 (6036-135) Highways Well B27 (6036-127) Highways Well B25 (6036-125)	10
Possible palaeovalley aquifer (moderate confidence level)	**PV – P** (green symbols used in data plots)	354 Mile Siding (5636-23) Hiern's Well (5736-20) Liffy's Well (5836-687) No.34 Bore (5837-64) Welcome Well (5836-16) Scott's Well (5936-35) PDH BB2 (5936-118) Wallabyng Range Well (5936-49) Bulyacobbie Bore (6036-109)	9
Unlikely palaeovalley aquifer (low confidence level)	**PV – U** (red symbols used in data plots)	Malbooma Swamp (5736-08) Malbooma Outstation (5736-07) Clayson's Well (5736-17) Warna Well (5836-20) Mullina Well (5836-42) North Well (5936-13) Mulga Well No.2 (6036-18) Monty's Well (6036-58)	8

6.3.2. Electrical conductivity and total dissolved solids

Many groundwater samples from the Kingoonya region are characterised by highly elevated levels of electrical conductivity (EC) and total dissolved solids (TDS). There is a strong positive correlation between EC and TDS with R^2 value of 0.9805 (Figure 55), although data for bore 5836-86 (Tarcoola Gold TW2) lies well above the correlation line and may be influenced by the elevated sulfate concentration. The slope of the EC–TDS correlation line is about 0.69, which is within the range of most natural waters (Hem, 1992). The mean TDS of all samples is close to that of seawater (~33,500 mg/L) and ranges to values indicative of hypersaline brine (maximum TDS ~133,500 mg/L). Only seven samples have TDS <5,000 mg/L. There are clear differences in EC values between the three aquifer categories previously defined (Section 6.3.1). In particular, samples which are considered unlikely to be sourced from palaeovalley aquifers, PV-U (i.e., possibly shallow fractured rock aquifers or near-surface perched watertable aquifers), have distinctly lower EC values (Figure 56).

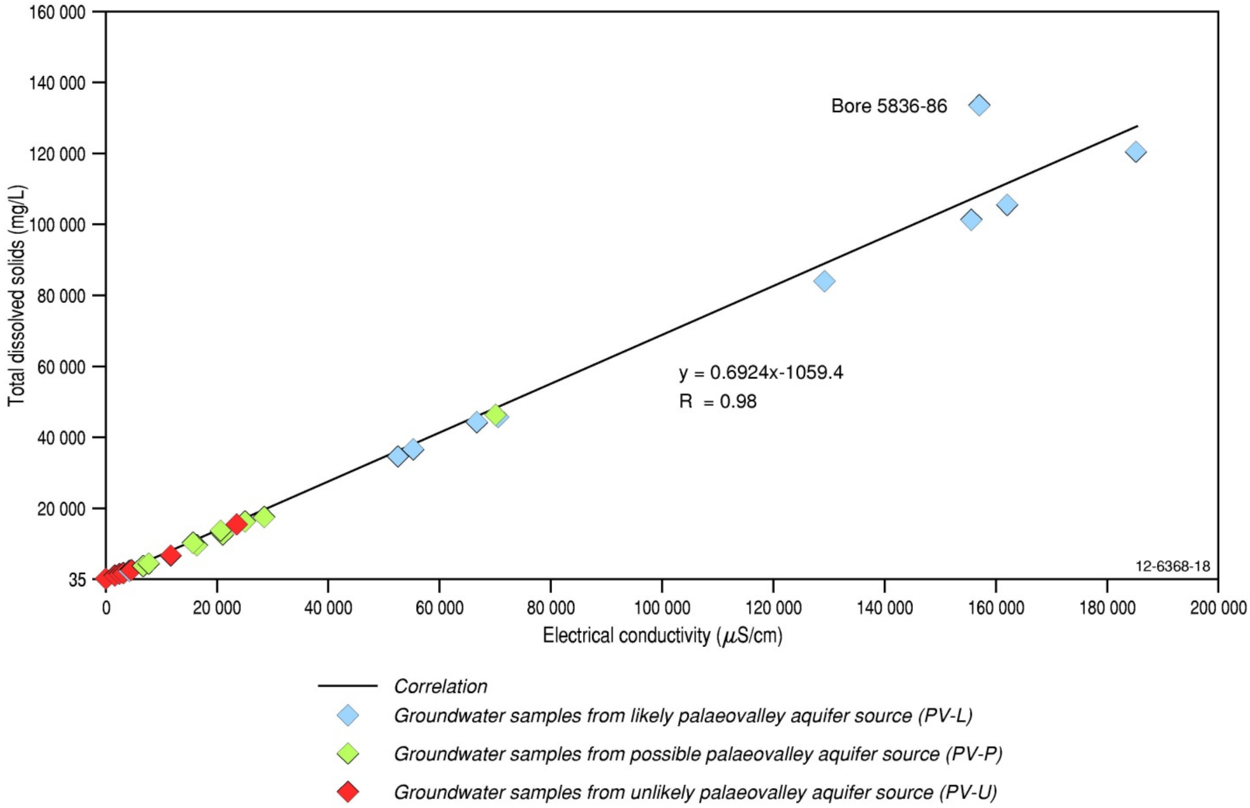


Figure 55: *Correlation of electrical conductivity and total dissolved solids for Kingoonya region groundwaters.*

6.3.3. pH and alkalinity

Most groundwater samples have pH in the near-neutral range (6.5–8.5) with similar mean and median values of 7.15 and 7.18, respectively (n=26). There are no major data trends evident for the different aquifer categories, although the PV-L group tend to be slightly more acidic and the PV-P group slightly more alkaline (Figure 57). There is one very acidic groundwater sample with pH of 3.64 (bore 6036-127, Highways Well B27) and, as discussed elsewhere, this sample has anomalous concentrations of many dissolved constituents compared with other Kingoonya groundwaters, along with relatively elevated redox potential, Eh ~550 mV (oxidising).

Laboratory-determined alkalinities (HCO_3^-) range from 0–846 mg/L, with a mean of 270 mg/L. The most saline samples (TDS >40,000 mg/L) have the lowest alkalinity and almost exclusively belong to the PV-L category, i.e., groundwater most likely sourced from a palaeovalley aquifer. However, sample 5736-15 (Bulga Well) is unusual compared with other PV-L samples as it has relatively high alkalinity (Table 8) and TDS (Appendix 4). In contrast to the PV-L category, the most alkaline groundwater samples generally have TDS < 20,000 mg/L and more commonly belong to either the PV-P or PV-U groups. These trends indicate that groundwater sourced from probable fractured rock aquifers surrounding the palaeovalleys is fresher and has significantly higher bicarbonate concentrations relative to other anions.

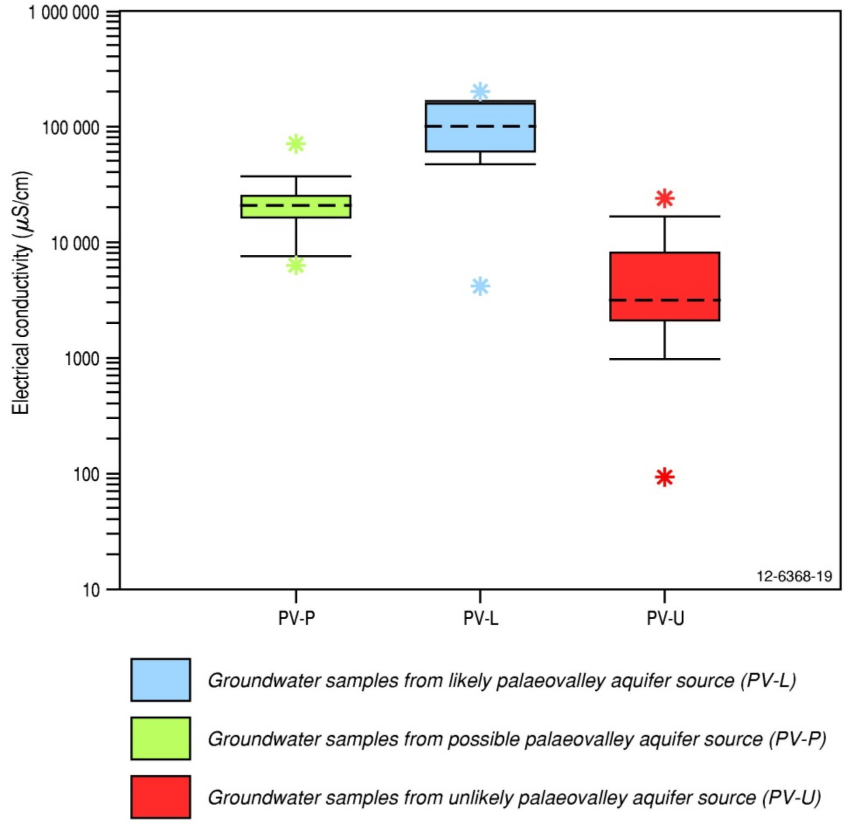


Figure 56: *Box-and-whisker plot of EC data from the Kingoonya region, based on the main aquifer categories defined for this investigation. The line in the middle of each box is the median value, and the lower and upper edges are the 25th and 75th data percentile, respectively. The whiskers extend to the minimum 10th percentile and maximum 90th percentile. Outliers are identified by the coloured stars above and below each box.*

6.3.4. Dissolved oxygen and redox

Kingoonya region samples are predominantly oxidising groundwaters with redox potential (Eh) mainly in the range of 50–500 mV and dissolved oxygen levels from 20–120 ppm (Figure 45). Two samples from the PV-U class have anomalously high dissolved oxygen concentrations >400 ppm (bore 5936-13, and bore 6036-58,), indicating that strongly oxygenated groundwaters may occur in non-palaeovalley aquifers, such as shallow fractured rock or perched watertable aquifers. Six samples have negative redox potentials (low of -132.4 mV) and correspondingly depleted concentrations of dissolved oxygen typical of anoxic conditions (Figure 45). Several PV-L samples also have relatively elevated Fe concentrations (enriched trace cations), suggesting that localised reaches of the palaeovalley aquifer are strongly reducing environments. In favourable pH and Eh conditions these could be sites of pyrite precipitation if sufficient S^{2-} is available in solution.

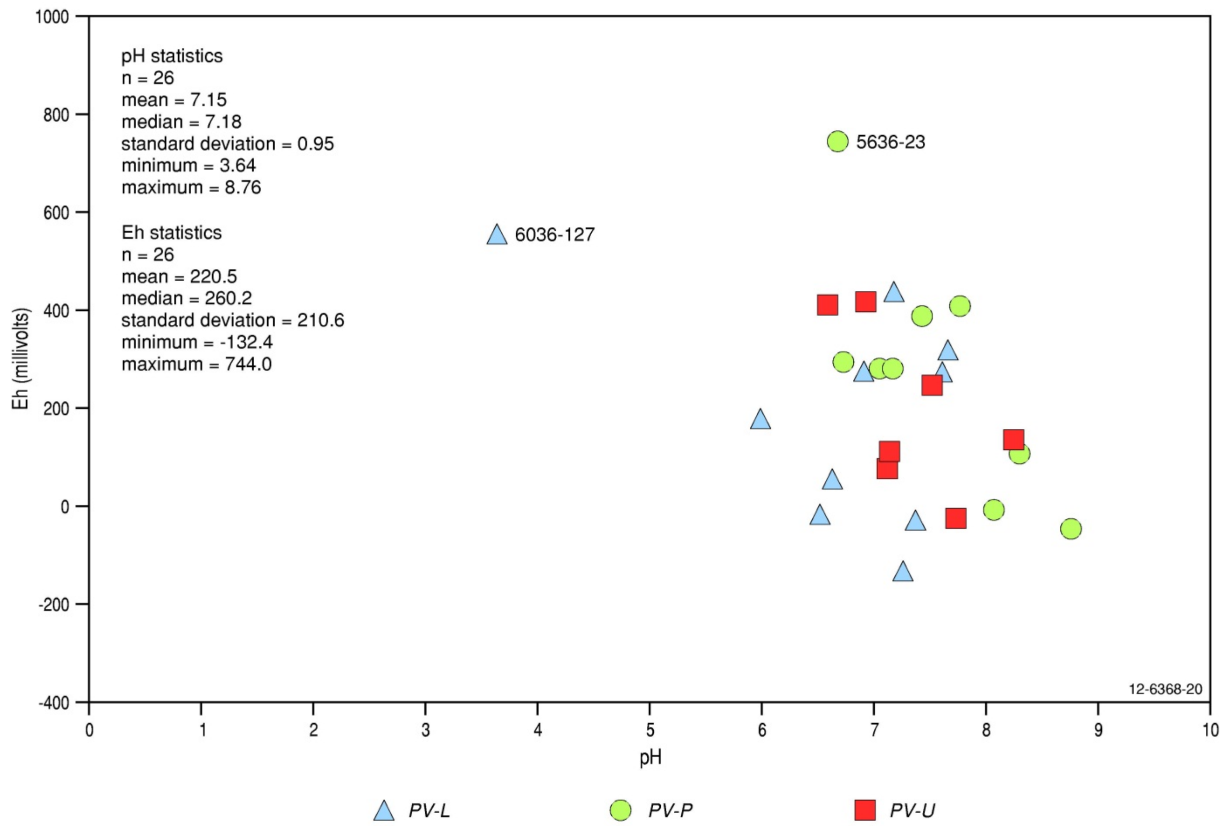


Figure 57: *pH vs. Eh for Kingoonya samples showing that groundwater is typically neutral and slightly–moderately oxidising. Two anomalous samples are distinct from the main data cluster, with sample 6036-127 highly acidic and oxidising, and sample 5636-23 highly oxidising.*

6.3.5. Major ions

Sodium is the most abundant cation species in all Kingoonya groundwater samples across each of the three aquifer categories (PV-L, PV-P and PV-U). For many samples, particularly at higher TDS, the total Na concentrations are greater than the combined sum of the other main cations (Ca+Mg+K). The dominance of Na ions in all groundwater systems is evident in the Piper diagram (Figure 58) and the Schoeller diagram (Figure 59). Elevated Na concentrations in Kingoonya groundwater samples, especially relative to other cation species, reflect the dominance of locally derived rainfall (originating via evaporation and condensation of nearby marine waters in the Southern Ocean) as the main input to local groundwater systems, as well as the effects of local evaporative concentration. Cations derived from weathering and dissolution of silicate minerals in the surrounding bedrock do not significantly affect the overall composition of the Kingoonya groundwater system, although this process may be locally significant.

Similar to the widespread dominance of Na ions, chloride is the most abundant anion species for Kingoonya groundwaters (Figures 58–59). There are distinct variations in the median Cl values for the three different aquifer categories, and the highest Cl concentrations occur in the PV-L class (Figure 60). Groundwaters collected from likely palaeovalley aquifers commonly have sulfate (SO_4^{2-}) as the next most abundant anion species (Figures 59–60), which may reflect sulfate input from dissolution of evaporites in the aquifer sediment profile. Gypsum is relatively widespread throughout the Kingoonya Palaeovalley sequence, and may form significant evaporite layers in some areas (Hou, 2004). Dissolution of evaporites is also supported by the presence of relatively low Br/Cl ratios for some samples (Figure 61f). The median bicarbonate level is greater than SO_4^{2-} in the PV-U groundwater class (Figures 59–60), indicating that sulfate-bearing minerals are less common in surrounding fractured rock aquifers.

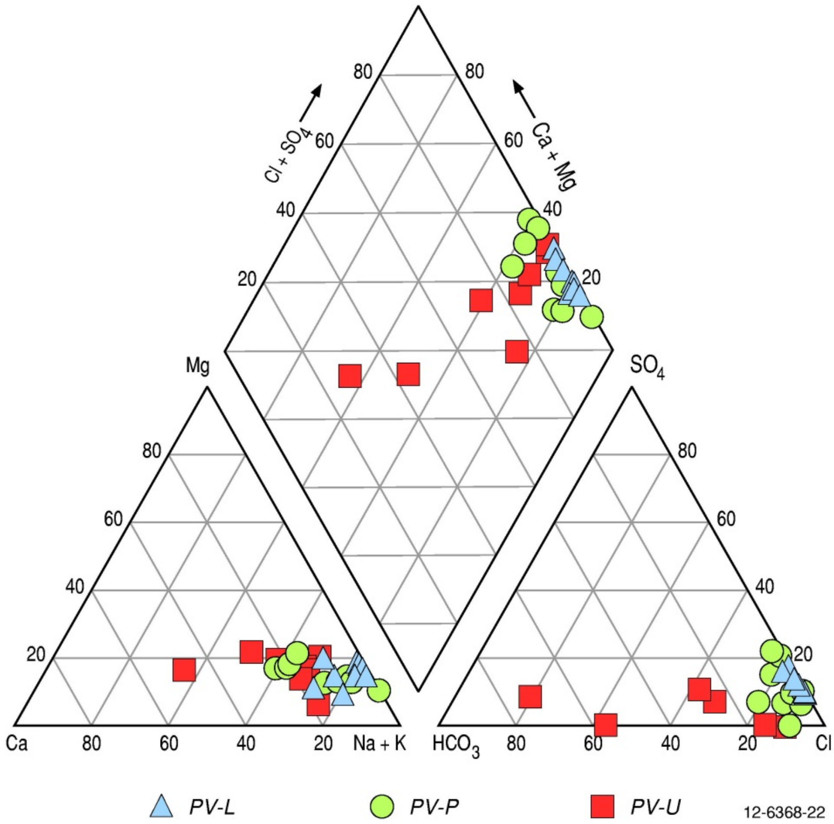


Figure 58: *Piper diagram of groundwater samples from the Kingoonya Palaeovalley region.*

A useful method to evaluate various relationships between major ionic species in groundwater is to generate scatter plots of different ions and ionic ratios (Figure 61a-f). These plots aid in identifying sources of major solutes in groundwater, and help to understand water–rock reactions that occur as groundwater evolves along its flowpath. Figure 61a-b shows strong positive correlations exist for major ions such as Na, Mg and Cl in the Kingoonya groundwater samples. In these plots samples mainly lie upon the seawater reference line, although there are clear discontinuities in the data, e.g., in Figure 61a most data cluster at <1,000 mmol/L for both Na and Cl, but a distinct group of enriched groundwater samples has Na and Cl >1,500 mmol/L. The plot of the Na/Cl ratio versus Cl (Figure 61c) shows a divergent spread of data at dilute salinities. Previous workers have suggested that this type of relationship may indicate the acquisition of Na in precipitation by partial dissolution of dust and wind-blown evaporites, as well as Na removal by interactions with clay minerals (Herczeg and Edmunds, 2000). At higher salinities, the Na/Cl ratio is relatively stable and lies close to the seawater reference line, reflecting the original marine origin of the regional groundwater system, and the dominant effects of evaporation.

The relationship between Ca and Cl in Kingoonya groundwaters is not as simple as for other major ions (Figure 61d). Only a few samples lie along the seawater reference line. Instead, there are two clear trends in these data, with one group of PV-L samples dominated by relative Ca depletion at high salinities, and the other group defining a trend of increasing Ca relative to Cl at significantly lower salinities. These trends may reflect the variable influence of gypsum dissolution and precipitation in the Kingoonya Palaeovalley. Calcite precipitation from groundwater can remove Ca from solution and result in low Ca/Cl ratios as seen in Figure 61d. Calculation of calcite saturation indices using PHREEQC (Parkhurst and Appelo, 1999) indicates that many groundwater samples are saturated with respect to calcite. The relative Ca enrichment in other samples may reflect addition of Ca from dissolution of other calcium-bearing minerals in the palaeovalley sediments and in surrounding fractured rock aquifers, e.g., water–rock interaction in granite leading to Ca-enriched groundwater, or dissolution of gypsum.

Br and Cl are useful tracers for groundwater studies as they are considered to act conservatively and, when used together, can provide information on salinity variations and sources (Figures 61e–f). The ratio of bromide to chloride (Br/Cl) in seawater is usually stable at ~1.57×10^{-3} (molar ratio), and the initial rainfall value can also be considered similar (Cook and Herczeg, 2000). Kingoonya groundwater samples (Figure 61e–f) are relatively enriched in Cl at higher salinities, whereas lower salinity samples tend to lie upon or close to the seawater reference line. Previous studies have shown that low Br/Cl ratios at higher salinities are characteristic of groundwater systems interacting with evaporite-bearing formations (Herczeg et al., 1991; Davis et al., 1998). Dissolution of low Br evaporites (e.g., halite) by groundwater in the Kingoonya Palaeovalley aquifer may be responsible for the range of Br/Cl data (see PV-L data distribution shown in Figures 61e–f).

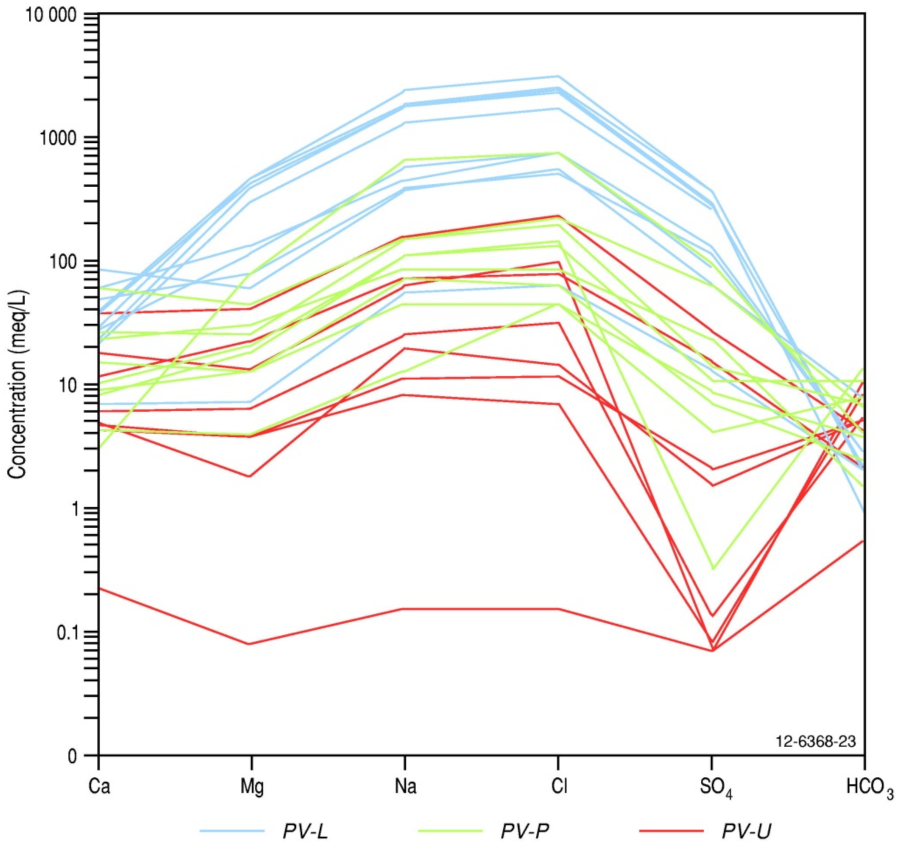
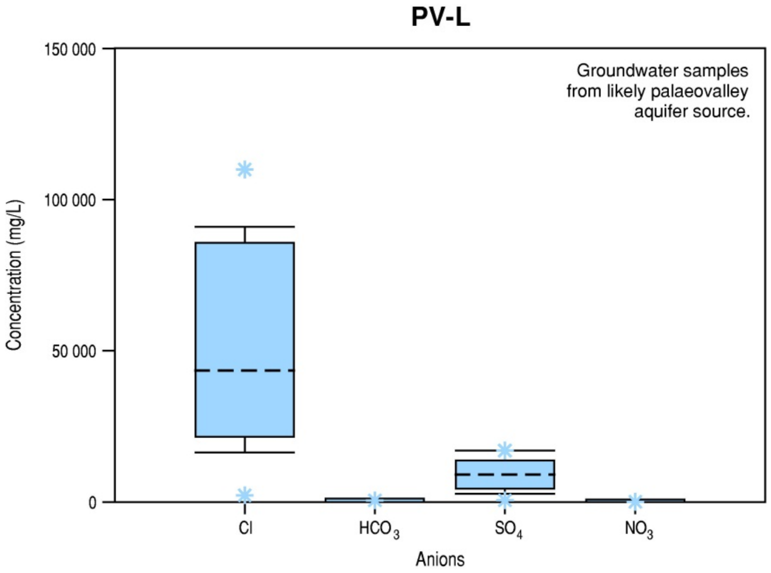
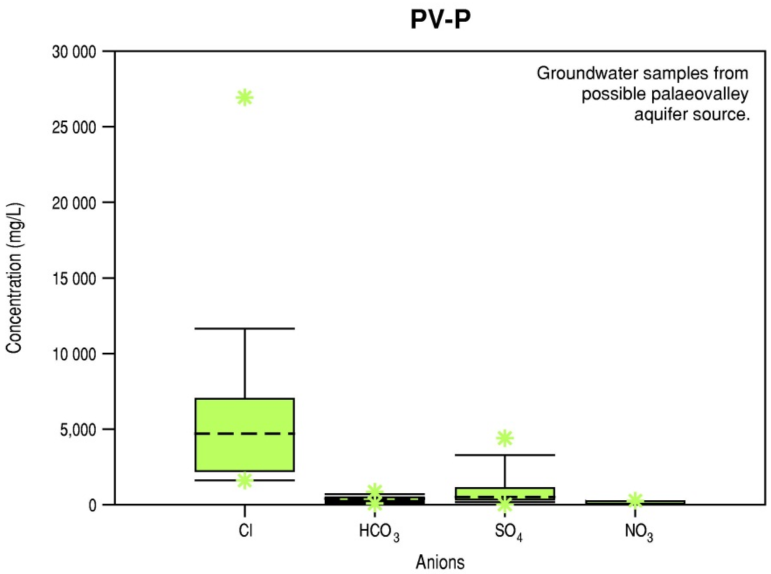


Figure 59: *Schoeller (fingerprint) diagram of Kingoonya region groundwater samples.*


PV-L
Groundwater samples
from likely palaeovalley
aquifer source.
150 000
100 000
50 000
0
Concentration (mg/L)
Cl
HCO3
SO4
NO3
Anions


PV-P
Groundwater samples from
possible palaeovalley
aquifer source.
30 000
25 000
20 000
15 000
10 000
5,000
0
Concentration (mg/L)
Cl
HCO3
SO4
NO3
Anions

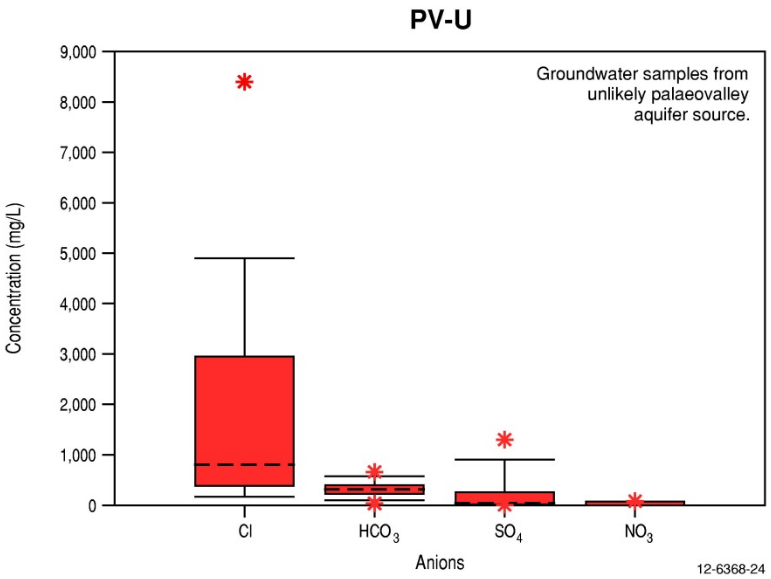

PV-U
Groundwater samples from
unlikely palaeovalley
aquifer source.
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000
0
Concentration (mg/L)
Cl
HCO3
SO4
NO3
Anions
12-6368-24

Figure 60: *(previous page) – Comparison box-and-whisker diagrams for the main anion species in the three groundwater categories (PV-L, PV-P, and PV-U) defined for the Kingoonya region (chloride, bicarbonate, sulfate and nitrate). Chloride is clearly the dominant anion across all 3 groundwater categories, with sulfate also an important component of the total anion composition (most abundant in the PV-L samples). The line in the middle of each box represents the median value, the lower and upper edges are the 25th and 75th data percentile, respectively, and the whiskers extend to the minimum 10th percentile and maximum 90th percentile data points. Maximum and minimum outliers are identified by the stars above and below each box.*

6.3.6. Trace elements

Low-level analyses for a wide range of trace cations were performed for the Kingoonya region groundwater samples using ICP-OES (ppm range) and ICP-MS (ppb range) analytical methods (Appendix 5). This work showed that the suite of metallic cations, rare earth elements and other trace elements are below the limit of detection for many of the 27 groundwater samples. Some minor concentrations of trace elements such as boron, silicon and strontium (Table 14) occur in most groundwater samples, although there are no highly anomalous levels (some samples were below detection for B and Si). The highest strontium values coincide with elevated Ca which is typical of the natural geochemical affinity of these elements.

Table 14: *Summary of statistical data for trace elements in the Kingoonya region groundwater samples analysed using ICP-OES (all data shown in ppm).*

	B	Fe	Mn	P	Si	Sr
Count	23	6	9	6	23	26
Mean	3.5	279	4.7	0.9	16.2	7.8
Standard Error	0.6	241	1.9	0.4	2.4	1.4
Median	2.8	45	2.4	0.7	14.0	5.8
Standard Deviation	3.1	589	5.7	0.9	11.4	6.9
Sample Variance	9.4	347,451	32.9	0.9	129.1	47.8
Range	13.4	1,475	18.2	2.3	39.6	25.5
Minimum	0.2	5	0.4	0.1	1.0	0.6
Maximum	13.6	1,480	18.6	2.5	40.6	26.1

There is strong correlation between samples containing elevated Fe and Mn concentrations above the detection level. Several of these Fe and Mn-bearing samples are from reducing groundwater systems (negative Eh), which is a common hydrochemical association and indicates that reduced iron minerals such as pyrite may form (e.g., 5836-27 and 6036-127). A few samples also contain trace levels of P, commonly <1 ppm.

For the suite of samples analysed using ICP-OES the following cations were below detection limits in nearly all samples (Appendix 5): Al, As, Cd, Co, Cr, Cu, Mo, Ni, Pb, Sb, Se, and Zn.

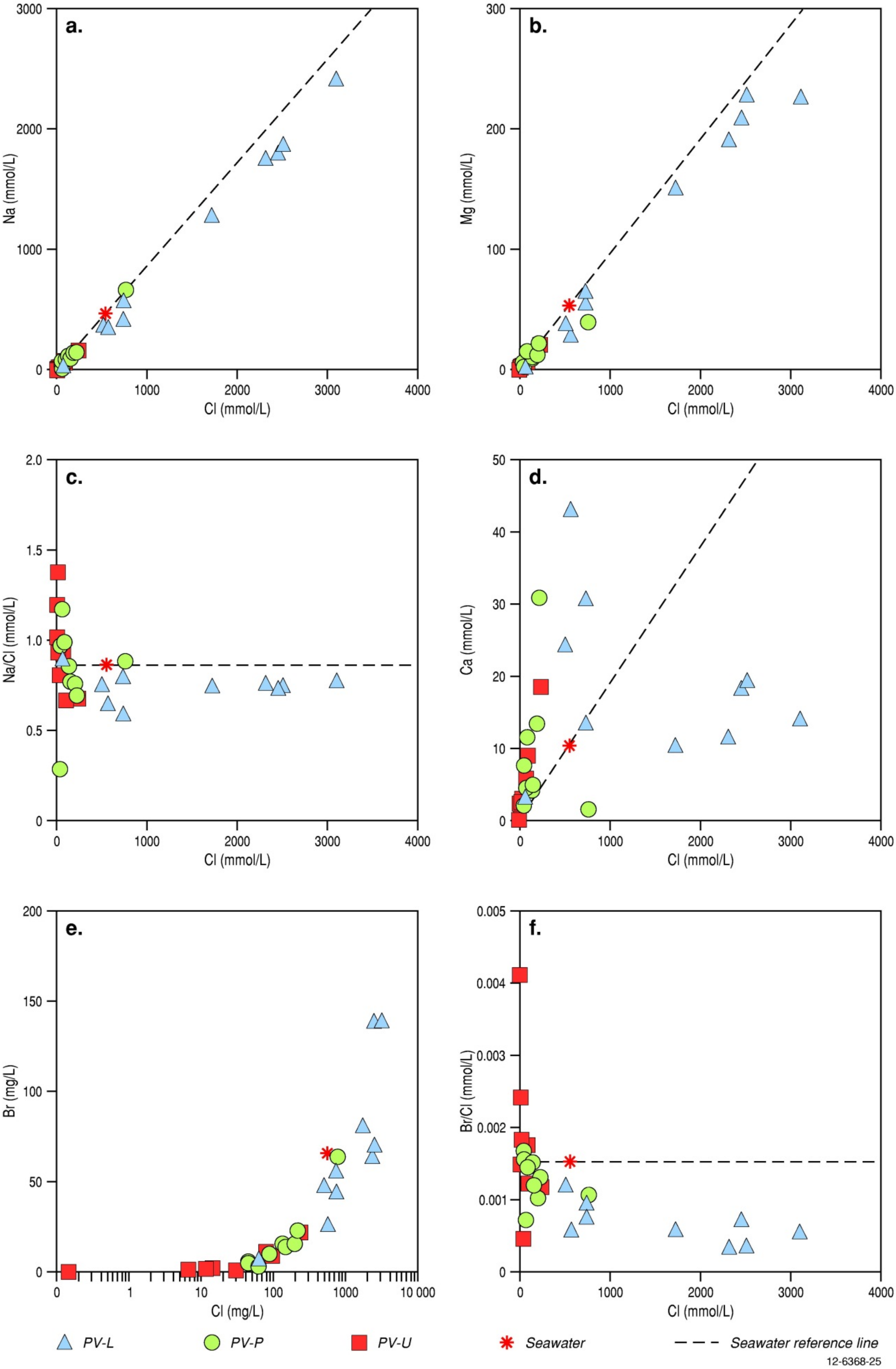


Figure 61: *Scatter plots of major ions and ionic ratios for Kingoonya groundwater samples.*

Based on the data generated from ICP-MS analyses (capable of ppb detection levels) of the Kingoonya region groundwater samples the highest trace element concentrations occur for: Mn, Li, Ga, Rb, Zn, and Ba (Table 15). The most trace element enriched samples are shown in Table 6, although other samples also have varying concentrations. Many samples have low levels of Th and U (Appendix 5), although none are significantly enriched in either. Most other trace elements occur below the limit of instrument detection.

In general, the extensive suite of trace element data indicates only sporadic and relatively low-level metal enrichment in groundwater from the Kingoonya region. Most enriched samples are from the PV-L category indicating that, within this area, the palaeovalley groundwater systems are more likely to contain dissolved metal constituents compared to adjacent fractured rock aquifers. The most trace element enriched sample collected during this study was from bore 6036-127 (Highways Well B27). This sample is highly saline (TDS = 120,000 mg/L) and very acidic (pH=3.64), and contains slightly to moderately anomalous levels of a wide suite of trace elements (including Au, Ag, rare earth elements and platinum group elements). As metal solubility is strongly influenced by pH, the correlation of low pH and metal-enrichment is not unexpected.

Table 15: *Summary of statistical data for selected trace elements in the Kingoonya region groundwater samples analysed using ICP-MS (all data shown in ppb).*

	Li	Mn	Zn	Ga	Rb	Ba
Count	13	26	26	18	15	26
Mean	296.3	2,325	154.2	19.2	125.1	136.8
Standard Error	149.0	1,010	76.2	5.8	58.4	33.9
Median	80.0	285	53.6	9.0	42.0	48.0
Standard Deviation	537.2	5,152	388.4	24.6	226.2	172.7
Sample Variance	288,612.6	26,547,543	150,846.6	604.3	51,177.4	29,810.1
Range	2,002	23,999	1,996	97	896	696
Minimum	8.0	0.5	4.0	0.8	4.0	4.0
Maximum	2,010.0	24,000	2,000.0	97.6	900.0	700.0

6.3.7. Oxygen-18 and deuterium

Oxygen and deuterium isotopes are commonly used in hydrogeological studies to evaluate the importance of various groundwater processes, including evaporation, mixing and recharge mechanisms (Mazor, 1997). Globally, there is almost world-wide correlation of oxygen and deuterium isotope compositions in groundwater, given by the Global Meteoric Water Line (GMWL) equation of:

$$\delta D = 8 \times \delta^{18}O + 10$$

Subtle variations to the GMWL equation occur around the world due to regional factors (e.g., latitude and climate), such that many local meteoric water lines (LMWL) are now defined. For example, the

LMWL for Adelaide and Alice Springs, which are the nearest and most relevant GNIP sites to the Gawler–Eucla region, are respectively defined as:

Adelaide LMWL: $\delta D = 7.84 \times \delta^{18}O + 10.7$

Alice Springs LMWL: $\delta D = 7.52 \times \delta^{18}O + 9.3$

These equations are provided by the Global Network of Isotopes in Precipitation (GNIP) program run by the International Atomic Energy Agency (IAEA). The equations have been defined by least squares regression of isotope data from precipitation, which has been semi-continuously collected on a monthly basis for ~50 years.

Previous research has shown that isotopic deviations from the GMWL (and LMWL) in many groundwater systems are caused by various physical and chemical processes (Cook and Herczeg, 2000). These processes cause isotopic fractionation of the water molecule and result in enrichment or depletion trends for both the oxygen and deuterium isotopes. The direction of isotopic shift away from the GMWL characteristically indicates the dominant process affecting the groundwater system during evolution from the isotopic signature of the original recharge, i.e., the source precipitation. Important processes identified based on stable isotope trends include evaporation, exchange with rock minerals and mixing between isotopically distinct reservoir sources (Mazor, 1997).

Oxygen and deuterium isotope compositions of the Kingoonya samples (Figure 49) provide strong evidence that evaporation is the dominant physical process affecting the regional groundwater system. Average groundwater values for oxygen and deuterium isotopes are significantly enriched relative to the Adelaide LMWL, although sporadic summer rainfall in Adelaide over the last 60 years has also had enriched isotopic signatures and may have similar initial compositions to Kingoonya groundwater (various climatic factors are commonly invoked to influence isotopic seasonality, such as vertical atmospheric stability and monsoonal patterns; refer to Liu et al., 2010 for further discussion).

Figure 49 shows a well-defined linear trend for the Kingoonya isotope data away from the Local Meteoric Water Line (LMWL) (with correlation coefficient of 0.948). The direction of this trend is entirely consistent with evaporation of locally derived precipitation which originated from the nearby Southern Ocean. Multiple data points are considerably enriched in relatively heavier isotopes (compared to standard seawater) suggesting that intensive evaporative concentration (over multiple cycles) of the local waters occurs in the Kingoonya region. Given the prevailing climatic conditions of overall low rainfall (e.g., 175 mm/year average at Tarcoola) and extreme evaporation (>3,000 mm/year average at Tarcoola), significant isotopic concentration is entirely consistent with the data. The trend of isotopic enrichment with increased salinity is shown in Figure 62, although there are also relatively ‘heavy’ deuterium isotopes at lower salinities, which may reflect seasonal variations in the initial isotope signature from specific recharge events.

6.3.8. Sulfur-34

Sulfur isotope compositions ($\delta^{34}S$ ‰) for Kingoonya groundwater samples were determined on dissolved sulfate fractions. Sulfate contained in groundwater may be derived from several sources including the atmosphere, seawater, oxidation of organic matter in sediments and by other water–rock interactions. Sulfur can also be added to groundwater by human activity, e.g., contamination from agricultural or industrial practices, although this is not an important source in the Kingoonya region.

The variation in sulfur isotope compositions with sulfate abundance in the Kingoonya groundwaters is shown in Figure 63.

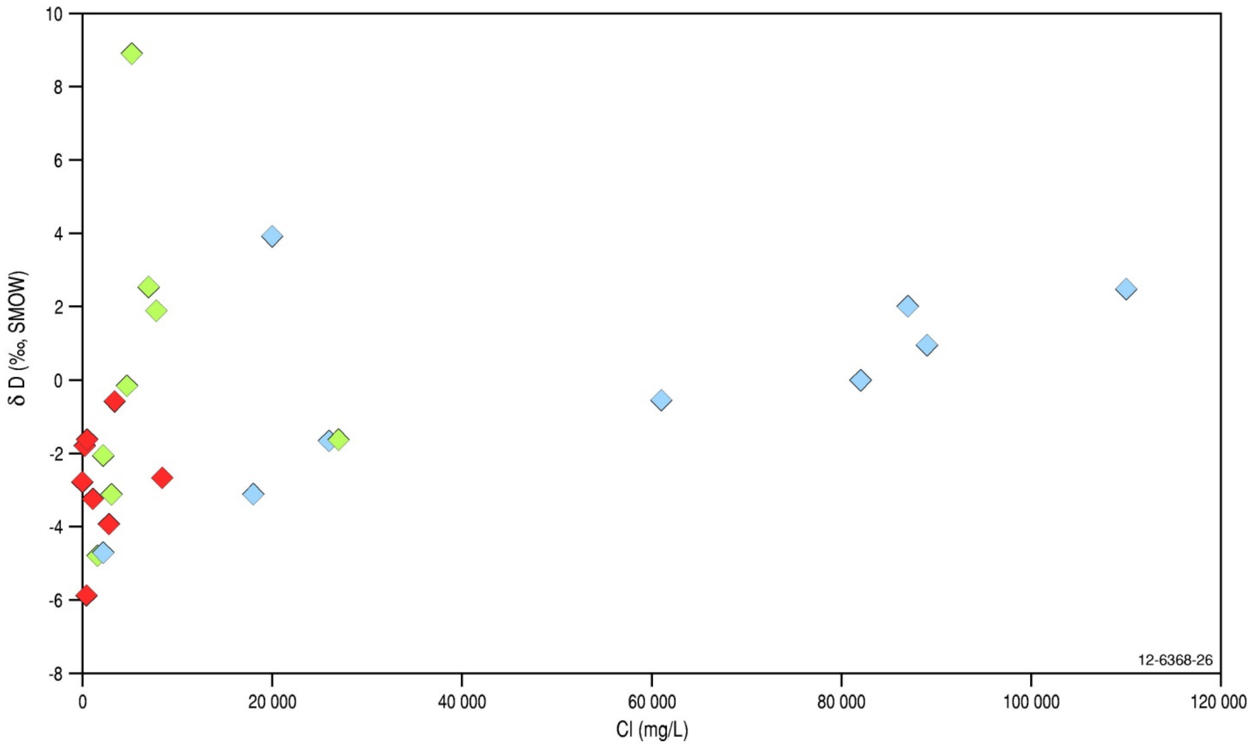


***Figure 62:** Deuterium vs. chloride plot for Kingoonya region groundwater samples showing trend towards isotopically enriched groundwater at relatively high salinities.*

The data range around the typical seawater composition (~19–21‰) although most data define a distinct cluster that has relatively lower Cl/SO_4 ratios and slightly depleted sulfur isotope compositions. These data indicate that a single source of sulfate is unlikely. Instead, sulfate in the Kingoonya groundwaters is probably derived from multiple sources that have distinct variations in isotopic compositions. Given the climatic and geological conditions of the region, the most likely sources of sulfate to explain the observed sulfur isotope data are:

- Sulfate derived from marine aerosols, i.e., seaspray incorporated into local precipitation;
- Sulfate derived from dissolution of gypsum deposits contained in the sediment profile of the Kingoonya Palaeovalley (or dissolution of other sulfate-rich evaporites); and
- Sulfate derived from reduced inorganic sulfur, e.g., fine grained pyrite in sediments produced by bacterial sulfate reduction.

The predominance of data with relatively depleted $\delta^{34}S$ compositions (relative to seawater) indicates that reduced inorganic sulfur is likely to be the most significant source of the overall sulfate load for the Kingoonya groundwater system. Previous geological investigations of the Kingoonya Palaeovalley (Hou, 2004) showed that fine grained pyrite occurs commonly in carbonaceous sediment horizons.

Under the generally oxidising conditions of the local groundwater system these sulfides could provide a significant source component to the overall groundwater sulfate load. The presence of several samples with sulfur isotope compositions similar to that of seawater indicates that marine aerosols also contribute to the sulfur isotope composition (and are likely to have been the major initial sulfur component in recharge waters). One sample with a relatively elevated sulfur isotope composition also indicates that dissolved evaporite deposits may contribute to localised sulfur isotope enrichment, as evaporites tend to have relatively enriched sulfur isotope signatures. Geochemical modelling using PHREEQC (Parkhurst and Appelo, 1999) shows that several samples are saturated with respect to gypsum.

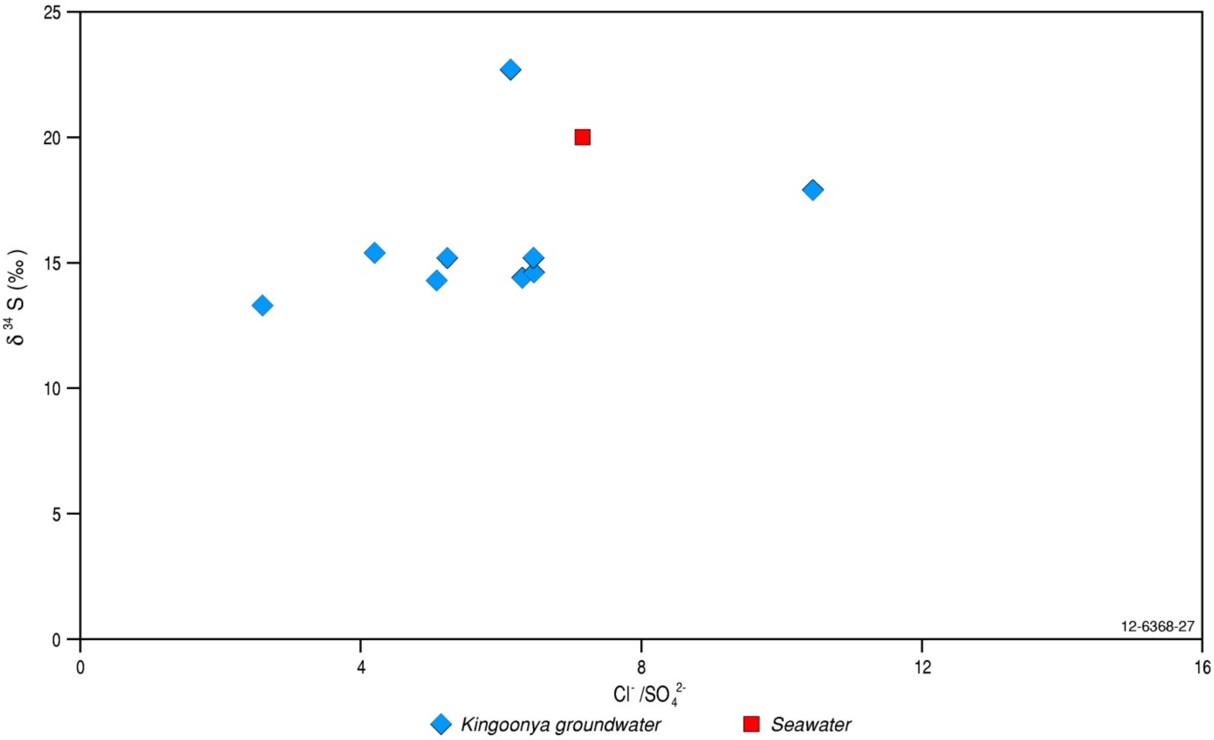


***Figure 63:** Variation in $\delta^{34}S$ with Cl^- / SO_4^{2-} for groundwater samples from the Kingoonya region. The main data cluster indicates depleted sulfur isotope signatures relative to seawater.*

6.3.9. Carbon-13

Most of the $\delta^{13}C$ isotope data for Kingoonya groundwater ranges from -12‰ to -5‰ (Figure 51). These values are typical of dissolved inorganic carbon (DIC) isotopes in most natural groundwaters, which are largely derived from dissolution of carbonate minerals in the aquifer. As shown in Figure 64 the carbon isotope data define a relatively consistent cluster with a few outliers. Samples that are isotopically enriched can be explained by reduction of DIC by bacteria which typically produces a trend towards more positive $\delta^{13}C$ isotopes. Bacterial reduction also tends to increase pH of the groundwater (Cartwright et al., 2010), and the two samples with relatively enriched carbon isotopes also have higher than average pH values for the region (Scott's Well, 5936-35, and Highway's Well B19, 6036-119).

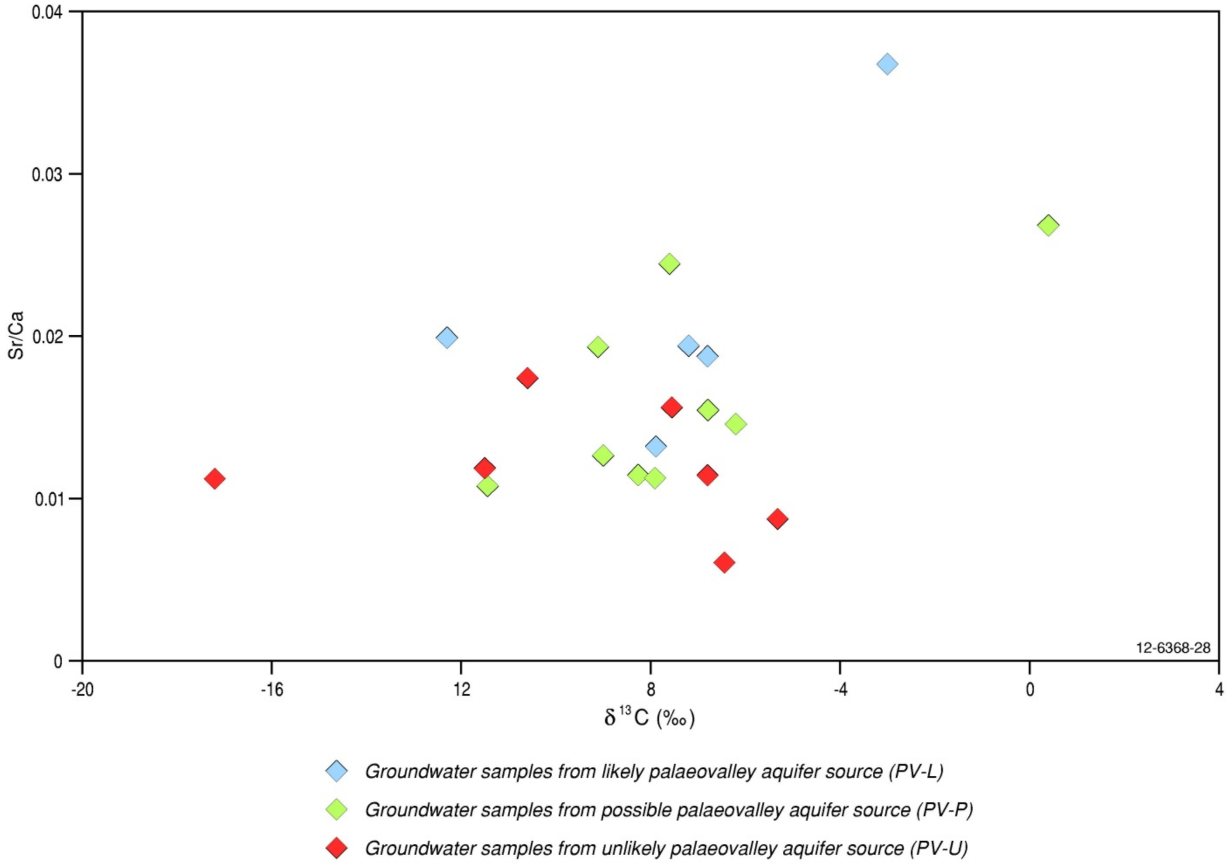


Figure 64: *Plot of Sr/Ca vs. $\delta^{13}C$ for Kingoonya groundwater samples collected during 2010.*

6.3.10. Radiocarbon

Radiocarbon data are commonly used to evaluate groundwater residence time. The radiocarbon values (here defined using percent Modern Carbon, or pMC) for the Kingoonya groundwater samples clearly show a bi-modal distribution (Figure 65). The main data cluster has a distinct ‘modern’ carbon signature characterised by percent Modern Carbon commonly >100, indicating the presence of radiogenic carbon produced by nuclear bomb testing in the 1950’s and 1960’s. The other significant cluster of data points has much lower percent Modern Carbon, commonly <40. There are three samples with pMC <10. Using the conventions of Stuiver and Polach (1977) and the Libby half-life for ^{14}C of 5,568 years, the radiocarbon data has been converted to conventional radiocarbon ages before present. However, the groundwater ages reported by the CSIRO and Rafter laboratories for the Kingoonya samples have not been corrected for possible influence of water–rock interactions (as this was beyond the original scope of this study), and hence the age dating can be considered to represent likely maximum values. Further groundwater studies on this palaeovalley aquifer would benefit by assessing the most applicable radiocarbon age correction method to apply to these raw data, and hence develop more robust estimates of groundwater age.

The radiocarbon data indicate that the groundwaters in the Kingoonya Palaeovalley region probably represent a variable mix of modern recharge water derived from precipitation in the post-1950’s period, as well as a distinctive and significantly older groundwater component that dates to recharge events >20,000 years ago. Only a few samples provide evidence for any significant degree of mixing between these two end-member groups, suggesting that the older groundwaters (deeper) are mostly isolated and have poor connection with the younger, near-surface groundwater dominated by modern recharge.

Most of the groundwater samples with low pMC belong to the PV-L group, indicating that the palaeovalley system (especially the deeper and possibly semi-confined basal thalweg aquifer) hosts the oldest groundwater in the Kingoonya region. In contrast, most of the 'modern' radiocarbon signatures are for groundwater in the PV-U group, suggesting that the groundwater hosted in near-surface fractured rock systems (or other non-palaeovalley aquifers) is dominated by modern recharge, and mostly lacks an older groundwater component. It is also possible that some apparently modern groundwater signatures are influenced by surface water run-off or direct infiltration to those wells which are open to the atmosphere, i.e., the larger hand-dug wells which occur at some sites.

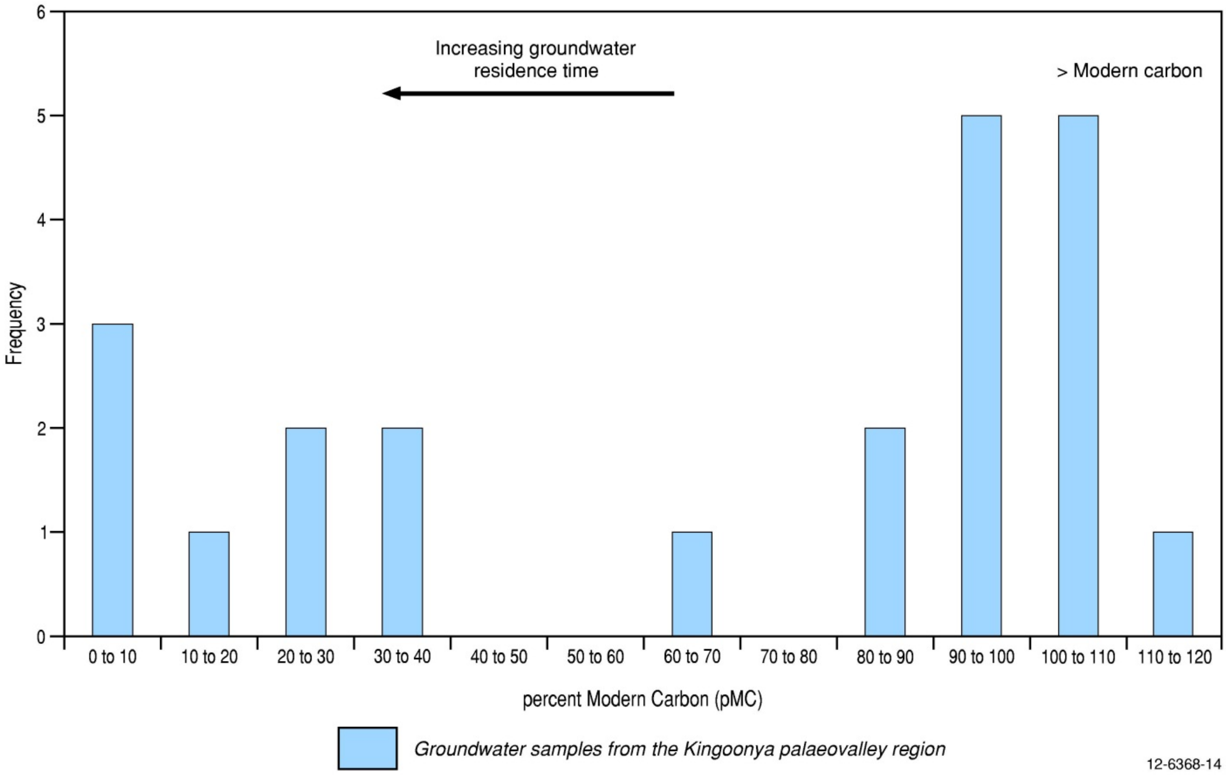


Figure 65: *Frequency histogram of percent Modern Carbon (pMC) in groundwater from the Kingoonya Palaeovalley region, collected during field operations in July and November 2010.*

6.3.11. Radon-222

The concentration of ^{222}Rn in natural groundwater is dependent upon the concentration of the localised parent radionuclide material present within the rocks that comprise the aquifer. Radon is a short-lived (half-life of 3.82 days) radionuclide produced through a multi-stage decay series starting at ^{238}U. Increased concentrations of ^{222}Rn are typically associated with granitic rocks as these tend to have naturally elevated levels of ^{238}U. However, concentrations of ^{222}Rn can vary widely even within the same hydrogeologic environment, indicating that the distribution of parent radionuclides is non-uniform (Cook et al., 2003).

Given the wide range of ^{222}Rn data previously reported for groundwater investigations, i.e., <3 to >1,000 Bq/L (Cecil and Green, 2000), the values obtained for the Kingoonya investigation are relatively well constrained. Most radon concentrations are relatively low (<20 Bq/L), indicating that radon has relatively limited application for the current investigation. As expected, the Kingoonya groundwater samples with the highest radon abundances correlate with relatively enriched uranium concentrations, e.g., groundwater from bore 5837-84 has ^{222}Rn of 81.7 Bq/L and uranium concentration of 24.8 ppm. Sporadic elevated uranium concentrations have been widely reported in groundwaters from the Gawler–Eucla region. For example, in the Warrior Palaeovalley, a smaller tributary of the Kingoonya system situated west of Tarcoola (unpublished and confidential Toro Energy Limited exploration data), low-level uranium mineralisation is a feature of the regional palaeovalleys.

Radon concentrations in groundwater have previously been used for a range of applications, including recharge studies, flow path determination and to better understand groundwater–surface water interactions. Radon is particularly useful for studies of groundwater discharge to rivers and streams, as most surface water bodies only obtain radon via groundwater input, and it has a short half-life. Radon has also been used to estimate groundwater flow velocities in fractured rock aquifers in South Australia, e.g., Green et al., 2007. As previously stated (Section 6.2.7), in bores or wells with high horizontal flow rates the concentration of radon in the initial unpurged sample is similar (commonly slightly greater) to that of the purged sample. Conversely, in bores/wells with low horizontal flow rates the concentration of radon in the unpurged sample will be significantly lower, as the radon will decay to background levels as it sits exposed to the atmosphere in the well (Love et al., 2002). Using this simple rule, our analyses of radon levels in groundwater collected for this study indicate that 6 bores/wells tap aquifers with relatively low horizontal flow rates, i.e., radon levels are much lower in the pre-purge samples (Table 16). Most of these samples are associated with the PV-L class, suggesting that aquifer flow rates are generally very low in the aquifers of the Kingoonya Palaeovalley. For most of the other samples collected with both types of radon data, the post-purge values are slightly less than the pre-purge values (Table 16). This may indicate degassing of groundwater in these bores/wells prior to sampling (Tania Wilson, pers. comm., 2012), which means that these samples should not be used to interpret relative flow rates in the aquifer.

Table 16: *Semi-quantitative interpretation of groundwater flow rates based on variations in radon data for Kingoonya region samples collected in 2010.*

Bore no.	Bore name	Aquifer type	Difference in radon conc. (Bq/L)	Interpreted flow rate
5636-23	354 Mile Siding	PV-P	0.65[a]	degassed?
5736-20	Hiern's Well	PV-P	38.28[a]	degassed?
5736-17	Clayson's Well	PV-U	0.10[a]	degassed?
5836-86	Tarcoola Gold TW2	PV-L	-41.80[b]	low flow rate
5836-27	RL33	PV-L	-16.33[b]	low flow rate
5837-84	Commrailways A37-10	PV-L	-61.60[b]	low flow rate
5837-64	No. 34 Bore	PV-P	3.30[a]	degassed?
5836-42	Mullina Well	PV-U	0.27[a]	degassed?
5936-35	Scott's Well	PV-P	0.05[a]	degassed?
5936-118	PDH BB2	PV-P	-13.84[b]	low flow rate

Bore no.	Bore name	Aquifer type	Difference in radon conc. (Bq/L)	Interpreted flow rate
5936-49	Wallabyng Range Well	PV-P	0.00[a]	degassed?
6036-119	Highways Well B19	PV-L	-6.04[b]	low flow rate
6036-135	Highways Well B29	PV-L	-16.15[b]	low flow rate
6036-58	Monty's Well	PV-U	-0.10[c]	high flow rate

The difference in radon level refers to the absolute difference between the purged and pre-purged groundwater samples – see Table 12 for actual values. Values shown with superscript (a) indicate that the pre-purged sample contains a greater amount of radon than the post-purge sample, and may indicate that the samples have lost dissolved radon gas. Values shown with superscript (b) indicate that the post-purge samples contain relatively more radon than the pre-purge samples, which may indicate low groundwater flow rates. The sample with superscript (c) has a small negative variation in radon, which may indicate a slightly higher flow rate.

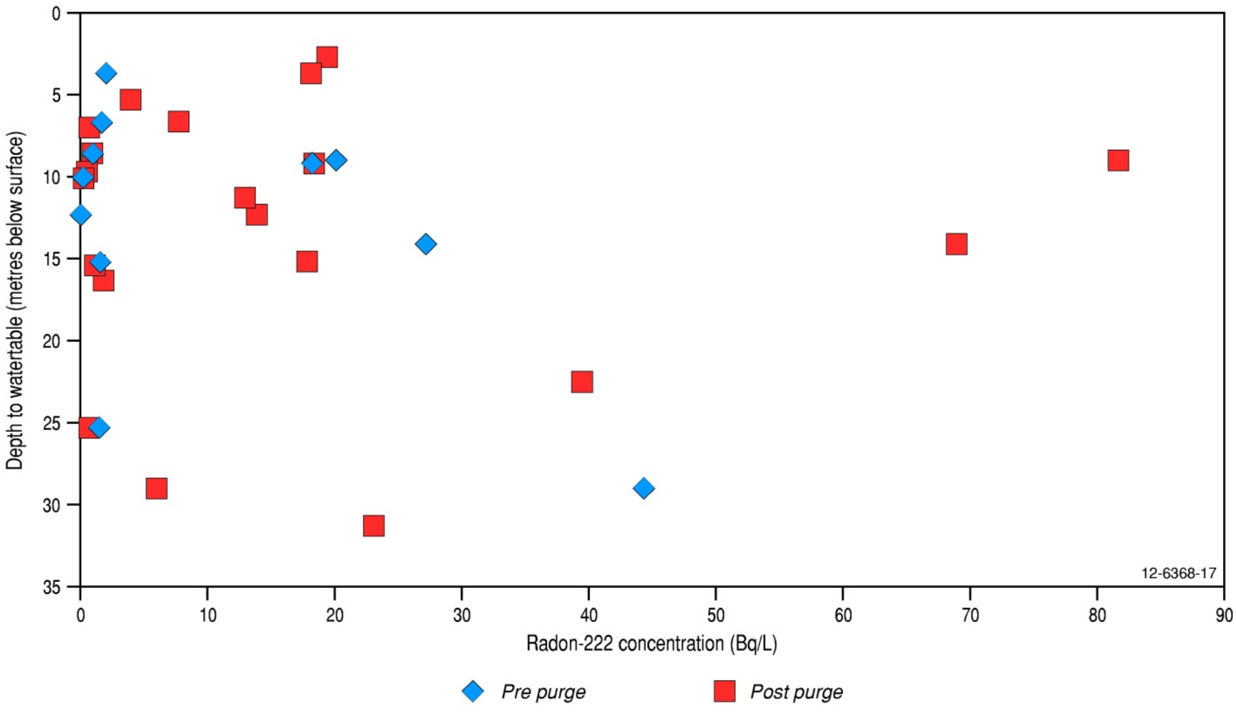


Figure 66: *Variation in radon-222 gas concentration with depth to watertable for Kingoonya region samples. Most groundwaters in the region have low radon concentrations, although some post-purge samples are elevated relative to pre-purge which may indicate low horizontal flow rates for these Kingoonya Palaeovalley aquifers.*

6.4. Summary

The key objective of this research project was to characterise baseline hydrogeochemical features of the groundwater system in the Kingoonya Palaeovalley. Based on our extensive analyses of spatial and hydrogeochemical data we confidently recognise that 10–12 of the sample sub-set (27 groundwater samples in total) represent groundwater of the Kingoonya Palaeovalley aquifer (termed the PV-L class in Section 6.3). Of the remainder, there are six samples that can confidently be considered non-palaeovalley groundwaters, probably from fractured and weathered bedrock aquifers surrounding the palaeovalley. The remaining samples are of uncertain derivation but likely represent a mix of these groundwater types or aquifer systems. As previously mentioned, there is no current means to definitively classify aquifer types without drilling new boreholes adjacent to the sampling sites and conducting detailed geological analysis of the sedimentary infill or weathered bedrock profile. However, based on the available information and the consistent application of our assessment methodology, we conclude with a high degree of confidence in the relative aquifer classifications defined for this study.

Analyses of groundwaters considered most likely to represent the Kingoonya Palaeovalley aquifer indicate that typical hydrogeochemical parameters of this groundwater system are:

1. Highly elevated levels of electrical conductivity and total dissolved solids, with salinities similar to seawater or hypersaline brine;
2. Near-neutral pH, tending slightly acidic, with generally low alkalinity – rare anomalous samples may be highly acidic (pH<4);
3. Predominantly oxidising groundwater, although may range to slightly reducing and anoxic conditions (negative Eh);
4. Dominated by Na as the major cation species, commonly at concentrations Na > (Ca+Mg+K);
5. Cl is the main anion species, with sulfate the next most common anion, although with considerable variability due to its sporadic addition from localised water–rock reactions – other anions are mostly at very low levels and relatively unimportant;
6. Using the hydrogeochemical facies concept, ~⅔ of the entire Kingoonya samples belong to the Na-Cl facies, including all of the samples from palaeovalley aquifers. Other facies types occur in the fractured rock groundwaters, and are mostly slight derivations from the Na-Cl facies, such as Na-Ca-Cl and Na-Mg-Cl;
7. Trace metal enrichment is not common, although localised exceptions occur due to interaction of groundwater and the heterogeneous sediment packages of the palaeovalley infill, or restricted input from surrounding bedrock-derived groundwater;
8. Oxygen and deuterium isotopes define a distinct evaporative trend away from the local meteoric water line (the Adelaide LMWL) and indicate multiple stages of evaporative cycling and relative enrichment of isotopic signatures from precipitation originally derived from nearby marine waters;
9. Sulfur isotope signatures are typically depleted relative to seawater, suggesting oxidation of reduced inorganic sulfur-bearing species contributes significantly to the overall sulfate load;
10. Moderately to slightly depleted ^{13}C isotope data form a fairly well constrained group that reflects buffering by dissolution of calcite in the aquifer;
11. Bi-modal radiocarbon distribution indicating that very old groundwaters (>20,000 years old) occur in the deeper confined palaeovalley thalweg aquifer, and ‘modern’ recharge groundwater is most likely in the shallower fractured rock and near-surface perched watertable sediment aquifers; and
12. Generally low levels of dissolved radon-222, with variations in pre-purge and purge samples suggesting low aquifer flow rates in the Kingoonya Palaeovalley.

7. The Kingoonya Palaeovalley Aquifer – discussion and conclusions

7.1. Conceptual model of the Kingoonya Palaeovalley groundwater system

The results of Geoscience Australia's investigation into regional aquifers associated with the Kingoonya Palaeovalley have yielded significant new hydrogeochemical data which can be used to interpret the origin and evolution of the active groundwater systems. These data establish hydrogeochemical baseline conditions for the palaeovalley aquifer and provide evidence of the key groundwater processes in the Gawler–Eucla region (a key objective of this study). Our interpretation of these data has led to development of a new hydrogeological conceptual model for the Kingoonya Palaeovalley (Figure 67). This model illustrates salient features of the regional groundwater system and explains the dominant hydrogeological processes and relationships of major elements in this arid zone region.

Key aspects of this conceptual hydrogeological model are:

1. The Kingoonya Palaeovalley was incised into the fractured and weathered bedrock of exposed Archean and Proterozoic basement (Gawler Craton) during multiple stages of episodic fluvial activity, mainly in the Eocene and Miocene. During its evolution as a major surface water system, climatic conditions were significantly different from modern times. In particular, this was a temperate environment that received relatively high rainfall and had lower evaporation rates compared to present, widespread aridity.
2. Episodic sedimentation during the Paleogene and Neogene Periods deposited a variable sequence of fluvial sediments in the upper and middle reaches of the palaeovalley, with estuarine systems prevailing further downstream proximal to the margins of the ancient Eucla Sea. A stacked succession of alluvial sedimentary facies formed in the incised valley which, in places, developed sequences up to several hundred metres thick.
3. Although the palaeovalley infill sequence is dominated by massive layers of fine-grained silt and clay, thinner horizons of relatively coarse-grained sand and gravel were deposited in the Kingoonya Palaeovalley, especially as basal layers in the main active river channel (thalweg). These zones now represent the most hydraulically transmissive sediments in the valley fill sequence, and form the main aquifer in the buried palaeovalley. In the modern-day setting basal sediments are typically saturated and mostly confined by the overlying finer-grained sediment layers.
4. Shallower, perched watertable aquifers may also occur in sections of the palaeovalley where favourable sandy horizons have developed higher in the stratigraphic sequence. However, these aquifers are not regionally extensive and likely represent localised groundwater systems of limited extent.

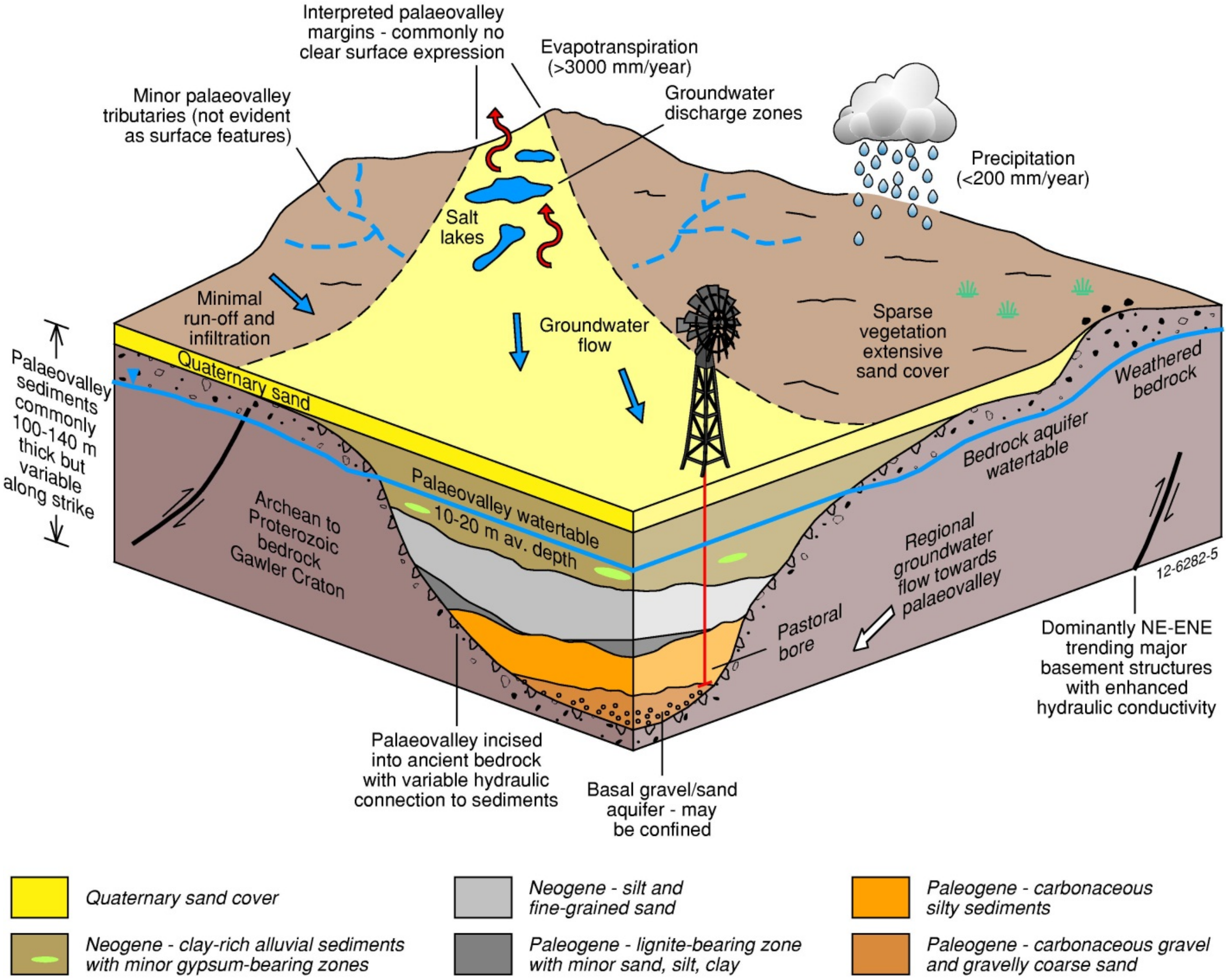


Figure 67: *Conceptual hydrogeological model for groundwater systems in the arid zone region of the Kingoonya Palaeovalley.*

5. The thickness and width of the main thalweg aquifer varies considerably along the length of the palaeovalley (as do the dimensions of other sedimentary sequences), but relatively good aquifer continuity exists along most of the upper and middle reaches forming an extensive aquifer network connected with many smaller tributaries that feed into the main trunk palaeovalley.
6. The chemical signature of Kingoonya groundwater systems (including the main palaeovalley aquifer, other sediment-hosted aquifers and nearby fractured bedrock aquifers) indicates that the ultimate source of groundwater recharge is precipitation derived by evaporation and condensation of nearby marine waters in the Southern Ocean.
7. The groundwater system receives very limited input from direct and diffuse recharge. Although no detailed studies have yet been done to quantify recharge values, we estimate recharge rates in the order of 0.5–1 mm/year. Rainfall is sporadic and of limited extent (generally an order of magnitude less than the annual evaporation rate), and the hydrologic system dynamics require significant levels of rainfall to facilitate even minor volumes of recharge, i.e., recharge is only likely to follow heavy rain events (>50–100 mm) associated with intense storm activity. Consequently, the groundwater system throughout the regional aquifers is sluggish, and minimal throughflow occurs. The most hydraulically transmissive aquifers are

the relatively porous basal sand and gravel (thalweg) horizons of the Kingoonya Palaeovalley, as well as major structural zones (faults and fractures) in the surrounding fractured bedrocks. In some places, these discontinuities may be in direct hydraulic connection with the palaeovalley sediments.

8. Despite low levels of recharge there is clear evidence from radiocarbon dating that modern rainfall does infiltrate some regional aquifers to replenish the groundwater systems. However, groundwater with a ‘modern’ radiocarbon signature occurs more commonly within the shallow non-palaeovalley aquifers of the region, such as weathered and fractured bedrock aquifers and localised perched watertable aquifers in Quaternary sediments and regolith material. Based on the uncorrected radiocarbon data the deeper groundwater systems of the palaeovalley thalweg aquifers (which may occur at depths of 100–150 metres below surface) are considered to have significantly longer residence times, i.e., groundwater residence times >20,000 years before present. This suggests that modern recharge takes many thousands of years to reach the basal palaeovalley aquifers, as the overlying sediments are predominantly silts and clays with very low vertical hydraulic conductivity. Hence, the main palaeovalley aquifer has a significant ‘fossil’ groundwater component, which is an important consideration for any future large-scale extraction scenarios that may occur.
9. The dominant physical process modifying groundwater in the Kingoonya Palaeovalley region is evaporation. The very high salinity levels (commonly greater than seawater throughout the region) and the characteristic trend of stable isotope data provides clear evidence that evaporation is the major process driving the evolution of the regional groundwater system. Strong evidence exists to indicate multiple cycles of evaporative concentration are a common and widespread feature of the regional hydrological cycle.
10. The hydrochemical data also indicates that some water–rock interactions modify local groundwater compositions. In particular, precipitation and dissolution of evaporites (halite and gypsum) and calcite in the aquifer sediments are the main reactions that occur in the aquifer and variably modify groundwater compositions (further discussed in Section 7.2).
11. Chains of salt lakes are relatively common and widespread along the upper and middle reaches of the Kingoonya Palaeovalley and likely represent large groundwater discharge zones. Further downstream, where the influence of marine transgressions is evident in the characteristic sedimentary facies of the valley infill, the palaeovalley widens and branches into multiple distributary channels where salt lakes are less common.
12. The palaeovalley aquifer is regionally connected to the surrounding fractured and weathered bedrock aquifers. The palaeovalley itself was originally incised into the bedrock of the Gawler Craton, with existing major structural features playing a significant role in the development of the valley morphology. The nature and extent of the hydraulic connectivity is not well understood, although horizontal flow rates are likely to be very low except in areas of direct connection between major structural conduits and the palaeovalley thalweg aquifer.

7.2. Geological influence on groundwater compositions in the Kingoonya Palaeovalley

The nature of sediment sequences in the Kingoonya Palaeovalley is markedly heterogenous (Figure 68). This reflects the complex interaction of fluvial, estuarine and marine environments over a prolonged period of geologic time during the Cenozoic (at least 35–40 million years). The dimensions and compositions of the many sediment packages hosted in the valley fill sequence vary considerably along the entire length of the palaeovalley, such that many cross-sections developed from detailed drilling by Hou (2004) show significant differences in sedimentary facies relationships (as well as valley shape). The inherent geological heterogeneity of the Kingoonya Palaeovalley plays an important role in the evolution of the palaeovalley groundwater system. As groundwater travels slowly along its aquifer flowpath many different chemical reactions occur due to the variable lithologic composition (at varying rates), thereby continually modifying the chemical and isotopic composition of the palaeovalley-hosted groundwater from the original signature. Physical processes such as evaporation and mixing of different water sources also occur.

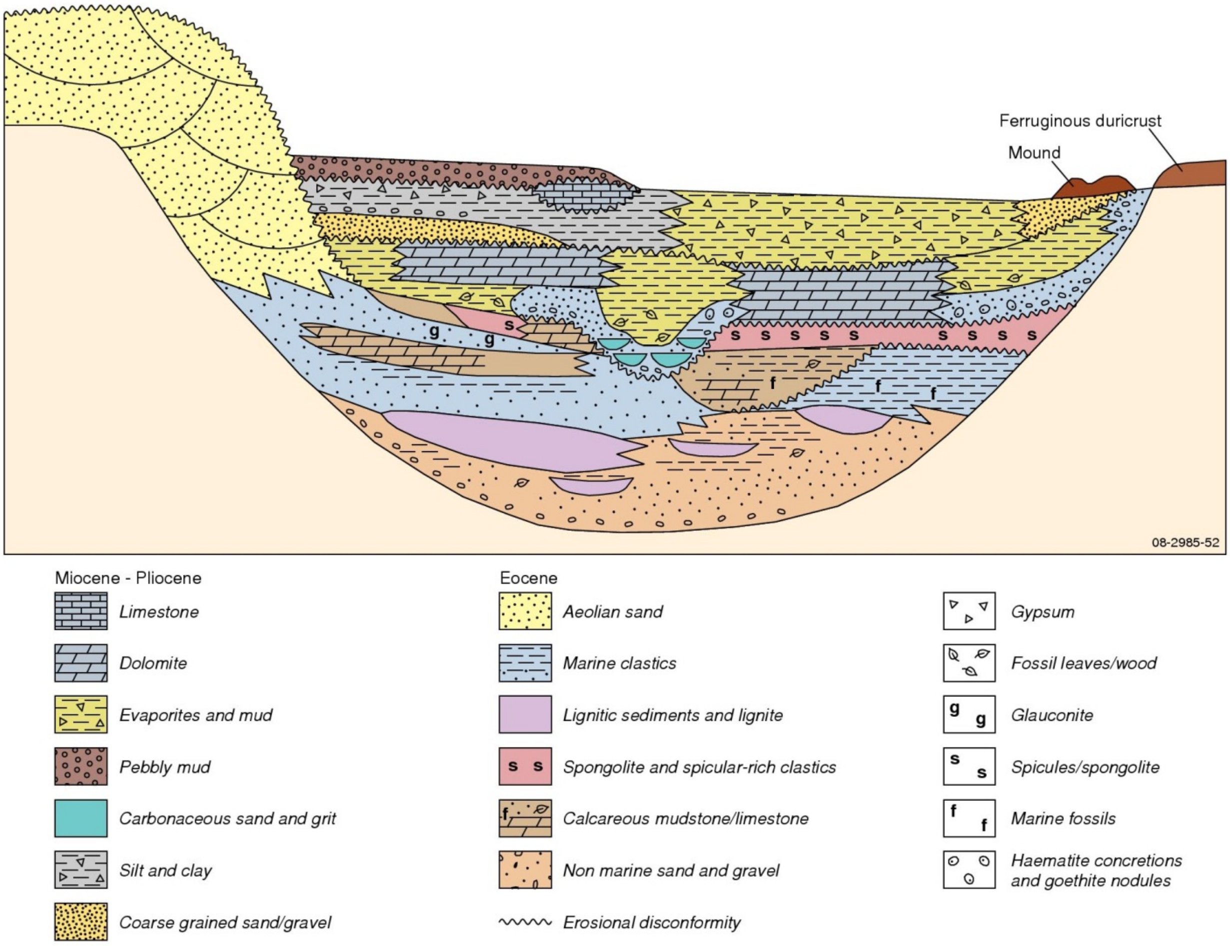


Figure 68: *Idealised composite cross-section of palaeovalley sediment types that occur in the Kingoonya Palaeovalley. A wide variety of sediment compositions and grain sizes is evident, reflecting the variable fluvial, estuarine and marginal marine conditions that influenced different reaches of the palaeovalley system (modified after Hou et al., 2001).*

The net result of ongoing water–rock interactions in the palaeovalley aquifers is reflected by variations in chemical compositions in the suite of analysed groundwater samples. Although the dominant feature of most Kingoonya groundwaters (i.e., abundance of Na-Cl major ions) largely reflects extreme and prolonged effects of evaporative concentration on original recharge (marine-derived rainfall), various chemical and isotopic indicators underline the role that heterogeneous sedimentary facies play in modifying groundwater compositions. Particular examples of water–rock reactions interpreted from the 2010 Kingoonya hydrogeochemical dataset include:

- Groundwater samples with the most elevated salinity levels have acquired NaCl directly from the dissolution of evaporites which occur in the sediment profile. In particular, the relatively low Br/Cl groundwater ratio evident at higher salinities provides compelling evidence for the role of halite dissolution in enhancing total salinity, i.e., salinity is mostly dependent on evaporation, but the highest TDS loads reflect input from water–rock reactions.
- Highly elevated dissolved sulfate levels in some Kingoonya groundwaters are clearly above the typical levels expected if sulfate was solely derived from rainfall. Gypsum is a widespread evaporite mineral in the Kingoonya Palaeovalley sequence, and dissolution and precipitation reactions involving gypsum are likely to play a significant role in buffering the overall levels of sulfate (and to a lesser extent Ca) in the Kingoonya groundwater system. Further evidence for the role of gypsum in water–rock reactions is provided by some relatively enriched sulfur isotope compositions.
- Significant carbonate-bearing sequences occur in the palaeovalley and many groundwater samples are saturated with respect to calcite. Consequently, reactions involving the dissolution and precipitation of calcite are locally important controls on the amount of Ca in solution and groundwater alkalinity. These reactions also buffer the ^{13}C isotope signature of the groundwater system and result in relatively consistent carbon isotopes, expect where localised bacterial reduction of dissolved inorganic carbon (DIC) has caused relative enrichment and a slight rise in pH.
- Reduced inorganic sulfide minerals occur commonly in some palaeovalley sequences, especially fine-grained pyrite hosted in carbonaceous silt- and clay-rich sediment horizons. There are significant carbon-bearing horizons, including lignite-rich layers with fossil plant materials, in the valley fill sequence. Fine-grained pyrite in carbonaceous sediments is typically formed by bacterial reduction of sulfur. The oxidation of such disseminated sulfides during groundwater interaction with reduced sediment horizons is implied by the cluster of sulfur isotope data depleted relative to typical seawater sulfate compositions.
- Input of groundwater from the adjacent fractured rock systems to the palaeovalley aquifer appears to only have minor overall impact on groundwater chemistry (probably localised to zones of enhanced hydraulic conductivity such as major faults). Silicate weathering reactions (e.g., breakdown of feldspars) and the formation of clay minerals probably occurs in bedrock granites and volcanics of the Gawler Craton. These may be locally significant reactions affecting the groundwater composition in the bedrock aquifer. However, minor variations in cation concentrations derived from silicate breakdown and clay-forming reactions (e.g., Ca and K) are largely obscured by the significantly greater abundance of Na in solution.
- Other possible water–rock reactions that may occur in the Kingoonya palaeovalley aquifer include interaction with Fe-bearing nodules and concretions (commonly formed of hematite and goethite), and the deposition of minor uranium mineralisation, typically in zones where oxidised groundwater carrying dissolved uranium encounters *in situ* reductants in the sediment sequence – these are commonly sites of accumulated organic matter within otherwise 'clean' sandy aquifers.

7.3. Comparison with groundwater systems in other Gawler–Eucla palaeovalleys

Comparison of the groundwater system in the Kingoonya region with palaeovalley aquifers previously investigated at Challenger Gold Mine (Challenger Palaeovalley, see Section 3.3.1) and Jacinth–

Ambrosia mineral sands deposit (Iluka Palaeovalley, see Section 3.3.2) shows many similarities. Although the previous mine site studies were localised, and aimed to target water resources for development and ongoing operational supplies (thereby lacking a wider regional perspective), it is possible to evaluate the characteristics of these aquifers in light of our new research findings. The key results from this comparison are:

- The main hydrogeochemical parameters of each palaeovalley system are remarkably similar and indicate that the dominant physico-chemical processes (i.e., evaporation and the various water–rock interactions) that affect the aquifers near the mine sites are similar throughout the Gawler–Eucla region. Groundwater systems of other regional palaeovalleys are likely to share similar characteristics, such as highly saline groundwater (average TDS range from 30,000–50,000 mg/L) dominated by Na-Cl facies, enriched though variable dissolved sulfate loads, neutral to slightly acidic pH, oxidising and low alkalinity systems. Trace element concentrations are largely unremarkable, though there are some anomalously enriched local groundwaters, particularly with elevated concentrations of Fe and Mn.
- The Kingoonya Palaeovalley has a significantly more complex and variable valley shape than the relatively simple U-shaped valleys which are interpreted at Challenger and Jacinth–Ambrosia. However, this may reflect the more localised nature of these mine site investigations, as some segments of the Kingoonya Palaeovalley also have simple U-shaped cross-sections (Hou, 2204).
- There is more variability in the depth of the valley infill sediment profile and the variation in facies in the Kingoonya Palaeovalley than occurs at Challenger and Jacinth-Ambrosia. However, as noted above, this may simply reflect the localised nature of mine-site studies.
- The sedimentary infill sequence for the Iluka Palaeovalley at Jacinth–Ambrosia differs slightly from Kingoonya, as the uppermost unit comprises Miocene age Nullarbor Limestone which has restricted distribution to the Eucla Basin. However, the basal sand-rich formation of the Iluka Palaeovalley is interpreted as the Eocene Pidinga Formation, similar to most other Gawler–Eucla palaeovalleys. This indicates that the Iluka Palaeovalley was largely influenced by fluvial deposition in the Eocene during regional marine regression of the ancient Eucla Sea.

7.4. The Kingoonya Palaeovalley groundwater resource

The Kingoonya Palaeovalley aquifer represents a significant saline groundwater resource within the Gawler–Eucla region. The fluvial-dominated section of the Kingoonya Palaeovalley, extending westwards from the upland headwaters east of the Stuart Highway past Tarcoola and towards the ancient coastal dune systems of the Barton and Ooldea Ranges, is about 250 km long (total length of all anastomosing segments). The previous detailed geological investigation presented by Hou (2004) indicated that the extent of the original incised valley (now completely obscured by aeolian sediments) ranges commonly from 5–20 km wide. The basal sand- and gravel-rich sedimentary facies is generally restricted to the deeper parts of the main channel (in some places multiple channels) but may be up to 1km wide and at least 5–10 metres thick. This facies represents the main palaeovalley aquifer, although there is clearly good potential for saturated sections of other palaeovalley sediment horizons to contribute to the overall volume of contained groundwater resource.

Applying conservative values for aquifer system dimensions as noted above, and assuming saturated conditions in the basal thalweg, we estimate that the likely minimum saline groundwater resource contained in the Kingoonya Palaeovalley is in the range of 1,000–1,500 x 10^6 m^3 (1,000 to 1,500 GL).

In comparison, the estimated total groundwater in storage in the Iluka Palaeovalley at Jacinth-Ambrosia is ~1,350 GL (Parsons Brinckerhoff, 2007). This first-order resource figure for the Kingoonya aquifer is likely to represent a minimum total resource given the potential for significantly thicker and wider segments of the palaeovalley infill sequence. Additionally, the basal sediments are considered to be hydraulically connected to the surrounding fractured and weathered bedrock aquifers, which could provide significant additional groundwater storage. Further induced leakage from saturated horizons within overlying sediments (i.e., finer grained sedimentary layers) of the valley fill sequence is also possible if groundwater is extracted from the main aquifer sequence, and this reserved storage could also significantly upgrade the total palaeovalley groundwater resource for the Kingoonya system. However, given the very old groundwater residence times recorded for the basal aquifer and the low recharge rates of this area, pumping of significant quantities of groundwater to support large-scale water resource requirements would effectively result in mining of the fossil groundwater system.

Our preliminary resource analysis indicates that the Kingoonya Palaeovalley has excellent potential to supply significant quantities of saline groundwater. Given its remote location and the nature of commercial activities in the region (largely mining and pastoral activities), the Kingoonya Palaeovalley is a viable long-term water resource, especially for large-scale mining developments. Although saline water could be used for many mine-site operations, including ore processing and construction, use of the resource for potable supplies would require development of an on-site reverse osmosis plant. Given the excellent metal endowment of the Gawler Craton and the high mineral prospectivity of this region, the current exploration activity could realistically lead to successful future discoveries. In this scenario, the groundwater resources of the Kingoonya Palaeovalley would represent an accessible, attractive and relatively easy-to-develop water resource target.

7.5. Recommendations for further work

Our hydrogeochemical study of the Kingoonya Palaeovalley has provided significant new insights into the processes and evolution of this major arid zone aquifer. This knowledge could assist future water resource studies in the Gawler–Eucla to better understand the characteristics of the regional groundwater systems as well as critical issues to address for future investigations, such as potential methodologies to follow and problems to avoid. However, as is commonly the case with new research programs, there is excellent potential to build upon the initial knowledge generated from this study to tackle other research questions that were beyond the scope of this preliminary investigation. Particular recommendations that we suggest for further groundwater studies in the Gawler–Eucla region include:

1. Undertake a more comprehensive groundwater investigation program in the Kingoonya Palaeovalley involving a multi-disciplinary and fully integrated approach. In particular, we consider it important to place better constraints on the origin of groundwater samples relative to the different aquifers that contribute to the regional hydrogeological system. A new research program could involve wide-ranging activities such as establishing new monitoring bores, installing downhole groundwater loggers, conducting detailed sampling and analysis of groundwater and aquifer materials etc. An integrated program of downhole and surface geophysical surveys would also provide an extra level of detailed information to assist with interpretation of hydrogeologic data. This type of work program could potentially involve collaborative effort with private companies or hydrogeological consultants that are currently interested in exploring the groundwater potential of palaeovalleys in the Gawler–Eucla region, e.g., to support mine water supply requirements.

2. Conduct similar groundwater sampling programs in other palaeovalleys of the Gawler–Eucla region to provide a more comprehensive regional hydrogeochemical database and baseline comparisons. This research plan could build-upon our initial Kingoonya sampling program, further extending the network of sampled bores to the other major systems such as the Narlaby, Anthony, Garford and Tallaringa palaeovalleys. The expanded knowledge base would allow for more detailed comparison between different palaeovalley systems to determine spatial trends, trace element enrichment variations and provide a wider number of isotopic signatures and groundwater residence times.
3. Apply alternative groundwater dating methods using other isotopes and hydrochemical tracers, such as tritium, chlorofluorocarbons (CFC), and sulfurhexafluoride (SF6). These could provide improved determination of modern recharge signatures (i.e., during the last 100 years) in different groundwater systems and aid improved understanding of variations in groundwater residence times. Additional work could also be undertaken with the radiocarbon data to correct for the effects of water–rock interactions, although this would require further determination of carbon isotope ratios for aquifer sediments and regolith material.
4. Improved groundwater resource estimates could be obtained by developing an accurate 3D hydrogeological model for the Kingoonya Palaeovalley. This could initially be based upon the detailed geological cross-sections and airborne geophysical datasets that already exist from previous studies conducted by the Geological Survey of South Australia. The saturated volume of the main thalweg aquifers could be more accurately modelled along the entire length of the palaeovalley to generate a more robust and geologically valid figure for the overall groundwater resource. Suitable 3D modelling software for this task includes GoCAD and Earth Vision.
5. Allied with efforts to develop a 3D model of the Kingoonya Palaeovalley, further work could also be conducted to build a steady state groundwater flow model to improve understanding of groundwater flow vectors and aquifer volumes.

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The software used in the depth to magnetic basement study was developed by Dr. Indrajit Roy at Geoscience Australia. Evaluation and testing of the software was carried-out with the assistance of Ashraf Hanna and Tony Meixner at GA. The depth to magnetic basement map for the Gawler–Eucla region was completed by Ashraf Hanna.

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Glossary

ADWG: Australian Drinking Water Guidelines, developed by the National Health and Medical Research Council (NHMRC) and the Natural Resource Management Ministerial Council (NRMMC) to provide an authoritative reference to the Australian community and the water supply industry on what defines safe, good quality water, how it can be achieved and how it can be assured.

Aeolian: Pertaining to wind; especially said of dune sands and finer sediments such as dust which are transported (blown) and laid down by the wind.

Aeromagnetic: Applying to airborne surveys that measure the total magnetic intensity of rock. Surveys typically follow a pre-determined survey grid, and data are interpreted in terms of changes in the properties of rocks and magnetic patterns.

Airborne Electromagnetic (AEM) survey: A geophysical survey method that maps the subsurface conductivity structure of the survey area using a loop which is mounted on a fixed-wing aircraft or carried beneath a helicopter. Many such systems exist with different specifications and performance, allowing the survey to be tailored to the needs of the user. Also known as Airborne EM.

Alluvial/alluvium: Sediments deposited by the action of rivers in low-lying areas and flood plains.

Anastomosing: Refers to an interlacing network of branching and reuniting channels.

Aquifer: A geological horizon that holds and conducts water, the water is contained within the pore spaces of the geological body. Aquifers may be unconfined, meaning they are open to the atmosphere, or confined, meaning they are capped by a relatively impermeable unit, or aquitard.

Aquiclude: A rock or sediment whose very low hydraulic conductivity makes it almost impermeable to groundwater flow (even though it may be saturated with groundwater). It limits the distribution of an aquifer, and may form confining strata.

Aquitard: A relatively impermeable geological layer that caps a confined aquifer. It has low hydraulic conductivity which allows some movement of water through the rock mass, but at much slower rates than that of adjacent aquifer.

Archean: Rocks older than 2.5 billion years (2,500 Million years); spelled Archaean in older literature.

Architecture: The relationship of different geological units to each other in space. For example, regolith architecture, sedimentary architecture etc.

Basement: The crust below the rocks of interest; in hydrogeology it means non-prospective rocks below accessible groundwater. Commonly refers to igneous and metamorphic rocks which are unconformably overlain by sedimentary beds or cover material, and sometimes used to indicate ‘bedrock’, i.e., underlying or encasing palaeovalley sediments.

Basin: Subsided part of the Earth’s crust in which sediments accumulate from surrounding higher areas.

Bed/bedding: Layers/layering of sediments or sedimentary rocks that reflect differences in grainsize, composition or colour of constituent grains.

Bedrock: Loose term given to any geological material that underlies the stratum of interest. Bedrock commonly consists of crystalline rocks such as granite or metasedimentary rocks.

Braid Plain (braided river, braided channel): A river course that consists of a number of small channels separated by bars of sediment. A braid plain may be laterally broad, have no confining banks, or lack stabilizing vegetation.

Brine: A concentrated solution of salts formed by the partial evaporation of saline water. A ‘brine pool’ typically underlies salt lakes, infusing pore spaces in the underlying sediments.

Calcrete: Calcium carbonate ($CaCO_3$) formed in soil or sediments in a semi-arid region under conditions of sparse rainfall and warm temperatures, normally by precipitation of calcium. Calcrete is common in low-lying areas in arid to semi-arid regions, particularly palaeovalleys (‘valley calcrete’), and may form aureoles around salt lakes. It is commonly a significant near-surface aquifer in the arid zone.

Capillary fringe: Zone above the saturated zone – neither saturated nor unsaturated but between the two.

Carbonate: Carried in solution in surface water or groundwater. The two main types are: pedogenic (or vadose) calcretes that form in the soil profile and groundwater (non-pedogenic or phreatic) calcretes which tends to precipitate at the watertable in the overlying capillary fringe.

Catchment: The area of land from which rainwater drains into a river, stream or lake. Catchments are separated from each other by divides or water sheds.

Cenozoic: Geologic era for the last 65.5 Ma (Million years) that encompasses three periods: Paleogene, Neogene and Quaternary. It is also sob-divided into the epochs: Paleocene, Eocene, Oligocene, Miocene, Pliocene, Pleistocene and Holocene (the latter two making up the Quaternary, see below). The Cenozoic was formerly referred to as the *Tertiary* and until recently the term *Cainozoic* was used.

Chalcedony: Variety of very fine grained quartz (SiO_2); may occur in silicified calcrete and form a significant near-surface aquifer.

Clay: Refers to either grainsize or mineralogy: (a) an earthy sediment composed of rock or mineral fragments or detrital particles smaller than a very fine silt grain; (b) clay minerals are hydrous aluminium silicates derived largely from feldspars, micas and carbonate by weathering.

Colluvium: Rock debris that has moved down a hillslope either by gravity or surface wash.

Confined aquifer: An aquifer that is sealed above and below by impermeable material.

Conglomerate: A sedimentary deposit formed by cementing gravels and cobbles together with minerals precipitated from groundwater.

Consolidated: See *cemented.*

Craton: Part of the Earth’s crust which is no longer affected by tectonic activity and has been stable for about a billion years (1,000 Million years).

Deflation: Removal of material from a land surface by aeolian processes. It is most effective where extensive unconsolidated sediments are exposed, as on dry lake or river beds.

Diagenesis: The changes that occur to sediments after they are deposited, including cementation and weathering.

DEM: See *Digital Elevation Models.*

Depocentre: A site of maximum deposition, where the thickest accumulation of sediment is found, within a sedimentary basin or valley.

Desiccation: The process of rocks or sediments drying-out.

Detrital: Material derived from the mechanical breakdown of rock by the processes of weathering and erosion.

Digital Elevation Models (DEM): Digital representations of the topography of the earth that are important components of geographic information systems (GIS). DEM are obtained by many systems, including ground surveying, airborne radar and laser surveys, or from satellite radar.

Discharge: The flow of groundwater to surface water, bores, from one aquifer to the other or the sea. Also includes evapotranspiration from shallow aquifers.

Discharge zone: An area in which subsurface water is discharged to the land surface; in the arid zone it is where evaporite minerals (salts) precipitate as the water evaporates to the atmosphere.

Dissected: A term applied to landscapes which have been extensively eroded by valleys and gullies.

Down-hole logging: A method of measuring the geophysical properties of the rocks, soils, or sediments penetrated by a drillhole. A tool that measures properties such as conductivity and natural gamma radioactivity is lowered down the borehole; data is recorded during both descent and ascent of the tool. Down-hole logging is a vital technique to calibrate conductivity and surveys and interpret geological logs.

Drawdown: The lowering of the watertable or potentiometric surface, normally as a result of the deliberate (or excessive) extraction of groundwater.

Duricrust: A hardened layer formed in the regolith by cementation of soil or sediment, generally by minerals rich in iron, sulfate, silica, or carbonate.

EC: Electrical Conductivity, a measure of conductivity and a proxy for salinity, typically measured in micro Siemens per cm (μS/cm). Ideally, fresh drinking water has EC<100 μS/cm, whereas seawater has EC ~54,000 μS/cm.

Eocene: Geologic epoch extending from 56 to 33.9 million years ago. Forms part of the Cenozoic era.

Erosion: Part of the process of denudation that includes the physical break-down, chemical solution, and transportation of earth materials. Movement of soil or rock is generally caused by natural agents such as flowing water, wind and gravity. Differential erosion pertains to adjacent or subjacent materials that have eroded differentially; the more reactive material is rapidly weathered and more easily transported, and tends to leave more recessive landforms relative to more resistant material which forms upstanding landforms.

Evaporative concentration: Concentration of solutes in groundwater owing to evaporation down-gradient in the flow path or at near-surface levels. The concentration of chemical constituents may remain fairly constant although the volume of water in which they are dissolved decreases owing to evaporation.

Evapotranspiration: Combined term for water lost as vapour from a soil or open water surface (evaporation) and from the surface of a plant (transpiration).

Fault: Fracture in a rock body along which displacement (movement) has occurred.

Feldspar: A common rock-forming mineral consisting of aluminium, silicon, oxygen and varying amounts of calcium, sodium, and potassium.

Ferricrete: A hardened iron-rich duricrust/weathering profile. Many Australian duricrusts formed during the Late Cretaceous and early Cenozoic when the climate was warm and humid. The term 'ferricrete' is preferred over the more obsolete term 'laterite' which has ambiguous definitions.

Fluvial: Pertaining to a river. Fluvial processes relate to water flow (within and beyond a stream channel) bringing about erosion, transfer and deposition of sediment. 'Fluviatile' relates to sediments of fluvial origin.

Fracture: Cracks in indurated rocks formed by stress and strain. Fractures along which significant movement has occurred are called faults.

Gamma ray logging: Down-hole geophysical logging technique that maps the gamma radiation released by naturally occurring uranium, thorium and radioactive potassium within rocks and regolith.

Geomorphology: The study of landforms.

Geophysics: The study of the physical properties of the earth, in particular magnetic, conductivity, and radiometric properties, or variations in the earth's gravity. Geophysical techniques are widely used in mineral exploration and can help to understand the subsurface structure of the earth, locate groundwater, and map salinity (as well as many other applications).

Geographic Information Systems (GIS): GIS are computer-based systems for creating, storing, analysing and managing multiple layers of spatial data. Such datasets may include maps of geology, topography, infrastructure, soils, vegetation, and land use. GIS allow users to create interactive queries to analyse trends and patterns in spatial information.

Gigalitre (GL): one billion litres (equivalent to 1000 megalitres, ML).

Gneiss: Coarse-grained banded crystalline rocks that formed from regional metamorphism; the banding reflects the separation of constituent mafic (iron and magnesium-rich) and felsic (feldspar and silica/quartz-rich) minerals.

GOCAD: 3D modelling software for building subsurface geologic models.

Goethite: A yellowish-brown iron hydroxide mineral that is common in soils and regolith.

Granite: A light coloured, coarse-grained crystalline igneous rock consisting mainly of quartz and feldspar, plus mica and accessory minerals.

Granules: Gravel-sized sediment between 2-4 mm in diameter.

Gravel: All loose, coarse-grained sediments with grains greater than 2 mm diameter.

Gypsum: Calcium sulphate ($CaSO_4.2H_2O$). 'Gypcrete' refers to indurated secondary precipitates of gypsum deposits which are common around salt lakes. 'Gypsiferous' refers to gypsum-rich material. Gypsiferous dunes, which commonly make islands and skirt the margins of salt lakes, have formed from gypsum crusts deflated from the lakebed and redeposited by aeolian action.

Haematite: A reddish-brown iron oxide mineral that is common in soils and regolith.

Hydraulic conductivity (permeability): The ability of a rock, unconsolidated sediment or soil to permit water flow through its pores.

Hydraulic gradient: A measure of the change in groundwater head over a given distance. Maximum flow will normally be in the direction of the maximum fall in the head.

Hydrogeology: The study of geological properties of rocks, soils, and sediments as they relate to groundwater movement and storage.

Hypersaline: More saline than seawater, which has total dissolved solids of approximately 35,000 ppm (mg/L).

Igneous: Applied to one of three main groups of rock types (igneous, metamorphic and sedimentary), to describe those rocks that have crystallized from magma.

Incised channel: A river channel that has cut down below its original flood plain. This commonly occurs in response to changes in river flow conditions or geological uplift.

Indurated: The process of hardening, such as occurs when sediments are turned into rock by various cementing agents, or surface hardening of some exposed rock surfaces that can occur during weathering.

Kilolitre (kL): Equal to 1,000 litres (cubic litre: m^3).

Lacustrine: Pertaining to, produced by, or formed in a lake.

LANDSAT: A polar-orbit satellite launched by NASA to collect *multispectral* images of the Earth surface. Seven satellites have been launched in the series. Commonly written as 'Landsat'.

Lignite: Peat or brown coal. Carbon-rich material formed from the remains of fossil plants that were deposited in lakes or swamps and subsequently buried, dehydrated and compressed.

Limestone: Sedimentary rock composed of calcium carbonate ($CaCO_3$) of organic, chemical or detrital origin.

Lithic: A term applied to sand or gravel where the particles are made up of rock fragments.

Mafic: Describes dark-coloured igneous rocks with a high proportion of iron- and magnesium-rich minerals.

Magnetic survey: A geophysical survey method that maps the distribution of magnetic materials in the earth. Magnetic surveys can be carried out on the ground or from aircraft, the latter termed 'aeromagnetic surveys'.

Megalitre (ML): Equal to one million (1,000,000) litres.

Metadata: Information about the source and accuracy of information used in a *GIS.*

Metamorphics: General term for rocks that have been recrystallised as a result of heat and pressure.

Milligal (mGal): A unit of acceleration used in the gravitational method of geophysical prospecting. It is about one millionth of the average value of the acceleration due to gravity at the Earth's surface; i.e., 1 milligal = 1 cm/s^2.

Mineralogy: Mineral composition of a rock or sediment.

Miocene: Geologic epoch extending from 23.03 to 5.333 million years ago. Forms part of the Cenozoic era.

Multispectral imagery: Images acquired by satellites or aircraft that capture more than the three colour bands visible to the human eye. Multispectral images can be manipulated and combined in a *GIS* to emphasise subtle features such as variations in soil composition or vegetation.

Oligocene: Geologic epoch extending from 33.9 to 23.03 million years ago. Forms part of the Cenozoic era.

Palaeochannel: Refers to the main channel of ancient rivers, sometimes called the 'thalweg', the lowest point of incision along the river bed where coarser sediments are commonly deposited. Former river channels that are recognised in the surface (from aerial or satellite images) or within the subsurface, such as from *AEM* surveys or by drilling.

Palaeogeography: The reconstruction of physical geography of past geologic ages in an attempt to restore areas to their depositional condition.

Palaeovalley: Ancient valleys infilled with sediments that were incised by past river systems. Palaeovalley sediments include (but are not restricted to) those of *palaeochannels*. Typically palaeovalley sediments are not associated with currently active river (fluvial) processes, although they are commonly significant aquifers.

Paleozoic: Geologic Era spanning approximately 542 Ma (million years ago) to 251 Ma. Australia was part of the Gondwana supercontinent during this time. Sometimes spelled 'Palaeozoic', especially in older literature.

Palynology: The study of microscopic particles of organic composition, such as pollen and spores, found in sediments, than enables stratigraphic dating (palynostratigraphy) and interpretation of depositional environments of the sediments in which they are found.

Palynomorphs: A palynomorph is a particle between 5 and 500 microns found in sedimentary rock, and composed of organic material such as chitin, pseudochitin and sporopollenin. Typically, palynomorphs are dinoflagellate cysts, acritarchs, spores, pollen, fungi, worms, arthropod organs, chitinozoans and microforams.

Pediment: A gently-sloping apron of exposed or shallowly buried bedrock surrounding hills and rises.

Pedogenic: Processes or features pertaining to soil formation.

Peneplain: An area of low relief mantled by continuous regolith and by wide shallow river valleys, a peneplain – the end-product of a cycle of erosion – is produced by denudation over a long period of time.

Permeability: See *Hydraulic conductivity*.

Phreatic: Refers to the zone of saturation, the soil or rock below the level of the watertable where all voids are saturated.

Porosity: Open spaces in rocks and sediments that can hold water. *Primary porosity* formed when the sediments were laid down; these spaces may be variably infilled by *cement*, leaving remnant primary porosity. *Secondary porosity* forms through modification of rocks, such as by dissolution of soluble grains, formation of *fractures*, or solution-forming *karst.*

Potable: Described fresh water that is safe to drink and palatable for human consumption – water in which the concentration of salts and other constituents are low or have been lowered sufficiently by treatment, for consumption.

Potentiometry/potentiometric: Representation of the level to which groundwater in a confined aquifer rises in boreholes. The potentiometric surface is mapped by interpolation between borehole measurements. The slope of the potentiometric surface defines the direction of groundwater flow in a confined aquifer.

Progradation: The seaward movement of the coastal zone caused by infilling of coastal environments by sediments derived from the land after a *transgression.*

Proterozoic: A geological era that encompasses the time between 2,500 and 545 million years ago. The Proterozoic is formally divided into the Paleoproterozoic (2,500 and 1,600 million years), Mesoproterozoic (1,600–1,000 million years), and Neoproterozoic (1,000–545 million years).

Provenance: The source or origin of detrital sediments**.**

Quartz: A very common mineral consisting of silicon dioxide that commonly occurs in river sands and as the main mineral in sandstones.

Quartzite: *Sandstone* consisting largely of quartz that has been recrystallised (metamorphosed) by exposure to geological heat and pressure.

Quaternary: Geological period spanning approximately the most recent 2.5 Ma (million years) of earth history. The Quaternary is sub-divided into two epochs, the Pleistocene (2.5 Ma to approximately 11,000 years ago) and the Holocene (11,000 years to the present). The Quaternary is characterised by extreme climate fluctuations, alternating glacial and interglacial periods, with aridification of the Australian inland as a legacy of the last glaciation.

Radiometrics: Also known as (airborne) gamma-ray spectrometry (AGS) or gamma-radiometric measurement. A spectrometer measures gamma-radiation from isotopes of potassium, thorium and uranium emitted from rocks and sediment to record the distribution of these elements in the landscape.

Recharge: The process by which water is added to an aquifer; the downward movement of water from the soil to the watertable. Also, the total volume of water added to the total amount of groundwater in storage within a given period of time. A ‘recharge area’ acts as a catchment for a particular aquifer.

Regolith: The earth materials that occur between fresh rock and fresh air, including *weathered* rocks, soils, shallow groundwater and sediments.

Relict: A term applied to landscape features that are no longer being actively formed. For example, the floodplain of the Ord River in north-western Australia is regarded as relict because, prior to dam construction, it was not being inundated during seasonal floods.

Rotary mud drilling: A relatively cheap drilling method that uses a rotating cutting bit to drill a hole in the earth. Samples are brought to the surface as cuttings supported by a circulated drilling fluid containing mud, and this also keeps the drillhole open. Samples are contaminated by the drilling fluid, and these are averaged over the sample interval (typically 1-5 m). Material from shallower depths can also contaminate samples drilled further down-hole. Also known as mud drilling, mud rotary or rotary drilling.

Salinity: Areas where salt is being deposited in the near-surface environment. Salinity is a natural phenomenon but can be increased through land use practices involving inappropriate types of soil management, vegetation clearing, cropping, and irrigation. Within the arid zone, salinity is largely 'Primary' or 'Natural' salinity, brought about steadily through aridification during the Quaternary. In disturbed agricultural lands, salinisation is commonly regarded as 'Secondary' or 'Anthropogenic' salinity.

Salinity ranges: For the purpose of the *Palaeovalley Groundwater Project* the following ranges have been used when discussing groundwater salinity: <1,000 mg/L TDS = fresh water, 1,001 to 10,000 mg/L = brackish water, 10,001 to 35,000 mg/L = saline water, >35,000 mg/L = hypersaline water.

Sandstone: A *sedimentary* rock composed of sand-sized particles.

Saprock: Compact, slightly weathered rock with low porosity; defined as having less than 20% of weatherable minerals altered but generally requiring a hammer blow to break. It may still contain rock structure.

Saprolite: Saprolite is weathered rock in which more than 20% of the weatherable minerals in the original rock have been altered *in situ*, with interstitial grain relationships being undisturbed. Saprolite is altered from the original rock by mainly chemical alteration and loss without any change in volume. This is sometimes referred to as constant volume alteration. Saprolite can be highly porous and permeable and may be an important aquifer.

Saprolith: Saprolith is all those parts of a weathering profile that have been formed strictly *in situ*, with interstitial grain relationships being undisturbed. This contrasts with residual material or pedolith, which has been disturbed. Saprolith is altered from the original rock by mainly chemical alteration and loss without any change in volume. It is subdivided into *saprock* and *saprolite*.

Schist: A regional metamorphic rock composed of mica, quartz, and mafic minerals that have a preferred orientation.

Sedimentary: Pertaining to deposition of sediments and sedimentary process, for example, a sedimentary rock is a rock once composed of sediments such as sand, gravel, silt, etc.

Shale: A *sedimentary* rock composed of clay particles.

Sheetwash: A geomorphologic process by which a thin layer of water flow over the surface of a hillslope and may transport surface regolith material downslope. It is important process in semi-arid regions, especially in mulga country.

Silica: Term applied to fine-grained *quartz* (SiO_2) cement in sediments and soils. 'Silcrete' is silica rich duricrust that functions as a cement.

Silicification: Process by which silica is deposited.

Siltstone: A *sedimentary* rock composed of silt-sized particles.

Succession: Term applied to a series of sedimentary or volcanic rock deposits.

Stratigraphy: The study of how different layers of sediments can be related to each other.

SRTM: *Digital Elevation Model* data collected during the 2000 STS-99 **S**huttle **R**adar **T**opography **M**ission by the Space Shuttle *Endeavour*. SRTM data is widely available at 3-arc second (~90 m) horizontal resolution and on a restricted basis at 1-arc second (~30 m) horizontal resolution.

Terrane: Used in geology to distinguish a fragment of crustal material of a particular rock type from an adjacent rock type (abbreviated from 'tectonostratigraphic terrane').

TDS: Total Dissolved Solids, measured in parts per million (ppm), equivalent to milligrams per litre (mg/L). Drinking water has a TDS of 100 to 1,000 ppm (mg/L); seawater has a TDS of approximately 35,000 ppm (mg/L).

Thalweg: The deepest continuous channel within a river valley, typically marking the course of the most active and fastest moving part of the main river channel. In palaeovalleys the thalweg usually contains the most coarse-grained and well sorted sediments, making it the most conductive aquifer zone in the buried valley sedimentary sequence, and a common drilling target.

Transgression: A long-term rise in relative sea-level causing flooding of the coastal zone, for example, after the end of the last ice age, or in the Cenozoic when palaeovalleys in the southern part of Australia because inundated by seawater and accumulated marine sediments, as in the Eucla Basin/Nullarbor Plain.

Transgressive: Pertaining to processes or sediments resulting from a (marine) *Transgression.*

Transmissivity: A measure of the ability of groundwater to pass through soil, sediment or rock making up an aquifer. The rate at which groundwater, under the hydraulic gradient, is transmitted.

Transpiration: Water given off by plants via pores in the surface tissues.

Unconfined: See *aquifer.*

Unconformity: A *bounding surface* where the rocks below rest at a different angle to those above, for example, where alluvial gravels rest on bedrock.

Unconsolidated: See *uncemented.*

Unsaturated zone: Occurs above the watertable and above the capillary fringe.

Vadose zone: The zone between the ground surface and the watertable. Also known as the soil-water, unsaturated, or aeration zone.

Watertable: The surface below which an *unconfined aquifer* is saturated with water. See also *potentiometric surface.*

Weathered/weathering: The physical and chemical changes that a rock undergoes when it is exposed to the atmosphere and shallow groundwater.

Wetlands: Low-lying areas subject to partial or continuous inundation. Also known as swamps.

XRD: X-ray diffraction. An analytical method used to determine the mineral composition of soil, sediment, and rock samples.

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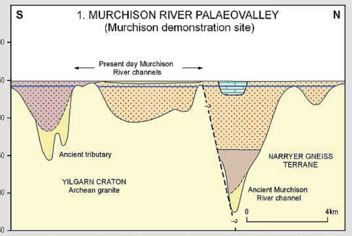
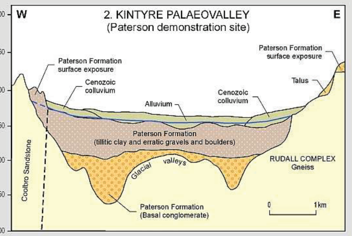
Appendix 1 – The WASANT Palaeovalley Map

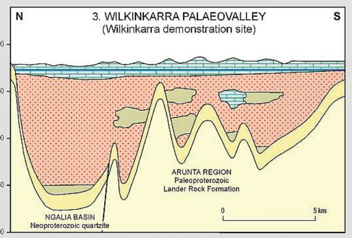
This appendix contains an A3 size reproduction of the WASANT Palaeovalley Map, which was one of the final outputs from the *Palaeovalley Groundwater Project*. This map is mentioned several times throughout this report, and is here reproduced as a handy reference. Please note that the original map was designed for printing at A0 size, so much of the text is difficult to read in the version contained in this appendix. For those interested, digital versions of this map (in either PDF or ArcGIS shapefile formats) are available for free download from the Geoscience Australia website at: http://www.ga.gov.au/cedda/maps/96.



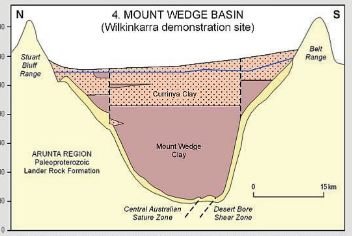
Murchison River cross section at Beringarra near the western edge of the Yilgarn Craton in the Murchison demonstration site, Western Australia. Palaeo-river incision here was along the contact between Archean granite and the Narryer Gneiss Terrane. Multiple buried river channels were spread over 16 kilometres, south to north. A gravity survey detected the eroded surface of fresh bedrock (buried basement topography). Weathered bedrock zones (saprolite) were disclosed through drilling. Palaeovalleys in the Murchison region are up to 200 metres deep, infilled with Late Cenozoic alluvium that is sandier than in most other parts of the Yilgarn Craton. Relatively large volumes of variable quality groundwater occur in these aquifers.



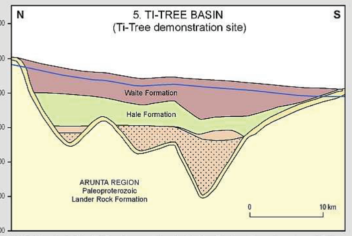
Kintyre Palaeovalley in the Rudall Uplands defined by airborne electromagnetic (AEM) data, in the Paterson demonstration site, Western Australia. This section, in the Yandagooge Creek catchment, shows crystalline Proterozoic bedrock deeply scoured, to 200 metres or more. The valley is infilled with Permian glaciogenic Paterson Formation sediments. This formation comprises basal gravels/conglomerate (target aquifer) and overlying thick tillitic clay, which in turn is overlain by Cenozoic alluvium. The basal Permian conglomerates and Cenozoic alluvium provide important water supplies.



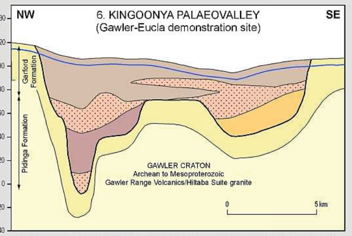
The Wilkinkarra Palaeovalley in the central Australian Wilkinkarra demonstration site, Northern Territory. Multiple irregular channels are incised into the underlying bedrock units. The sediment infill sequence is sand-dominated, typical of moderately to highly energetic fluvial deposition. A thin calcrete horizon is extensively developed at the surface. Lithology and structure based on detailed drilling and ground geophysics. Previously unknown fresh groundwater supplies were encountered in palaeovalleys beneath dunefields in the area.



The Mount Wedge Basin in the Wilkinkarra demonstration site, Northern Territory. This mountain-front basin contains nearly 500 metres of Cenozoic sediment infill, interpreted to have formed in lacustrine to alluvial fan depositional environments. Significant fresh to brackish quality groundwater resources occur in this palaeovalley system. Lithology and structure based on ground geophysics and drilling.



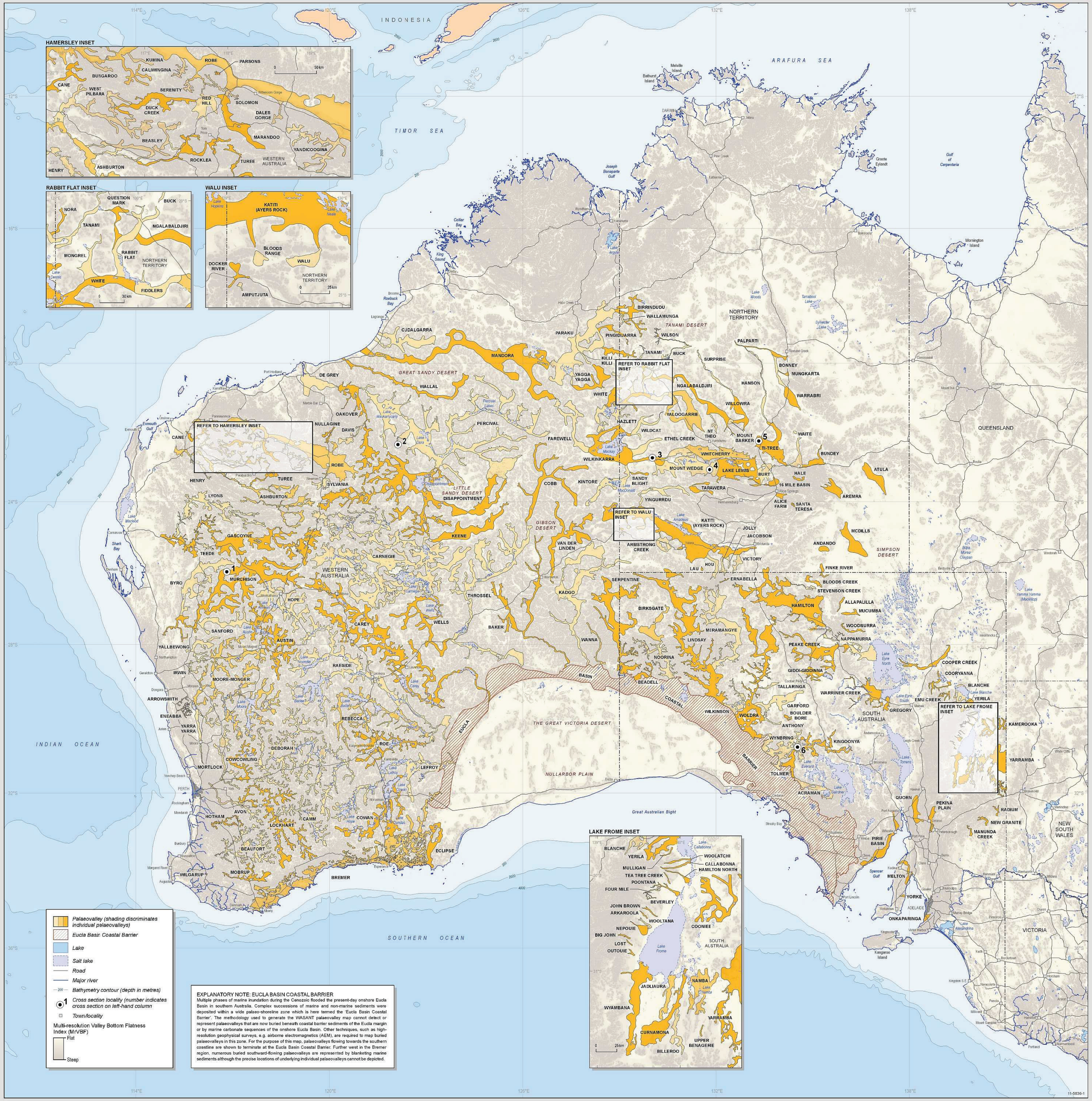
The Ti-Tree Basin in the Ti-Tree demonstration site, Northern Territory. Cenozoic sediment infill is over 300 metres deep in some places, although the basement surface is irregular and sediment facies vary across the basin. Typical of most central Australian palaeovalleys the sedimentary sequence is overprinted by intense chemical weathering. The lithology and structure are based on extensive drilling and airborne electromagnetic (AEM) data. Large volumes of good quality groundwater are stored in the basin.



The Kingoonya Palaeovalley in the Gawler-Eucla demonstration site, South Australia. This section shows two distinct palaeochannels infilled with a variable Cenozoic sedimentary sequence, and seperated by a buried basement high. The coarse sand and gravel sequence in the south-east is the highest yielding aquifer interval (lithologic compositions based on detailed rotary drilling transect; *after Hou, 2004*).

Calcrete · *Clay* · *Carbonaceous clay and lignite* · *Clayey silt and sand lenses* · *Silty clay and sand lenses* · *Sandy clay* · *Sandy silt and sand lenses* · *Clayey sand* · *Silty sand* · *Sand* · *Gravelly clay* · *Coarse sand and gravel* · *Conglomerate* · *Weathered basement* · *Basement* · *Water table* · *Fault zones* · *Inferred fault* · *Facies* · *Inferred facies*

CROSS SECTION NOTE:
Detailed technical reports for each demonstration site listed in these cross sections are available as Geoscience Australia Records *(GA Record 2012/05 to 2012/09)* and can be downloaded from the GA internet site at: http://www.ga.gov.au/cedda/publications/96



EXPLANATORY NOTE: EUCLA BASIN COASTAL BARRIER
Multiple phases of marine inundation during the Cenozoic flooded the present-day onshore Eucla Basin in southern Australia. Complex successions of marine and non-marine sediments were deposited within a wide palaeo-shoreline zone which is here termed the 'Eucla Basin Coastal Barrier'. The methodology used to generate the WASANT palaeovalley map cannot detect or represent palaeovalleys that are now buried beneath coastal barrier sediments of the Eucla margin or by marine carbonate sequences of the onshore Eucla Basin. Other techniques, such as high-resolution geophysical surveys, e.g. airborne electromagnetics (AEM), are required to map buried palaeovalleys in this zone. For the purpose of this map, palaeovalleys flowing towards the southern coastline are shown to terminate at the Eucla Basin Coastal Barrier. Further west in the Bremer region, numerous buried southward-flowing palaeovalleys are represented by blanketing marine sediments although the precise locations of underlying individual palaeovalleys cannot be depicted.

Australian Government
Geoscience Australia
National Water Commission

WASANT PALAEOVALLEY MAP

SCALE 1:4 500 000

0 100 200 300 400 500 Kilometres

MERCATOR PROJECTION
Central Meridian: 126°E Standard Parallels: 26°S
Geocentric Datum of Australia

PREFACE:

This map of palaeovalleys in arid and semi-arid parts of Western Australia (WA), South Australia (SA) and the Northern Territory (NT), shows the interpreted distribution of palaeovalleys including those obscured beneath desert dunefields. The map extent is defined by the Köppen-Geiger classification of arid and semi-arid zones of WA, SA and NT (Figure 1). This map was produced as part of the 'Water for Australia's arid zone – identifying and assessing Australia's palaeovalley groundwater resources project' (termed the 'Palaeovalley Groundwater Project') that was funded by the National Water Commission (NWC) and led by Geoscience Australia, with support from respective state and territory government agencies. The four-year project (2008-2012) aimed to provide information about the role of palaeovalleys as aquifers in widespread regions where groundwater resources are scarce or need to be investigated for the future.

EXPLANATORY NOTES:

The map was compiled using national-scale datasets (including Digital Elevation Models and geological maps), existing geoscientific data and reports in combination with expert knowledge. New information was obtained through demonstration studies in selected sites (Figure 2); examples of palaeovalley cross sections from these sites are shown on the left-hand column of the map. The methodology used to produce the map is described in the companion project summary report by English et al. (2012), cited below. This broad-scale map is intended to enhance our knowledge of Australian arid zone palaeovalleys as widespread but little understood geologic elements and potentially contribute to an improved understanding of palaeovalley aquifers. The palaeovalleys shown on the map do not necessarily correspond with underlying groundwater resources or indicate prospective borehole sites. Rather, the map serves as a guide for more detailed future hydrogeological investigation in areas of interest.

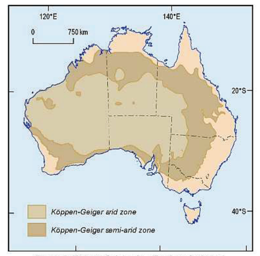


Figure 1: Köppen-Geiger classification of arid and semi-arid zones (reference 4 below).

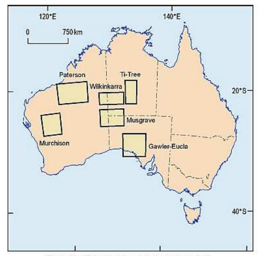


Figure 2: Palaeovalley demonstration sites.

CROSS SECTION NOTES:

1. Examples of cross sections shown in the left-hand column illustrate the heterogeneity and complexity (in terms of size, shape, structure and sediment infill) of palaeovalleys within the arid and semi-arid zone.
2. Most palaeovalleys shown on the map are now infilled with variably thick sequences of Cenozoic sediments, although some contain older (Mesozoic and Paleozoic) sequences, such as the Permian glacial-derived sediments in the Paterson Province (WA).
3. The infill sequences depicted in these sections range from unconsolidated sediments to fully lithified sedimentary rocks. For consistency, the lithologic descriptions used here refer to the primary sediment type regardless of the degree of lithification.
4. The sediment infill sequences are variably affected by chemical weathering. In places this has overprinted the original sediment compositions and also destroyed much of the primary sedimentary fabric.
5. In most cases relatively thin (less than two metres) deposits of regolith and aeolian sands blanket the uppermost palaeovalley sediment layers, although dunes up to 20 metres high may occur in desert regions. These cover sequences were not deposited by fluvial or lacustrine processes associated with the palaeovalleys so have not been shown.
6. To maximise the display of information the cross sections have inconsistent scales, conveying the significant variations in palaeovalley depths and widths.

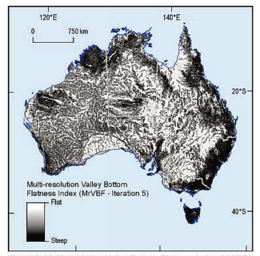


Figure 3: Multi-resolution Valley Bottom Flatness Index (MrVBF) Digital Elevation Model (Gallant and Dowling, 2003).

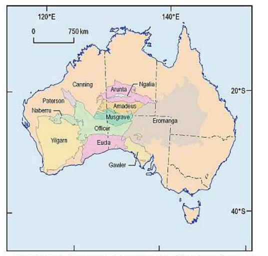


Figure 4: Geological provinces within the WASANT study area.

REFERENCES:

1. English, P.M., Lewis, S.J., Bell, J.G, Wischusen, J.D.H., Woodgate, M.F., Bastrakov E.N., Macphail, M.K., and Kilgour, P.L., 2012. *'Water for Australia's arid zone – identifying and assessing Australia's palaeovalley groundwater resources: Project summation. National Water Commission: Waterlines Report Series', August 2012*.
2. Gallant, J.C. and Dowling, T.I., 2003. *'A multi-resolution index of valley bottom flatness for mapping depositional areas'*, Water Resources Research **39** (12): 401-413.
3. Hou, B., 2004. *'Kingoonya palaeochannel project South Australia. Department of Primary Industries and Resources. Report Book', 2004/1.*
4. Köppen-Geiger classification of arid and semi-arid zones: http://www.bom.gov.au/climate/environ/other/koppen_explain.shtml

ACKNOWLEDGEMENTS:

This map has been produced by Geoscience Australia and funded by the National Water Commission. The map was compiled by J.G. Bell, P.L. Kilgour, P.M. English, S.J. Lewis and J.D.H. Wischusen *(Geoscience Australia)* and M.F. Woodgate *(NT Department of Natural Resources, Environment, the Arts and Sport (NRETAS)* with contributions from D.P. Commander, A.M. Kern and E.L. Leonhard *(WA Department of Water)*, B. Hou *(Geological Survey of South Australia)*, and S.J. Tickell *(NT NRETAS)*.

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Compiled by the Groundwater Group, Geoscience Australia.
Cartography by Silvio Mezzomo and Theo Chiotis, Products and Promotion, Geoscience Australia.

BIBLIOGRAPHIC REFERENCE:

Bell, J.G., Kilgour, P.L., English, P.M., Woodgate, M.F., Lewis, S.J. and Wischusen, J.D.H. (compilers), 2012.
WASANT Palaeovalley Map – Distribution of Palaeovalleys in Arid and Semi-arid WA-SA-NT (First Edition), scale: 1:4 500 000.
Geoscience Australia Thematic Map (Geocat № 73980) – hard-copy and digital data publication: http://www.ga.gov.au/cedda/maps/96

DISCLAIMER:

Copies of this map may be downloaded from the Geoscience Australia internet site at:
https://www.ga.gov.au/products/servlet/controller?event=GEOCAT_DETAILS&catno=73980, or by contacting:
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Phone (02) 6249 9966, Facsimile (02) 6249 9960, Email: sales@ga.gov.au
GeoCat № 73980
ISBN № 978-1-922103-74-1

Appendix 2 – ArcHydro GIS toolset

Water is fundamental to human life. The scope and scale of water resources problems makes geographic information systems (GIS) software a powerful tool for developing solutions. Hydrologists use many data sources to assess water quality, determine water supply manage water resources etc. in the 1990s, GIS emerged as a significant support tool for hydrologic modelling, in particular providing consistent method for watershed and stream network delineation using digital elevation models (DEM).

While GIS is now widely accepted as a useful tool for assembling water resources information, a few issues remain of great importance such as data interoperability between organisations systems, standards and models, the huge size of datasets involved such as DEMs, taxonomy and definition of geological units .etc.

Purpose

This work instruction describes the process of using ArcHydro tools to help map groundwater resources in palaeovalleys. Although ArcHydro tools offer more options for catchment analysis and water resources management and water flow modelling, the scope of this work is to focus on the functionality that helps in mapping palaeovalleys (rather than water resources management). The resulting dataset can be integrated with other datasets to better understand and map palaeodrainage systems. The use and development of ArcHydro in the *Palaeovalley Groundwater Project* continues to be refined, and future updates to this work instruction throughout the remainder of the project are likely. However, this document sets-out the current status of operations for the Project thus far.

ArcHydro tools are composed of separate toolsets for surface water and Groundwater applications. The ArcHydro tools are a set of public domain utilities developed jointly by the Center for Research in Water Resources (University of Texas at Austin) and ESRI. These tools provide functionalities for terrain processing, watershed delineation and attribute management. They operate on top of the ArcHydro data model.

The ArcHydro Groundwater tools package set has been developed by Aquaveo and ESRI, and is composed of 3 themes: 1. Groundwater Analyst, 2. MODFLOW Analyst, and 3.Subsurface Analyst. The Groundwater Analyst component is provided free-of-charge, and access to the other systems requires licence payments.

Installing ArcHydro Tools

For the ArcHydro Groundwater toolset, the install file can be downloaded from the link below http://www.aquaveo.com/archydro-groundwater.

Preparing the DEM

Raster analysis using fine resolution DEMs (e.g. LIDAR) is only practical over limited areas due to size limitations (ArcInfo Grid size), but the results can be combined with vector data for regional studies. When Using ArcHydro tools it is suggested that the following two steps are carried out initially in preparation to use the tools.

- Save a copy of the grid as “integer”. This can be done using the “Raster Calculator”. The reduction in the quality is not an issue, as the advantage gained in processing time is very valuable, plus the new grid is only used for ArcHydro; and
- It is also important to use the grid in projected units and not geographic latitude and longitude coordinates.

Creating the ArcMap project

Start ArcMap and make sure the ArcHydro Toolbox is loaded. Add the DEM dataset to the project and save the project. It is critical to save the project before attempting any of the ArcHydro functions, because when saving the project ArcHydro will create new directories and Geodatabases for saving the layer it creates.

Creating synthetic stream

Water and land interact with one another: the shape of the land surface directs the drainage of water through the landscape, while the erosive power of water slowly reshapes the land surface. Streams, rivers and water bodies form in the valleys and hollows of the land surface and water flows (drainage) from the higher land areas downstream forming these water systems. Therefore, DEMs can be used to analyse and drive the drainage patterns of the land surface terrain.

Drainage is the flow process by which water moves from area of precipitation down to a stream, then a river and finally to the sea. Drainage areas can be delineated using DEMs, by determining how water flows from cell to cell (based on its elevation). Drainage patterns are complex; thus, automated processing removes the need for the hydrogeologist to spend endless hours trying to interpret drainage patterns from contour lines on topographic maps. Nevertheless, digital elevation models are only an approximate representation of the land surface and manual editing of drainage boundaries may be necessary especially in regions with very flat terrain havening many constructed rather than natural drainage channels.

In order to determine the surface water flow, ArcHydro uses the digital elevation model for creating “Synthetic Streams”

Filling Sinks

If a cell is surrounded by higher elevation cells, the water is trapped in that cell and cannot flow. The Fill Sinks function modifies the elevation value to eliminate these problems.

Flow Directions

The Flow Direction function takes a grid ("e.g., Hydro DEM") as input, and computes the corresponding flow direction grid (e.g. "FlowDirG”). The values in the cells of the flow direction grid indicate the direction of the steepest descent from that cell.

Flow Accumulations

The Flow Accumulation function takes as input a flow direction grid and computes the associated flow accumulation grid that contains the accumulated number of cells upstream of a cell, for each cell in the input grid.

Flow accumulation processing is very time consuming task and can take a lot of time to complete. It requires significant computer memory (at least 64MB of RAM, preferably more) and a significant amount of hard disk space (about 5 times the size of the final flow accumulation GRID). If the function fails to operate properly, the most likely reason is the lack of hard disk space. The lack of memory can greatly increase the time required for processing.

Stream Definitions

The Stream Definition function takes a flow accumulation grid as input and creates a Stream Grid for a user-defined threshold. This threshold is defined either as a number of cells (default 1%) or as a drainage area in square kilometres.

In general, the recommended size for stream threshold definition is 1% of the overall area. For increased performance on large DEMs (over 20,000,000 cells), the size of the threshold may be increased to reduce the stream network and the number of catchment polygons.

The area may be entered only if the ground unit has been set in the spatial references. The resulting stream grid contains a value of "1" for all the cells in the input grid that have a value greater than the given threshold. All other cells in the Stream Grid contain no data.

Stream Segmentations

The Stream Segmentation function creates a grid of stream segments that have a unique identification. Either a segment may be a head segment, or it may be defined as a segment between two segment junctions. All the cells in a particular segment have the same grid code that is specific to that segment. The input Sink Watershed grid is optional and may be used to specify the areas located within sink drainage areas, where the stream links should not be generated. The input Sink Link is also optional – it may be used also to specify the areas where the stream links should not be generated. These 2 grids may be created with the function Flow Direction with Sinks. The Sink Link grid may be combined with the Stream Link grid generated by the current function by using the function Combine Stream Link and Sink Link to create a Link grid that will represents both dendritic (streams) and deranged (sinks) terrain.

The "Sink Watershed Grid" and the "Sink Link" input are optional.

Appendix 3 – ASEG depth to magnetic basement mapping poster

This appendix contains a copy of the poster presented at the August 2010 conference to the Australian Society of Exploration Geophysicists (ASEG), which focused on the depth to magnetic basement mapping work completed at Geoscience Australia as a collaborative effort for both the *Palaeovalley Groundwater Project* and other geophysical research.

Australian Government
Geoscience Australia

Mapping the depth to magnetic basement in the Gawler-Curnamona region using the spectral domain method

Tony Meixner, Indrajit G. Roy and Ashraf L. Hanna

GEOSCIENCE AUSTRALIA

Introduction

Two overlapping depth to magnetic basement maps have been constructed in the Gawler-Curnamona region of South Australia using the spectral domain method to estimate depth to magnetic source. The overlapping maps were produced for the Onshore Energy Geodynamic Framework Project, part of the Onshore Energy Security Program, and the Groundwater Project (Figure 1). The spectral domain method was selected over a number of other depth to magnetic source estimation methods due to its ability to rapidly produce reliable results over large areas. The implementation of this method into a semi-automated routine resulted in the production of regional scale maps within a realistic time frame.

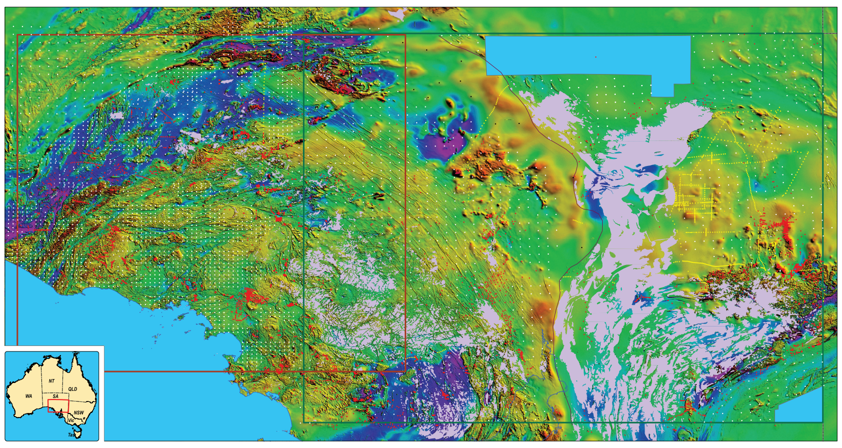
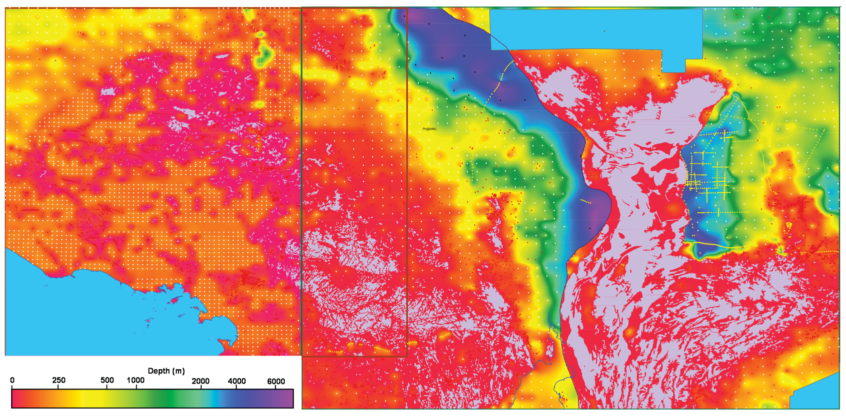


Figure 1a. Total magnetic intensity reduced to pole image of the Gawler-Curnamona region.



1b. Depth to magnetic basement image of the region in figure 1a. Brown box – outline of the depth to magnetic basement produced for the Ground Water Project; green box – outline of the depth to magnetic basement produced for the Geodynamic Framework Project; light blue polygon – substandard magnetic data; grey polygons – basement outcrop; white points – spectral domain method depth estimates; black points – 2D forward modelling depth estimates; red points – basement intersections from drill holes; yellow points – interpreted basement intersections from seismic data; and, purple line – to the west of this line the Neoproterozic of the Adelaide Rift System has been assigned to the cover, while to the east of this line these sequences have been assigned to the basement due to a change in the magnetic character. For a full explanation of which units have been assigned to the cover and which to basement refer to the published map http://www.ga.gov.au/minerals/research/national/oegf/index.jsp

The maps provide a useful tool for the mineral explorer as they delineate, in regions obscured by cover sediments, the depth to economic basement for the mineral explorer; basement unconformity depth for the Uranium explorer; thickness of cover for the geothermal explorer; and sediment thickness and basement structure for the groundwater explorer. The eastern map, produced for the Onshore Energy Geodynamic Framework Project, is currently available and can be downloaded from http://www.ga.gov.au/minerals/research/national/oegf/index.jsp. The western map produced for the Ground Water Project will be available soon.

Map construction

The depth to magnetic basement maps were constructed from a compilation of point located depth values in meters below topography consisting of depth to magnetic source estimates, basement drill hole intersections and interpreted seismic depth estimates. These point depths were combined with Geoscience Australia's 1:1 000 000 scale geology map to delineate the outcropping basement, and gridded using Intrepid's* variable density gridding routine.

The depth to magnetic basement points consist of the following:

- Depth estimates generated from gridded magnetic data using the spectral domain method (Spector and Grant, 1970).
- Depth estimates from manual 2D forward modelling.
- Basement intersections from drill hole data supplied by PIRSA (Cowley, W.M, PIRSA, pers.com., 2010).
- Basement intersections from drill hole data sourced from PIRSA's Curnamona Province – 3D Sedimentary Basin model†
- Depth estimates to interpreted magnetic basement from seismic lines 03GA-CU1, 09GA-CG1, 08GA-A1, 09GA-C1, 03GA-OD1 and 03GA-OD2‡.
- Seismic depth to basement estimates from PIRSA's Curnamona Province – 3D Sedimentary Basin model†
- Unassigned depths from PIRSA's Curnamona Province – 3D Sedimentary Basin model†

Spectral domain method

The majority of the depth to magnetic source estimates were generated using the spectral domain method of Spector and Grant (1970). This method is applied to the radially averaged power spectrum within a window of gridded magnetic data. Analyses of the slope of straight line segments within the power spectrum are used to compute the ensemple average depth for magnetic sources within that window. The spectral domain method has been incorporated into software that we have developed which automates the process of subsectioning grids based on a moving overlapping window. Power spectrums are then generated for each window in batch mode using Intrepid* software. The spectrums are then loaded into in house developed software that allow for semi-automated manual picking of straight line segments from which the magnetic depth estimates are generated. Figures 2 and 3 show typical power spectrums over areas with differing magnetic signature and magnetic basement depth. In both instances there is a good correlation between the depth estimates and depths from drill hole and seismic data.

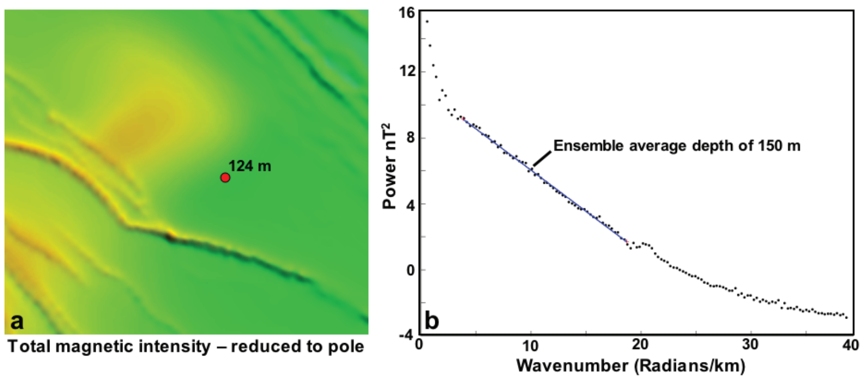


Figure 2a. Colour magnetic image of a 10 km window showing northwest-trending magnetic dykes which have intruded a non-magnetic sandstone. The red point shows the location and depth of a drill hole that has intersected the sandstone unit. **2b.** Shows the power spectrum and the straight line segment (blue) from which the interpreted depth to magnetic basement has been computed.

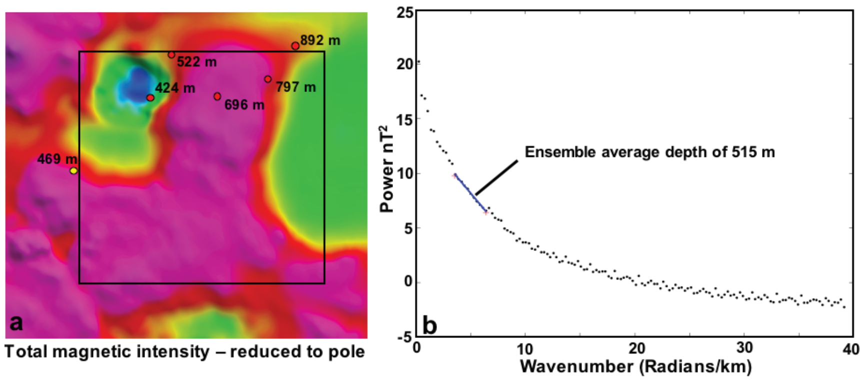


Figure 3a. Colour magnetic image showing the location of a 20 km window (black square). The red dots show the locations and depth of interpreted magnetic basement intersected by drill holes. The yellow dot shows the location and interpreted depth to magnetic basement from the eastern end of seismic line 03GA-OD2. **3b.** shows the power spectrum and the straight line segment (blue) from which the interpreted depth to magnetic basement has been computed. The straight line segment is of a lesser magnitude and, therefore, not as wen defined as the straight line segment in Figure 2, and is probably the result of the variation of the depth to basement within the window. The computed average depth for the window area, however, corresponds well with the drill hole and seismic data.

The window size is an important factor in the reliability of the depth estimates. A range of window sizes were tested with 10 km windows producing the most reliable results for regions where the magnetic basement is less than approximately 500 m depth. For magnetic basement ranging from approximately 500 m to 2000 m, a 20 km window produced reliable results. Larger window sizes allow for longer maximum wavelength anomalies and hence the ability to resolve deeper magnetic sources. Large windows, however, will enclose a larger geographic area over which the magnetic basement depth may significantly vary. This variability will produce a power spectrum that lacks an obvious straight line segment and will therefore, not produce reliable depth estimates. It was found that for window sizes larger than 20 km, the spectrum tended to be hard to interpret and so for basement depths greater than approximately 2000 m magnetic depth estimates were generated by manual 2D forward modelling from magnetic profiles extracted from the gridded magnetic data.

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*http://www.intrepid-geophysics.com/ig/index.php?lang=EN&menu=products-intrepidsoftware

†http://www.pir.sa.gov.au/minerals/geology/3d_geological_models/curnamona_sedimentary_basin_model

‡http://www.gov.au/minerals/research/national/seismic/index.jsp

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APPLYING GEOSCIENCE TO AUSTRALIA'S MOST IMPORTANT CHALLENGES

Appendix 4 – Field parameter data for Kingoonya groundwater samples

This appendix contains a table listing all of the field parameter data acquired for the Kingoonya region groundwater sampling program.

Table 17: *Field parameters for groundwater samples from the Kingoonya Palaeovalley collected during July 2010 and November 2010.*

SA bore no.	Bore name	Date	Long.	Lat.	Well depth (m)	Depth to water (m)	Sample depth (m)	Temp. °C	pH	EC µS/cm	TDS (mg/l)	Alkalinity (mg/l)	Redox (mV)	Dissolved oxygen (ppm)
5736-08	Malbooma Swamp	08/07/2010	134.158	30.666								nr		
5736-07	Malbooma Outstation	08/07/2010	134.176	30.685	4.6	2.7		18.29	6.59	94	52	nr	410.7	15.9
5636-23	354 Mile Siding	08/07/2010	133.884	30.694	35?	25.3		23.90	6.68	7,657	4,410	nr	744.0	1.6
5736-20	Hiern's Well	09/07/2010	134.326	30.790	60?	29	50	24.22	8.30	16,340	9,543	nr	106.8	0.1
5736-17	Clayson's Well	09/07/2010	134.356	30.746	36?	15.4		23.20	8.25	3,131	1,738	nr	135.2	1.3
5736-15	Bulga Well	10/07/2010	134.395	30.679	11.4	11.2		17.43	7.61	52,610	34,617	nr	273.0	23.3
5736-41	West Pinding Tank	10/07/2010	134.411	30.730		31.3		19.17	7.66	4,166	2,320	nr	318.2	96.2
5836-86	Tarcoola Gold TW2	10/07/2010	134.550	30.709	>100	14.1		24.22	5.99	157,000	133,450	nr	178.0	6.7
5836-126	TPH PC1	11/07/2010	134.872	30.685	6.5	5.2		22.37	7.18	70,120	46,419	nr	437.0	80
5836-27	RL33	11/07/2010	134.523	30.561	31	15.19		25.31	6.52	66,600	44,089	nr	-17.0	1.3
5837-84	Commrailways A37-10	12/07/2010	134.525	30.420	34	9		24.30	6.91	55,180	36,529	nr	275.0	41.1
5836-687	Liffy's Bore	12/07/2010	134.557	30.564	46			22.49	7.17	6,660	3,750	nr	280.9	82.8
5837-64	No. 34 Bore	13/07/2010	134.878	30.465				22.48	6.73	28,470	17,338	nr	293.6	69.8
5836-16	Welcome Well	13/07/2010	134.793	30.740	32.14	22.5		21.98	7.05	20,930	12,411	nr	280.3	52.2
5836-20	Warna Well	13/07/2010	134.862	30.834	15.5	13.7		17.29	7.12	11,630	6,664	nr	76.8	3.4
5836-42	Mullina Well	14/07/2010	134.687	30.802				22.74	7.14	4,640	2,589	nr	111.7	
5936-35	Scott's Well	17/11/2010	135.368	-30.587	13.6	8.6	12.0	24.66	7.43	25,015	16,260	234	387.6	71.8
5936-118	PDH BB	18/11/2010	135.383	-30.651	32.3	12.3	30	25.84	8.76	70,474	45,800	1,110	-46.7	25.0
5936-13	North Well	18/11/2010	135.312	-30.846	18.8	16.3	17.5	15.47	7.52	2,487	1,616	214	247.3	445.7
5936-49	Wallabyng Range Well	19/11/2010	135.358	-30.770	14.9	10.1	13.0	23.78	7.77	20,737	13,480	290	408.1	113.2
6036-119	Highways Well B19	19/11/2010	135.522	-30.779	33.0	6.7	20.0	25.82	7.26	129,224	83,990	30	-132.4	4.0
6036-135	Highways Well B29	20/11/2010	135.549	-30.877	19.2	3.7	15.0	25.30	7.37	162,164	105,460	70	-28.9	9.4
6036-18	Mulga Well No.2	20/11/2010	135.521	-30.841	13.9	9.7	13.0	24.05	7.73	1,584	1,030	378	-24.9	6.3
6036-127	Highways Well B27	21/11/2010	135.645	-30.877	20.7	5.3	15.0	26.61	3.64	185,304	120,300	0	555.3	8.3
6036-125	Highways Well B25	21/11/2010	135.688	-30.902	39.8	11.3	30.0	25.54	6.63	155,703	101,200	100	54.8	5.6
6036-58	Monty's Well	21/11/2010	135.680	-30.935	12.2	9.2	11.2	24.45	6.93	23,601	15,340	142	417.3	401.0
6036-109	Bulyacobbie Bore	22/11/2010	135.803	-30.918	112.0	7.0	11.0	24.40	8.07	15,742	10,230	680	-7.6	4.2

Appendix 5 – Trace element data for Kingoonya groundwater samples

This appendix contains a complete listing of the trace element data acquired for the Kingoonya region groundwater samples collected for the *Palaeovalley Groundwater Project.* Due to the extensive range of trace elements analysed for during this project, the following data are presented in Tables 18-20.

Table 18: *Trace element data for Kingoonya region groundwater samples – page 1 of 3.*

Field name	Unit no.	Al	As	B	Cd	Co	Cr	Cu	Fe	Mn	Mo	Ni	P	Pb	Sb	Se	Si	Sr	Zn	Li	Sc
		ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppm	ppb	ppb
Malbooma Swamp	5736-08	<0.25	<0.25	3.3	<0.25	<0.25	<0.25	<0.25	<0.5	<0.25	<0.25	<0.25	<0.5	<0.25	<0.5	<0.25	11.8	3.61	<0.25	40	8
Malbooma Outstation	5736-07	<0.05	<0.05	<0.1	<0.05	<0.05	<0.05	<0.05	<0.1	<0.05	<0.05	<0.05	0.128	<0.05	<0.1	<0.05	3.17	<0.05	0.0779	<2	<2
354 Mile Siding	5636-23	<0.25	<0.25	0.584	<0.25	<0.25	<0.25	<0.25	75.7	1.26	<0.25	<0.25	<0.5	<0.25	<0.5	<0.25	14.6	3.28	<0.25	<4	12
Hiern's Well	5736-20	<0.25	<0.25	1.7	<0.25	<0.25	<0.25	<0.25	<0.5	<0.25	<0.25	<0.25	<0.5	<0.25	<0.5	<0.25	14	3.23	<0.25	54	12
Clayson's Well	5736-17	<0.25	<0.25	1.42	<0.25	<0.25	<0.25	<0.25	<0.5	<0.25	<0.25	<0.25	1.36	<0.25	<0.5	<0.25	30.1	0.592	<0.25	<4	20
Bulga Well	5736-15	<2.5	<2.5	<5	<2.5	<2.5	<2.5	<2.5	<5	<2.5	<2.5	<2.5	<5	<2.5	<5	<2.5	14.1	6.11	<2.5	60	<20
West Pinding	5736-41	<0.25	<0.25	2.45	<0.25	<0.25	<0.25	<0.25	<0.5	<0.25	<0.25	<0.25	<0.5	<0.25	<0.5	<0.25	13.9	1.81	0.448	<10	10
Tarcoola Gold TW2	5836-86	<5	<5	<10	<5	<5	<5	<5	15	7.61	<5	<5	<10	<5	<10	<5	<5	14.6	<5	<100	<100
TPH PC1	5836-126	<2.5	<2.5	9.05	<2.5	<2.5	<2.5	<2.5	<5	<2.5	<2.5	<2.5	<5	<2.5	<5	<2.5	7.2	10.7	<2.5	120	<40
RL33	5836-27	<2.5	<2.5	7.33	<2.5	<2.5	<2.5	<2.5	1480	18.6	<2.5	<2.5	<5	<2.5	<5	<2.5	<5	26.1	<2.5	20	<20
Commrailways A37-10	5837-84	<2.5	<2.5	13.6	<2.5	<2.5	<2.5	<2.5	<5	<2.5	<2.5	<2.5	<5	<2.5	<5	<2.5	6.78	19.6	<2.5	<20	<20
Liffy's Bore	5836-687	<0.25	<0.25	0.624	<0.25	<0.25	<0.25	<0.25	<0.5	<0.25	<0.25	<0.25	<0.5	<0.25	<0.5	<0.25	8.48	0.955	<0.25	<4	8
No. 34 Bore	5837-64	<0.5	<0.5	2.83	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<1	<0.5	<1	<0.5	9.46	7.17	<0.5	<8	8
Welcome Well	5836-16	<0.5	<0.5	1.09	<0.5	<0.5	<0.5	<0.5	<1	<0.5	<0.5	<0.5	<1	<0.5	<1	<0.5	18.7	2.04	<0.5	<8	16
Warna Well	5836-20	<0.25	<0.25	1.7	<0.25	<0.25	<0.25	<0.25	9.28	2.37	<0.25	<0.25	<0.5	<0.25	<0.5	<0.25	15.9	4.05	<0.25	<8	16
Mullina Well	5836-42	<0.05	<0.05	<0.1	<0.05	<0.05	<0.05	<0.05	<0.1	0.402	<0.05	<0.05	0.273	<0.05	<0.1	<0.05	40.6	1.05	<0.05	<4	32
Scott's Well	5936-35	<0.25	<0.25	5.12	<0.25	<0.25	<0.25	<0.25	<0.5	<0.25	<0.25	<0.25	0.15	<0.25	<0.5	<0.25	27.2	15.7	<0.25	80	<200
PDH BB2	5936-118	<1.25	<1.25	4.38	<1.25	<1.25	<1.25	<1.25	<2.5	<1.25	<1.25	<1.25	<2.5	<1.25	<2.5	<1.25	<2.5	1.47	<1.25	508	<20
North Well	5936-13	<0.05	<0.05	0.622	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.1	<0.05	<0.1	<0.05	37.5	1.03	0.348	8	<20
Wallabyng Range Well	5936-49	<0.25	<0.25	3.75	<0.25	<0.25	<0.25	<0.25	<0.5	<0.25	<0.25	<0.25	1.17	<0.25	<0.5	<0.25	19.9	7.88	<0.25	<20	<100
Highways B19	6036-119	<2.5	<2.5	2.62	<2.5	<2.5	<2.5	<2.5	89.2	3.49	<2.5	<2.5	<5.0	<2.5	<5.0	<2.5	<5.0	15.7	<2.5	320	<200
Highways B29	6036-135	<2.5	<2.5	2.52	<2.5	<2.5	<2.5	<2.5	<5.0	<2.5	<2.5	<2.5	<5.0	<2.5	<5.0	<2.5	1.26	14.8	<2.5	360	<200
Mulga Well 2	6036-18	<0.05	<0.05	0.222	<0.05	<0.05	<0.05	<0.05	<0.05	2.22	<0.05	<0.05	<0.1	<0.05	<0.1	<0.05	13.6	1.09	<0.05	<30	<200
Highways B27	6036-127	2.58	<2.5	3.94	<2.5	<2.5	<2.5	<2.5	<5.0	5.72	<2.5	<2.5	<5.0	<2.5	<5.0	<2.5	14.6	14	<2.5	2010	<200
Highways B25	6036-125	<2.5	<2.5	3.82	<2.5	<2.5	<2.5	<2.5	5.04	<2.5	<2.5	<2.5	<5.0	<2.5	<5.0	<2.5	1.03	9.03	<2.5	200	<100
Monty's Well	6036-58	<0.25	<0.25	4.02	<0.25	<0.25	<0.25	<0.25	<0.5	<0.25	<0.25	<0.25	<0.5	<0.25	<0.5	<0.25	37.9	13	<0.25	72	<20
Bulyacobbie	6036-109	<0.25	<0.25	2.78	<0.25	<0.25	<0.25	<0.25	<0.5	0.545	<0.25	<0.25	2.46	<0.25	<0.5	<0.25	9.69	5.42	<0.25	<10	<60

Table 19: Trace element data for Kingoonya region groundwater samples – page 2 of 3.

Field name	Unit no.	V	Cr	Mn	Co	Ni	Cu	Zn	Ga	As	Rb	Y	Zr	Nb	Mo	Ag	Cd	Sn	Sb	Ba	Ce	La
		ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb
Malbooma Swamp	5736-08	<0.2	0.4	28.86	0.38	2.8	24.0	140.8	4.6	<0.2	8	0.15	2.0	1.6	2.4	0.11	0.24	3	1	26.4	0.15	0.15
Malbooma Outstation	5736-07	1.6	<0.2	3.30	0.06	0.6	16.8	76.8	2.0	0.18	<2	0.08	0.2	<0.4	<0.4	0.01	0.06	1.0	<0.5	6.8	0.44	0.28
354 Mile Siding	5636-23	5.2	0.8	1480	5.46	4.0	<0.8	73.6	40.4	1.0	4	0.25	2.0	<0.8	<0.8	<0.01	<0.04	2	<1	221	0.47	0.06
Hiern's Well	5736-20	2.7	1.2	310.32	0.10	1.8	<1	13	49.2	<0.3	<6	0.22	6.0	1	<1	<0.01	<0.06	6	<2	271	0.16	0.04
Clayson's Well	5736-17	1.4	<0.4	84.66	0.23	2.4	<0.8	67.2	24.6	1.4	<4	0.05	0.8	<0.8	<0.8	<0.01	<0.04	<1	<1	108.8	0.06	0.02
Bulga Well	5736-15	3	<2	260.1	0.56	6	<4	68	18	<0.9	<20	0.52	<2	<4	<4	<0.03	<0.2	10	<5	108	0.42	0.15
West Pinding	5736-41	3.0	1	11.4	0.12	2	8	362	9.0	<0.5	<10	<0.02	<1	<2	34	<0.02	<0.1	6	<3	40	<0.03	<0.02
Tarcoola Gold TW2	5836-86	<5	<10	10100	8.4	<10	<20	140	10	5	<100	0.6	<10	<20	<20	<0.2	<1	<30	<30	40	1.2	1.2
TPH PC1	5836-126	<2	<4	12.6	0.16	<4	<8	32	4	<2	<40	0.16	<4	<8	<8	<0.06	1.2	<10	<10	24	<0.1	0.18
RL33	5836-27	<1	2	24000	4.60	2	<4	28	9	<0.9	60	0.20	<2	<4	<4	<0.03	0.2	10	<5	56	0.60	0.21
Commrailways A37-10	5837-84	29	4	24.6	0.84	2	<4	12	4	0.9	<20	0.12	<2	<4	28	<0.03	<0.2	15	<5	24	0.12	<0.03
Liffy's Bore	5836-687	1.0	<0.4	0.48	<0.01	<0.4	0.8	6.4	1.0	<0.2	<4	0.01	<0.4	<0.8	5.6	<0.01	0.12	4	<1	4.0	0.01	<0.01
No. 34 Bore	5837-64	0.8	<0.8	12.6	0.04	<0.8	10	10	4.0	<0.4	32	0.02	<0.8	<2	2	<0.01	0.08	4	<2	22	<0.02	<0.01
Welcome Well	5836-16	8.8	0.8	3.7	0.04	<0.8	8	90	6.8	1.2	<8	<0.02	<0.8	<2	4	<0.01	0.08	2	<2	34	<0.02	<0.01
Warna Well	5836-20	<0.4	<0.8	2680	0.94	0.8	<2	14	97.6	<0.4	<8	0.04	<0.8	<2	<2	<0.01	<0.08	6	<2	490	<0.02	0.01
Mullina Well	5836-42	7.6	1.2	456	0.17	0.8	<0.8	12.0	39.8	<0.2	<4	0.16	1.6	<0.8	<0.8	<0.01	0.08	6	<1	190	0.34	0.06
Scott's Well	5936-35	40	<4	<8	<0.2	<2	<10	80	<4	<20	42	<6	<100	<6	<80	<0.6	2	<10	<200	80	<1	<4
PDH BB2	5936-118	<1	<0.4	712.0	0.08	1.0	<1	4	0.8	2	192.6	<0.6	<10	1.8	<8	<0.06	1.2	<1	<20	20	<0.1	<0.4
North Well	5936-13	21	<0.4	3.2	0.06	<0.2	3	348	<0.4	<2	12.0	<0.6	<10	<0.6	<8	<0.06	<0.2	<1	<20	184	<0.1	<0.4
Wallabyng Range Well	5936-49	5	<2	16	0.9	<1	<5	40	<2	<10	21	<3	<50	<3	<40	<0.3	<1	<5	<100	360	<0.5	<2
Highways B19	6036-119	<10	<4	5016	16.8	4	<10	2000	<4	<20	156	<6	<100	<6	<80	<0.6	2	<10	<200	40	<1	<4
Highways B29	6036-135	<8	<3	1988	0.4	<2	<8	<30	<3	<20	195	<5	<80	<5	<70	<0.5	4	<8	<200	30	<0.8	<3
Mulga Well 2	6036-18	<8	<3	2618	1.8	<2	<8	30	<3	<20	15	<5	<80	<5	<70	<0.5	<2	<8	<200	360	<0.8	<3
Highways B27	6036-127	<8	<3	8855	411.6	196	<8	90	21	<20	900	235	<80	5	<70	<0.5	6	<8	<200	<30	157.6	42
Highways B25	6036-125	<5	<2	1020	5.6	9	<5	220	<2	<10	180	<3	<50	6	<40	<0.3	3	<5	<100	40	<0.5	<2
Monty's Well	6036-58	75	<0.4	4.0	0.20	0.8	<1	32	<0.4	6	45.6	<0.6	<10	0.6	<8	<0.06	0.6	<1	<20	76	<0.1	<0.4
Bulyacobbie	6036-109	<3	<1	754	1.14	1.8	<3	20	<1	<6	14	<2	<30	<2	<20	<0.2	<0.6	<3	<60	700	<0.3	<1

Table 20: Trace element data for Kingoonya region groundwater samples – page 3 of 3.

Field name	Unit no.	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	Ta	W	Pb	Th	U	Au	Pd	Ag	Pt
		ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppb	ppt	ppt	ppt	ppt
Malbooma Swamp	5736-08	0.14	0.15	0.15	0.15	0.14	0.15	0.15	0.14	0.15	0.15	0.13	0.14	2.0	0.18	0.8	1.44	3.3	2.4	<5	<1	<25	<1
Malbooma Outstation	5736-07	0.06	0.16	0.04	0.02	0.03	0.02	0.03	0.02	0.02	0.02	0.02	0.02	0.2	0.04	<0.1	3.44	0.35	<0.08	<5	<1	<25	<1
354 Mile Siding	5636-23	0.04	0.13	0.05	0.03	0.06	0.02	0.06	0.02	0.03	0.01	0.02	0.01	0.8	0.04	<0.2	1.28	12.2	2.8	<5	1	<25	<1
Hiern's Well	5736-20	0.01	0.08	0.02	<0.02	0.02	<0.01	0.03	<0.01	0.02	<0.01	0.02	<0.01	7.2	0.20	<0.3	9.5	6.4	4.8	<5	<1	<25	<1
Clayson's Well	5736-17	<0.01	0.05	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.4	0.03	0.2	2.88	0.6	0.6	<5	<1	<25	<1
Bulga Well	5736-15	0.06	0.40	0.03	0.03	0.06	<0.01	0.08	0.01	0.03	<0.01	0.02	<0.02	2	0.15	<1	3.6	3.0	<0.8	<5	1.4	28	1.4
West Pinding	5736-41	<0.01	<0.02	<0.02	<0.01	<0.02	<0.01	<0.01	<0.01	<0.02	<0.01	<0.01	<0.01	<0.5	0.09	<0.5	4.0	0.6	12.8				
Tarcoola Gold TW2	5836-86	<0.1	0.2	<0.2	<0.05	<0.2	<0.05	<0.1	<0.05	<0.2	<0.05	<0.1	<0.1	<5	0.3	<5	8	6	<4	<5	<1	<25	<1
TPH PC1	5836-126	<0.04	0.08	<0.06	<0.02	<0.06	<0.02	<0.04	<0.02	<0.06	<0.02	<0.04	<0.04	<2	0.1	<2	6.4	1	<2	<5	<1	47	<1
RL33	5836-27	0.02	0.08	<0.03	<0.01	<0.03	<0.01	<0.02	<0.01	<0.03	<0.01	<0.02	<0.02	1	0.25	<1	5.2	40.0	3.2	<5	<1	<25	<1
Commrailways A37-10	5837-84	<0.02	0.04	<0.03	<0.01	<0.03	<0.01	<0.02	<0.01	<0.03	<0.01	<0.02	<0.02	2	0.20	<1	10.8	2.0	24.8	<5	<1	<25	<1
Liffy's Bore	5836-687	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.2	0.05	<0.2	3.68	0.2	7.2	<5	<1	<25	<1
No. 34 Bore	5837-64	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	0.8	0.06	<0.4	15.3	1.6	9.3	<5	<1	<25	<1
Welcome Well	5836-16	<0.01	<0.02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.4	0.04	<0.4	2.8	0.6	15.3	<5	<1	<25	<1
Warna Well	5836-20	<0.01	<0.02	<0.01	0.03	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.4	<0.02	<0.4	10.6	1.4	<0.3	<5	<1	60	1.5
Mullina Well	5836-42	0.03	0.13	0.03	0.02	0.03	<0.01	0.04	<0.01	0.02	<0.01	<0.01	<0.01	0.8	0.05	<0.2	3.20	0.7	<0.2	<5	<1	<25	<1
Scott's Well	5936-35	<1	<2	<4	<2	<2	<0.6	<2	<0.6	<0.6	<0.2	<1	<0.4	<200	<0.8	<40	<20	<200	9.0	<5	3.9	31	2.9
PDH BB2	5936-118	<0.1	<0.2	<0.4	<0.2	<0.2	<0.06	<0.2	<0.06	0.12	0.02	0.1	0.08	<20	<0.08	<4	14	<20	<0.06	<5	6.1	34	<1
North Well	5936-13	<0.1	<0.2	<0.4	<0.2	<0.2	<0.06	<0.2	<0.06	<0.06	<0.02	<0.1	<0.04	<20	<0.08	<4	<2	<20	0.84	<5	3.9	35	<1
Wallabyng Range Well	5936-49	<0.6	<1	<2	<0.8	<0.8	<0.3	<1	<0.3	<0.3	<0.1	<0.5	<0.2	<100	<0.4	<20	<10	<100	1.2	<5	29.7	38	<1
Highways B19	6036-119	<1	<2	<4	<2	<2	<0.6	<2	<0.6	<0.6	<0.2	<1	<0.4	<200	<0.8	<40	<20	<200	<0.6	<5	4.2	71	<1
Highways B29	6036-135	<1	<2	<3	<1	<1	<0.5	<2	<0.5	<0.5	<0.2	<0.8	<0.3	<200	<0.7	<30	<20	<200	<0.5	<5	5	32	<1
Mulga Well 2	6036-18	<1	<2	<3	<1	<1	<0.5	<2	<0.5	<0.5	<0.2	<0.8	<0.3	<200	<0.7	<30	<20	<200	<0.5	<5	2.8	<25	<1
Highways B27	6036-127	24	116	21	5	29	4.0	28	6.0	18.5	2.4	12.0	1.8	<200	<0.7	<30	40	<200	3.0	6.8	14.4	312	3.9
Highways B25	6036-125	<0.6	<1	<2	<0.8	<0.8	<0.3	<1	<0.3	<0.3	<0.1	<0.5	<0.2	<100	<0.4	<20	<10	<100	1.5	<5	6.5	151	<1
Monty's Well	6036-58	<0.1	<0.2	<0.4	<0.2	<0.2	<0.06	<0.2	<0.06	<0.06	<0.02	<0.1	<0.04	<20	<0.08	<4	<2	<20	7.20	<5	3.5	37	5.2
Bulyacobbie Bore	6036-109	<0.4	<0.6	<1	<0.5	<0.5	<0.2	<0.6	<0.2	<0.2	<0.06	<0.3	<0.1	<60	<0.2	<10	<6	<60	0.2	<5	3.9	23	<1