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Water for Australia's arid zone – identifying and assessing Australia's palaeovalley groundwater resources: summary report

Pauline English, Steven Lewis, Joseph Bell, John Wischusen, Maria Woodgate, Evgeniy Bastrakov, Mike Macphail, Penny Kilgour

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Waterhole in Cotton Creek near Parnngurr community, Karlamilyi National Park (formerly Rudall River National Park) in the Paterson Province, Western Australia. This waterhole is located between the Great Sandy Desert and the Little Sandy Desert. The creek is incised into granite-gneiss of the Proterozoic Rudall Complex (approximately 1775 million years old) and may have originally been scoured by glaciers melting from the Pilbara Ice Cap during the Permian, around 290 million years ago. The creek is ephemerally active, draining a large area of incised bedrock ranges, and flows north into the Great Sandy Desert where its outwash flood deposits terminate against large sand dunes 20 km north of the ranges. *Eucalyptus camaldulensis* ssp. *arida* (coolibah) grow at the water line, indicative of reliable watertables. The creek is characterised by sandy alluvium that may provide suitable bore sites for future high-quality water supplies for the community of over 100 Martu traditional owners at Parnngurr whose current water supplies are of poor quality.

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Abbreviations and acronyms

ADWG	Australian Drinking Water Guidelines
AEM	Airborne electromagnetics
AHD	Australian Height Datum
APY	Anangu Pitjantjatjara Yankunytjatjara
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
BIF	Banded iron formation
BP	Before present
CID	Channel iron deposits
CSIRO	Commonwealth Scientific and Industrial Research Organisation
Czk	Cenozoic calcrete
DEM	Digital elevation model
DfW	Department for Water (South Australia)
DID	Detrital iron deposits
DMITRE	Department for Manufacturing, Innovation, Trade, Resources and Energy (South Australia)
DOW	Department of Water (Western Australia)
EM	Electromagnetic
GA	Geoscience Australia
GAB	Great Artesian Basin
GDE	Groundwater-dependent ecosystem
GIS	Geographic information system
GMWL	Global meteoric water line
GSSA	Geological Survey of South Australia
GSWA	Geological Survey of Western Australia
LMWL	Local meteoric water line
Ma	Million years ago
MODIS	Moderate Resolution Imaging Spectroradiometer

MrVBF	Multi-resolution Valley Bottom Flatness Index
NCGRT	National Centre for Groundwater Research and Training
NOAA-AVHRR	National Oceanic and Atmospheric Administration – Advanced Very High Resolution Radiometer
NRETAS	Department of Natural Resources, Environment, the Arts and Sport (Northern Territory)
NSW	New South Wales
NT	Northern Territory
NTGS	Northern Territory Geological Survey
NTIR	Night-time infra-red
NWC	National Water Commission
NWI	National Water Initiative 2004
PGE	Platinum group elements
pMC	Percent modern carbon
PSC	Project Steering Committee
PV	Palaeovalley
Qa	Quaternary alluvium
RN	Registered numbers
RNWS	Raising National Water Standards
SA	South Australia
SARIG	South Australian Resources Information Geoserver
SMOW	Standard mean ocean water
SRTM	Shuttle Radar Topography Mission
SWL	Standing water level
TAR	Telfer Access Road
TDS	Total dissolved solids
WA	Western Australia
WASANT	WA–SA–NT

Units

µS/cm	micro-siemens per centimetre
cm	centimetres
GL	gigalitre: one billion litres (equivalent to 1000 megalitres, ML)
kL	kilolitre: 1000 litres (equivalent to one cubic metre: m^3)
km	kilometres
L/s	litres per second
m	metres
mg/L	milligrams per litre
ML	megalitre: one million (1 000 000) litres
mm	millimetres
mS/m	milli-siemens per metre
ppm	parts per million
S/m	siemens per metre

Salinity

For the purpose of the *Palaeovalley Groundwater Project*, the following intervals for total dissolved solids (TDS) have been used to classify groundwater salinity:

- <1000 mg/L TDS = fresh water
- 1001 to 10 000 mg/L TDS = brackish water
- 10 001 to 35 000 mg/L TDS = saline water
- >35 000 mg/L TDS = hypersaline water.

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Executive summary

Palaeovalley aquifers are relied upon in outback Australia by many groundwater users and help underpin the economic, social and environmental fabric of this vast region. ‘Water for Australia’s arid zone – Identifying and assessing Australia’s palaeovalley groundwater resources’ (the *Palaeovalley Groundwater Project*) investigated palaeovalleys across arid and semi-arid parts of Western Australia (WA), South Australia (SA) and the Northern Territory (NT). The project aimed to (a) generate new information about palaeovalley aquifers, (b) improve our understanding of palaeovalley groundwater resources, and (c) evaluate methods available to identify and assess these systems.

Palaeovalleys

Palaeovalley networks are an integral component of inland Australia’s near-surface environment. They have evolved over very long periods of geologic time in response to extreme climate changes, such as the onset of aridity. Palaeovalleys are mostly well preserved in desert regions even though their existence is usually not apparent at the surface due to widespread cover by sand dunes and other younger sediments.

Palaeovalleys are significant aquifers, especially in regions where no perennial surface water and no deeper groundwater systems exist. In many areas of Western Australia, South Australia and the Northern Territory, and to a lesser extent in other parts of Australia, palaeovalley aquifers provide the only water source for mining and pastoral activities, towns and communities, and remote outback infrastructure. The shallow depths of most palaeovalley aquifers means that arid-zone vegetation and associated ecosystems also commonly access their groundwater resources.

The original valleys were formed by fluvial (river), tectonic, or glacial processes. Valleys were incised into bedrock terrains, to variable depths of tens or hundreds of metres, and were subsequently infilled with sediments. Coarse-grained sands and gravels within deep valley channels are the most favourable water-bearing units because of high porosity, storage capacity and hydraulic conductivity. Although the original rivers no longer exist because of the now arid climate (established several hundred thousand years ago) the buried valley sediments contain active groundwater systems. The *Palaeovalley Groundwater Project* developed from the need to better understand (a) where palaeovalleys occur, (b) the extent of their cover sequences, (c) their dimensions, (d) the nature of their sedimentary infill, and (e) their hydrogeologic properties.

Palaeovalley Groundwater Project

The *Palaeovalley Groundwater Project* was led by Geoscience Australia, with support from respective state/territory government agencies. Magee (2009) compiled existing data, maps, reports and information about palaeovalleys and associated groundwater for arid and semi-arid Australia. This initial work provided recommendations and helped guide the ensuing project.

Project activities mainly focused on five regional demonstration sites across Western Australia, South Australia and the Northern Territory (Gawler-Eucla, Murchison, Paterson, Ti Tree and Wilkinkarra). Research efforts broadly evaluated the nature of palaeovalley aquifers in different geologic provinces, and coincided with areas where increased knowledge of groundwater resources may improve regional or state/territory groundwater management. Studies also tested different methods to detect, map and characterise palaeovalleys and their groundwater resources, to provide guidelines for future investigations and assessments.

Demonstration sites ranged from remote 'greenfield' palaeovalleys about which little was known, to relatively well-studied areas where previous hydrogeological work was built upon for this study. 'Greenfield' sites included the Wilkinkarra (Lake Mackay) region in southern Northern Territory, and the Murchison and Paterson Provinces of Western Australia. Some aspects of the palaeovalleys in the Ti Tree (NT) and Gawler-Eucla (SA) regions had been previously studied. Further detailed work for the present project involved drilling to bedrock more than 300 m deep in the Ti Tree Basin, and detailed hydrochemical and isotope analysis of palaeovalley groundwater in the Gawler-Eucla region.

Techniques applied in the demonstration studies involved both desktop and field-based methods. These involved a variety of innovative methods, some not typically applied for hydrogeological studies. Techniques included application and development of digital elevation models (DEM), remote-sensing interpretation, airborne and ground geophysical surveys (airborne electromagnetics–AEM, gravity and seismic), drilling, analysis of sedimentology, stratigraphy and palynology of palaeovalley sediments, 3D modelling, and hydrochemical and isotopic analysis of groundwater.

Demonstration studies

The demonstration studies represented the core of the *Palaeovalley Groundwater Project* and provided new information about palaeovalleys in diverse regions. Complementary desktop studies were undertaken in the Musgrave and Tanami regions to further test many remote-sensing techniques. The field-based demonstration studies produced integrated datasets to improve knowledge of palaeovalleys and groundwater resources:

- **Gawler-Eucla region, SA:** Research in the Kingoonya Palaeovalley augmented earlier geological studies of palaeovalley structure to significantly improve knowledge of groundwater compositions, processes and evolution. This knowledge will assist with ensuring safe and sustainable water supplies for existing and future users, such as communities, miners and pastoralists.
- **Murchison region, WA:** The reconnaissance investigation defined palaeovalleys using derived DEM, ground gravity surveying and investigative drilling and bore installation. For the first time the Murchison palaeovalleys were drilled to bedrock, revealing deeper palaeovalleys, to 150–200 m, and much sandier sedimentary infill than elsewhere in the Yilgarn Craton. The study also characterised groundwater ages and hydrochemistry. These efforts will support expanding iron ore and gold mining in the province, as well as town water supplies.
- **Paterson region, WA:** The 'greenfield' investigation used regional AEM survey data to reveal ancient glacial palaeovalleys and widespread fluvio-glacial sediments beneath dense dune fields at the edge of the Great Sandy Desert. The AEM data also depicted diverse bedrock aquifers and hydrogeologically significant structural features. The study generated 3D models based on integrated AEM data, drill-hole information and surface maps. Groundwater ages and hydrochemistry of palaeovalley aquifers were also characterised in this highly mineralised remote desert region.
- **Ti Tree Basin, NT:** This Cenozoic basin-style palaeovalley has been investigated for groundwater resources since the 1960s, and the shallow aquifers presently supply water for horticulture and local communities. The project drilled several holes to depths greater than 300 m to investigate the deeper sediment layers and groundwater systems. These drilling data helped develop a new three-layer aquifer model that may apply to other central Australian Cenozoic basins. These basins generally have thicker sediment sequences and contain more abundant groundwater resources than the linear fluvial palaeovalleys that typify other regions, such as those in the Murchison and Paterson.

- **Wilkinkarra, NT:** This study focused on palaeovalleys at Kintore and Nyirripi, and the Central Mount Wedge Basin. Reconnaissance ground geophysics and drilling helped define the shape, structure and sediment infill of the fluvial palaeovalleys. A small-scale seismic reflection survey provided detailed information on the stratigraphy of the Central Mount Wedge Basin, and was used to site a ~470 m deep drill hole to basement. Analysis of hydrochemistry data provided greater understanding of palaeovalley groundwater compositions and aquifer residence times. The groundwater resources of the Central Mount Wedge Basin may be used in the future to supply water to remote communities.

Synthesis

The data, results and key findings of the demonstration studies are documented in detailed reports (section 1.6) and have helped develop the *Palaeovalley Investigative Toolbox* (Gow et al., 2012). The toolbox describes the many techniques that may be used to detect, map, investigate and analyse palaeovalleys, and their sediments and groundwater. Hydrochemical characterisation of groundwater from each demonstration site has shown some broad-scale similarities and confirmed that evapotranspiration predominantly affects most arid-zone palaeovalley aquifers. This process concentrates dissolved ions in groundwater and causes the brackish to saline compositions common in many shallow aquifers. The demonstration studies have also revealed that most palaeovalleys contain substantial volumes of groundwater and that the quality of this water is highly variable (within and between systems), from fresh to hypersaline. Significantly, analysis of groundwater residence times has shown many palaeovalleys contain a variable mix of ‘fossil’ groundwater (palaeowater) and groundwater derived from more modern recharge.

The integrated geographic information system (GIS) and field investigations for the *Palaeovalley Groundwater Project* have helped to develop the WASANT Palaeovalley Map covering much of arid and semi-arid Australia (Chapter 3). These studies have shown that there is considerable variability in the structure, sedimentary infill and hydrostratigraphy of palaeovalleys. Consequently, detailed aquifer characterisation studies are needed to ensure future palaeovalley groundwater extractions are sustainably managed. Long-term monitoring of groundwater levels and quality in palaeovalley systems is also important, and should be well planned and implemented prior to development.

1. Introduction

Palaeovalley groundwater systems are widely used, providing an important water resource in many regions of arid and semi-arid Australia. This is particularly the case in outback areas of Western Australia (WA), South Australia (SA) and the Northern Territory (NT). Most of these regions lack the large permanent surface-water and groundwater resources that characterise the Great Artesian Basin and the Murray-Darling Basin of eastern Australia. Extensive palaeovalley networks, largely buried beneath Quaternary sand and other regolith cover, supply water to pastoralists, mine sites, tourist centres and remote communities across Australia's vast interior. These diverse groundwater users range from horticultural enterprises in the central Australian Ti Tree Basin, through numerous remote Aboriginal communities, to the major ore-processing operations in the Goldfields region of Western Australia. The widespread distribution of palaeovalley groundwater users makes these aquifer systems vital to the economic, social and environmental well-being of regional Australia. A far greater understanding of these distinctive groundwater resources is required for their ongoing sustainable use and long-term management.

The complex pattern of palaeovalley aquifers across arid and semi-arid Australia is largely the result of different geologic and climatic conditions that have affected the continent during the Cenozoic Era (the past 65.5 million years)[1] as Australia was drifting northwards away from Antarctica after the break-up of the Gondwana supercontinent. Palaeogeographic reconstructions of Australia indicate how the landmass has evolved throughout the Cenozoic (e.g. Langford et al., 1995) and show major river systems forming an inter-connected network across large tracts of the now perennially dry landscape (Figure 1). Temperate climates characterised by higher rainfall patterns and lower rates of evaporation during the Cenozoic sustained extensive fluvial environments across the interior cratons and sedimentary basins of Australia (Macphail, 2007). Major river valleys accumulated heterogeneous sedimentary deposits in complex stratigraphic sequences, commonly to 150–300 metres (m) thick in many inland drainage basins (Magee, 2009).

An important legacy from the evolution of Australia's ancient inland river systems is the complex network of buried palaeovalley aquifers extant within the present-day landscape. Although reliable integrated surface-water systems no longer flow within arid-zone palaeovalleys, the subsurface alluvial sediments are capable of storing and transmitting significant quantities of groundwater. Of particular interest are the basal channel sediments representing the original river channel (on the valley thalweg), or series of channels. These zones are commonly porous and contain hydraulically conductive gravels and coarse sands that may be good aquifers. Despite the widespread aridity across outback Australia over tens to hundreds of thousands of years, many of these aquifers contain large volumes of fresh to slightly brackish groundwater suitable for domestic and stock consumption, as well as for irrigated agriculture. Saline to hypersaline groundwater is also locally present, associated with salt lakes, and even some of this poorer quality water is being used.

1.1 The need to know more about palaeovalley groundwater

Palaeovalley aquifers and groundwater systems are little understood despite their role as major water sources in arid and semi-arid Australia. Although larger palaeovalleys have been

1 A copy of the International Stratigraphic Chart is reproduced in Appendix 1 to outline the temporal distribution of geological periods mentioned in this report.

mapped locally (nominally at up to 1:250 000 scale) and also at state and territory scale[2], there has not been a coordinated or comprehensive national evaluation of palaeovalley aquifers and their hydrogeologic significance. There is also scant documentation on preferred methodologies for mapping and delineating Australia's palaeovalleys, especially for detecting those obscured beneath widespread dune fields, or for conducting groundwater assessments.

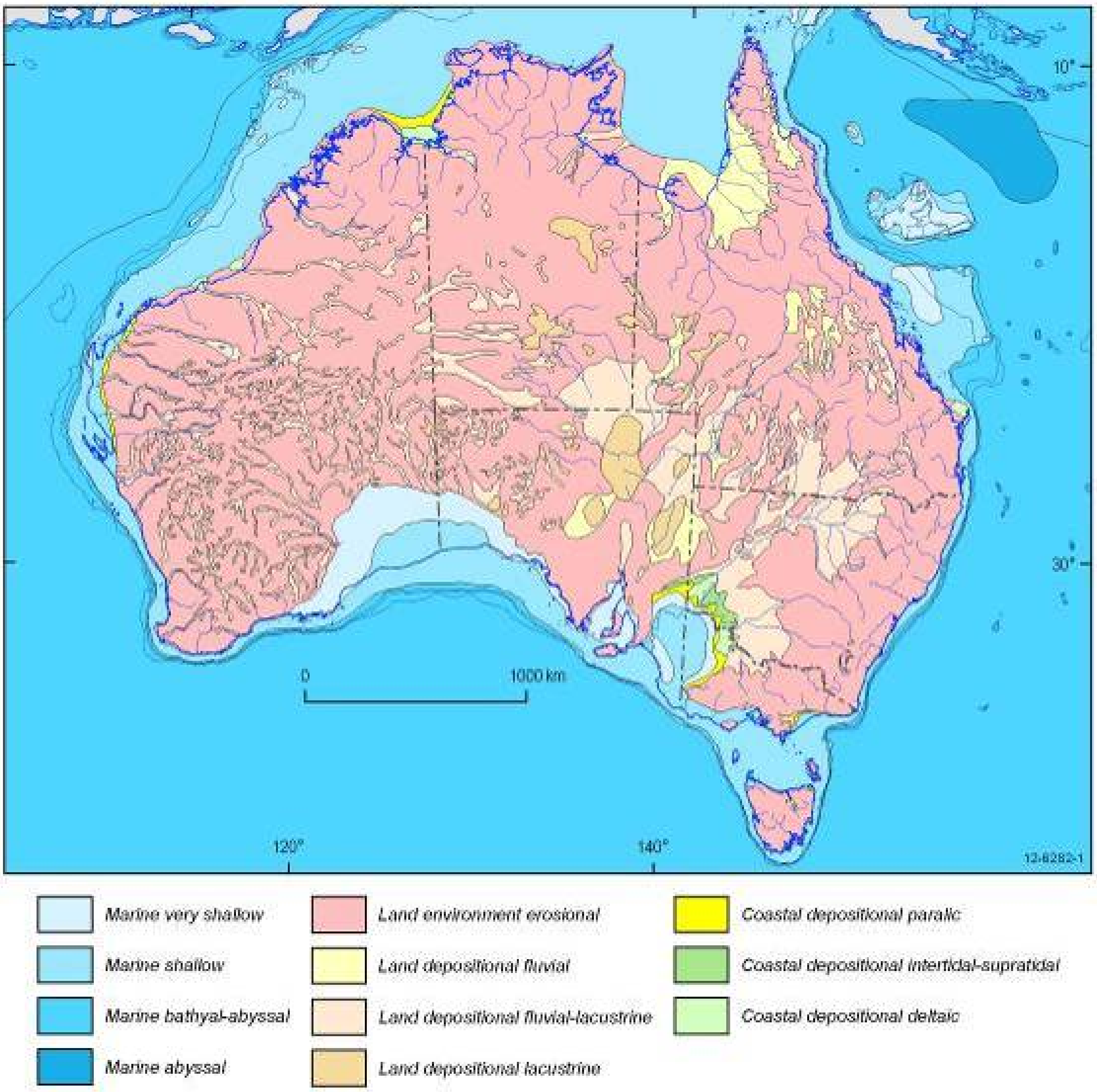

Figure 1: Reconstruction of Cenozoic palaeogeography of Australia approximately 20 million years ago during the Early Miocene (modified from Langford et al., 1995). Modern perennial to ephemeral rivers are shown by thin blue lines.

Further major developments and water resource demands are projected at many arid sites across Australia. These will mainly be focused on new resource discoveries and mining operations and could include the ongoing expansion of iron ore mining in Western Australia and new uranium mining in central Australia and South Australia. Consequently, an imperative exists for more comprehensive and up-to-date information on the nature of palaeovalley aquifers. This knowledge will assist in the exploration and assessment of these vital arid-zone groundwater resources.

2 Nominally at 1:2 or 1:2.5 million scale; e.g. Commander, 1989 for Western Australia; Hou et al., 2007 for South Australia; and Tickell, 2008 for the Northern Territory

A review of current groundwater use and projected future trends clearly indicates the importance of palaeovalley groundwater resources in Western Australia, South Australia and the Northern Territory. This study assesses present-day groundwater extraction rates across these states and territory to be in the order of 250 to 300 gigalitres (GL) per year. Typical of palaeovalley systems, groundwater resources currently being extracted vary widely in quality, from potable for town or community supplies through to hypersaline for processing gold-bearing ores. A brief review of the main Western Australia, South Australia and Northern Territory palaeovalley groundwater users follows.

1.1.1 Western Australia

Western Australia contains the greatest number of arid-zone palaeovalleys in Australia (Chapter 3) and is also the major user of these groundwater resources nation wide. Most extraction is for the mining industry, particularly in the Goldfields of the eastern Yilgarn Craton where the Roe, Rebecca, Carey and Raeside palaeovalleys contain significant aquifers (Johnson et al., 1999; Johnson, 2007). Their saline to hypersaline groundwater (see Units or Glossary for salinity definitions used in this report) is used primarily in processing of gold-bearing ores, so they yield most of about 200 GL per year presently being extracted for mining in the Goldfields. Extraction volumes are expected to increase steadily over coming years at 3–5 per cent under moderate development scenarios (Resource Economics Unit, 2008a).

In the Pilbara region, palaeovalleys contain both the iron ore bodies and the groundwater resources for mining of the Hamersley Province. The palaeovalleys contain iron-rich sediments eroded from the adjacent banded iron formation (BIF) bedrock exposures and deposited as thick alluvial sequences (during earlier geologic times) to form widespread channel iron deposits (CID) and detrital iron deposits (DID). Although extensive groundwater extraction is needed for the safe and effective mining of iron ore, it also provides the water supplies for mine operations, infrastructure and towns.

Palaeovalley groundwater systems are important sources of water in other areas, including the Paterson, Murchison, Gascoyne and Greenough regions where they supply diverse mining operations, small towns, communities or pastoral stations. Palaeovalleys could potentially provide water supplies for future platinum group element (PGE) and nickel laterite mining in the Musgrave Province, as well as planned uranium mining in the Paterson and Yilgarn regions. An extensive region of intricate palaeovalley networks in the south-western Yilgarn shares the modern landscape of the Western Australian Wheatbelt with its secondary salination of waterways and wide-ranging agricultural management issues. About 250 GL per year of groundwater is sourced from palaeovalley systems across Western Australia for consumptive use. Sources include near-surface calcrete aquifers, basal thalweg deposits, and induced lateral or vertical inflow from hydraulically connected aquifer systems such as weathered or fractured bedrocks during or after pumping from palaeovalley aquifers.

1.1.2 South Australia

Current annual groundwater extraction from palaeovalley aquifers in South Australia is conservatively estimated at 13.5 GL, with this figure projected to rise significantly over the coming 5–10 years (>20 GL by 2020; Aurecon, 2010). The mining industry is the main user of palaeovalley groundwater resources, with most extractions occurring in the Gawler Craton – Eucla Basin, and the Frome Embayment. Major mines reliant on palaeovalleys include the Jacinth-Ambrosia mineral sands deposit in the eastern Eucla Basin (Parsons Brinckerhoff, 2007), the Challenger Gold Mine in the western Gawler Craton (REM, 2002) and the Cairn Hill Magnetite-Copper-Gold Mine (IMX, 2008) also in the Gawler Craton. In addition to supplying groundwater, palaeovalleys in the Frome region of eastern South Australia host uranium deposits such as at the Beverley and Honeymoon Mines. Minor groundwater users include some small Aboriginal communities in the Anangu Pitjantjatjara Yankunytjatjara (APY) Lands of north-western South Australia and Maralinga Lands in the west of the state, various pastoral enterprises, and several small towns, such as Kingoonya. Most of these resources are in non-prescribed groundwater areas so there is very poor documentation of annual groundwater extraction, estimated in the order of 500–700 megalitres (ML).

1.1.3 Northern Territory

Preliminary analysis indicates about 50 palaeovalley systems in the arid and semi-arid parts of the Northern Territory (Appendix 2). Included are several basin-like palaeovalleys (or lake-basin palaeodrainage systems), common within the ranges of the central Australian uplands. The main users of palaeovalley groundwater resources are horticultural enterprises and communities of the central Australian Ti Tree Basin, which annually extract ~2500 ML of potable groundwater to irrigate crops such as table grapes. Significant volumes of saline palaeovalley groundwater are also used by gold mining operations in the Tanami region, with extraction volumes of roughly similar magnitude to Ti Tree Basin. Alice Springs[3] and Tennant Creek have a combined annual extraction of ~2250 ML from palaeovalleys, whereas Yulara tourist resort, servicing visitors to Uluru–Kata Tjuta National Park, annually extracts >750 ML of groundwater from the Dune Plains Palaeovalley (English, 1998). Aboriginal communities scattered across remote central Australia[4] are another main user of palaeovalley groundwater. Numerous bores on Northern Territory pastoral leases pump variable quality groundwater for cattle.

1.2 The Palaeovalley Groundwater Project: background and overview

This report summarises the main activities, findings, achievements and recommendations of the Raising National Water Standards project: ‘Water for Australia’s arid zone – identifying and assessing Australia’s palaeovalley groundwater resources’ (*Palaeovalley Groundwater Project*), undertaken over a four-year period from 2008 to 2012.

The National Water Initiative recognises that there are many important issues that require significant action to improve the understanding and management of Australia’s groundwater resources (http://www.nwc.gov.au/reform/nwi). A key objective of the *Palaeovalley Groundwater Project* was to provide improved understanding for a widespread and important ensemble of aquifers that support significant population centres; mining, agricultural and tourist developments; and various natural ecosystems in arid Australia, but which remain poorly understood across most of the region.

Arid Australia is about 48 per cent of the continent, with a further 31 per cent semi-arid, based on the Köppen-Geiger climate classification scheme[5]. The jurisdictions with the greatest proportion of arid environments – Western Australia, South Australia and the Northern Territory (Figure 2) – were the exclusive focus of activities for the *Palaeovalley Groundwater Project*. Although significant parts of Queensland and New South Wales also have arid or semi-arid climates, the present project deliberately concentrated on central and western parts of Australia because of the strong regional reliance on palaeovalley groundwater resources. Major groundwater resources are commonly more accessible in eastern Australia, including the Great Artesian Basin and the Murray-Darling Basin, where there has generally been

3 Most of Alice Springs’ potable water is supplied from the Devonian Mereenie Sandstone in the Amadeus Basin. Around 750 ML per annum of non-potable groundwater is extracted from the Alice Springs Town Basin aquifer, a Cenozoic palaeovalley recharged from the Todd River.
4 In the context of this project, central Australia is defined as that part of the Northern Territory south of latitude 19°.
5 http://www.bom.gov.au/climate/environ/other/koppen_explain.shtml

substantial hydrogeology work through recent decades and less reliance on palaeovalley aquifers. Notwithstanding, many of the key project findings are equally relevant to arid or semi-arid parts of eastern Australia, and some to other arid zones of the world such as parts of Saharan or southern Africa, and South America.

Geoscience Australia was the lead investigator and manager of the *Palaeovalley Groundwater Project*. Significant project support was provided by the Western Australian, South Australian and Northern Territory governments' water resource departments and geological surveys. Each government agency contributed expert geoscientific and hydrologic staff to the Technical Advisory Group and Project Steering Committee. Additionally, several mining and exploration companies (e.g. Toro Energy Limited, NuPower Resources, Uramet Minerals Limited, Aditya Birla Minerals, Newcrest Mining Limited and Cameco Australia), and various hydrogeological consultants associated with these companies, provided considerable support by allowing the project team to access geologic and hydrogeologic data relevant to palaeovalleys and the broader objectives of the project. Carriage of the work program was the responsibility of Geoscience Australia's Groundwater Group, Environmental Geoscience Division, with in-kind support provided by colleagues in the Minerals and Natural Hazards Division, especially for the acquisition, processing and interpretation of geophysical datasets.

1.3 Study locations

A comprehensive investigation program, comprising integrated office and field-based activities, addressed fundamental gaps in our national understanding of palaeovalley systems to achieve the goals of the *Palaeovalley Groundwater Project*. Site-based work programs are outlined in a series of separate demonstration study reports that underpin this summary document. These site reports are published and freely available as Geoscience Australia Records (Table 1).

Demonstration site locations in Western Australia, South Australia and the Northern Territory were selected following consultation with the project Technical Advisory Group. This focused research investigations on six main sites (Figure 2):

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

In addition, preliminary analysis of remote-sensing data was undertaken for the Tanami region of the Northern Territory and Western Australia. Key criteria in selecting the demonstration sites included:

- the presence of major palaeovalley systems, either visible in the present-day landscape or inferred to exist beneath dune cover
- the reliance on palaeovalley groundwater resources in these regions
- the overall requirement (as articulated by Technical Advisory Group representatives) to increase understanding of the most significant characteristics of palaeovalley aquifers, such as their hydrostratigraphy, spatial extent and structure, and groundwater chemistry, residence time and major hydrogeologic processes.

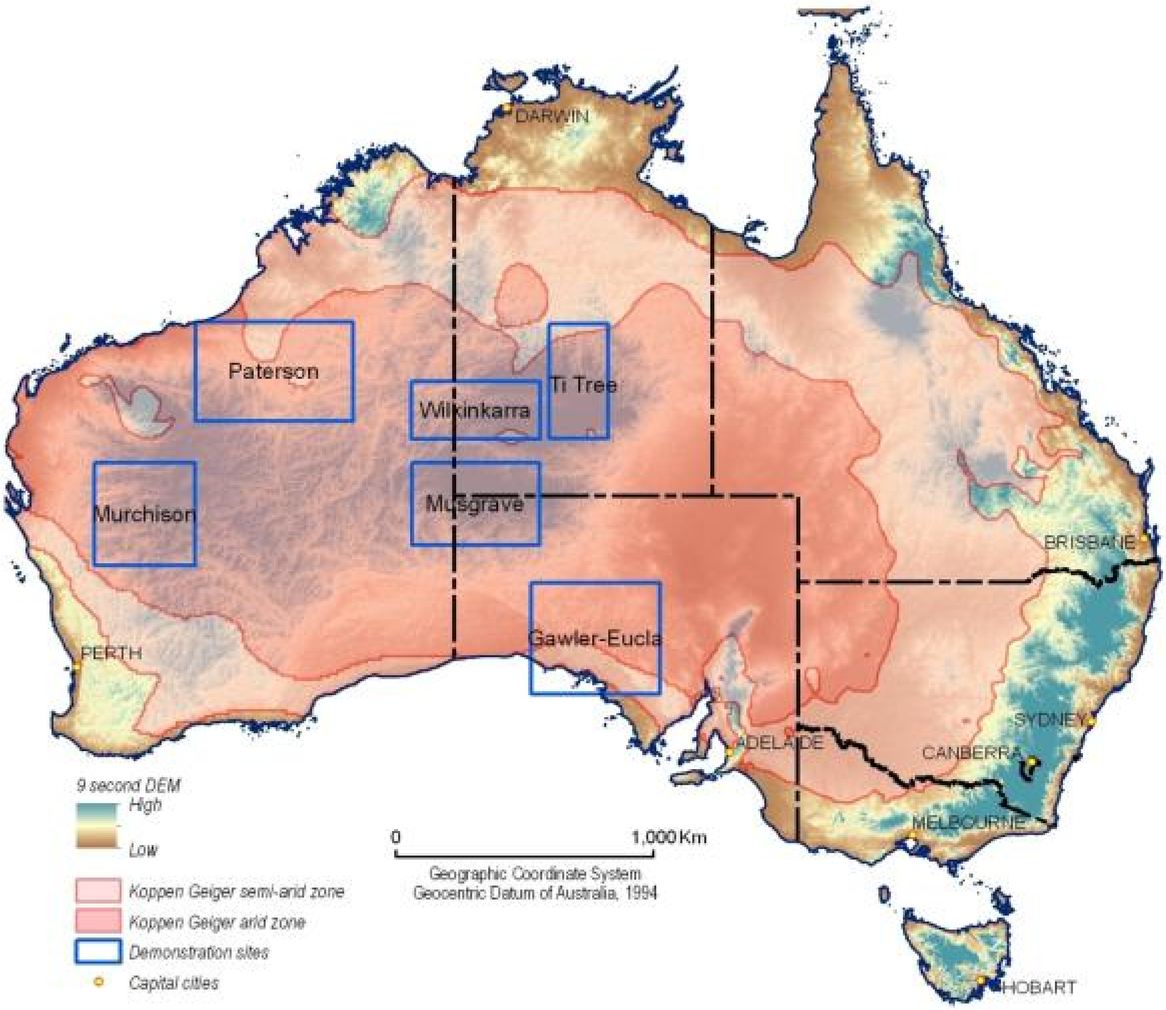

Figure 2: Regional demonstration sites for the *Palaeovalley Groundwater Project*.

This rationale and specific objectives aimed to provide a regional context for understanding palaeovalleys not only to support sustainable use of groundwater resources therein, but also to contribute to knowledge about palaeovalleys as significant near-surface geologic entities in Australia's arid environment.

The geoscientific and hydrologic information and knowledge of the demonstration sites prior to the *Palaeovalley Groundwater Project*, ranged from the relatively well-studied (though still enigmatic) Ti Tree Basin, through to the 'greenfield' Murchison Province and Wilkinkarra with scant information about regional palaeovalleys. Given the large size of each study area, up to several thousands of square kilometres, and the reconnaissance nature of the investigations, this project did not focus on generating actual limits (volumes) or specific management rules for sustainable extraction of groundwater from individual palaeovalley aquifers. Instead, the project sought to improve the overall understanding of palaeovalley aquifers, in order to assist individual jurisdictions to better plan and manage the ongoing extraction of groundwater resources across these regions and within Australia overall.

Investigative methods were diverse at the five (excluding Musgrave) field-based demonstration sites so as to address specific research questions identified from initial reviews of available information, remote-sensing studies, and consultation with local experts. The field investigation program included a range of standard hydrogeologic methods such as geophysical techniques, ground-based reconnaissance and mapping, water-bore drilling, and sediment and groundwater sampling. Some more innovative methods were trialled as part of the multi-disciplinary approach, including application of regional airborne electromagnetic (AEM) data (where available) and various satellite-borne remote-sensing platforms, for example Landsat, MODIS and NOAA-AVHRR. The knowledge gained has enabled characterisation of respective palaeovalleys and assisted in developing conceptual hydrogeologic models of different palaeovalley types in the arid zone, so providing an understanding of important considerations and constraints for managing groundwater resources. Further, this improved understanding of buried palaeovalley aquifers has helped the development of an updated compendium of user-friendly methods and criteria to locate potable (low salinity) groundwater resources in arid Australia, published as the *Palaeovalley Investigative Toolbox* (Gow et al., 2012).

1.4 Project 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 reach 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 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
- 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 the production of a Palaeovalley Thematic Map of the arid and semi-arid zones of WA, SA and NT, and an accompanying geographic information system (GIS) package of national-scale geologic and interpretative data layers and compilation of attribute tables for the 200 major palaeovalleys.

1.5 This summary report: focus and format

The knowledge gained from detailed site-based investigations has been assessed by the *Palaeovalley Groundwater Project* team and used to develop an improved understanding of significant features of, and processes associated with, palaeovalley groundwater systems. The aim of this report then is to summarise the main outcomes and findings that have resulted from the multi-disciplinary work program. This report synthesises the most significant information generated from the breadth of project activities, and outlines the key regional- and national-scale scientific advances. For specific details of actual work programs, data and interpretations from field-based investigative studies, refer to the relevant Geoscience

Australia Record (Table 1). A general overview of palaeovalley groundwater systems across arid and semi-arid Australia is provided by Magee (2009).

The four main parts of this report follow this introductory chapter, with each focusing on a key component of the project to:

- provide a brief overview of the work programs and key research outcomes arising from investigations at the field demonstration sites (Chapter 2)
- outline the process involved in developing the new thematic palaeovalley map of arid and semi-arid WA–SA–NT (referred to herein as WASANT), and the recommended use and application of this new Geoscience Australia map (Chapter 3)
- discuss key areas in which overall understanding and knowledge of arid-zone palaeovalley systems and their groundwater resources have been improved by virtue of knowledge generated from this project (Chapter 4)
- provide a summary of the key project outcomes, recommendations and lessons learnt from the multi-disciplinary investigative approach (Chapter 5).

1.6 Related outputs from the Palaeovalley Groundwater Project

This summation provides information that builds upon other key project outputs (Table 1). Significant products include a compendium of previously unavailable information on arid-zone aquifers across each demonstration site, along with consensus on appropriate methodologies for delineating palaeovalleys and some fundamental considerations for managing groundwater resources at the regional, state/territory and national scale. Each of the five demonstration site reports is accompanied by digital datasets including spatial geodatabases in ArcGIS format to allow further application, analysis, interpretation and plotting of specific data discussed in each report. Access to these publications is available from Geoscience Australia's website: http://www.ga.gov.au/cedda/publications/96.

1.7 Palaeovalley definitions and terminology

Inconsistent use of terms relevant to palaeovalleys and their groundwater systems, both within the published scientific literature and in technical discussions with colleagues, has been identified. Thus, the following nomenclature and definitions of Magee (2009) have been adopted for the *Palaeovalley Groundwater Project* and their application is recommended to avoid future confusion:

- **Palaeovalley** refers to the valley landforms that were incised by ancient fluvial systems, or 'palaeorivers' (Figure 3). Their dimensions may be from less than a kilometre to many kilometres in width, up to or over 100 m deep and hundreds of kilometres long. Given that many palaeovalley systems formed when Australia was part of the Gondwana supercontinent and evolved over tens or hundreds of millions of years under highly variable climatic regimes, their dimensions cannot be predicted intuitively. Commonly, trunk palaeovalleys are now almost completely infilled with sediments and are beneath relatively flat plains or obscured by sand dunes, but may contain chains of salt lakes. Palaeovalleys may also be substantially filled with lacustrine or swamp sediments, additional to fluvial sediments (alluvium). Accordingly, the distribution of coarse- to fine-grained sediments infilling a palaeovalley, and depositional settings and evolutionary processes, may be very difficult to predict from the landscape surface.

- **Palaeochannel** refers to the main channel of ancient rivers, formed by higher velocity river flows, sometimes termed the 'thalweg' meaning the lowest point of incision along the river bed. Coarser sediments (gravels and coarse-grained sands) are commonly deposited in the palaeochannels whereas finer grained sediments (silts and clays) are deposited in non-channel settings, including overbank or floodplain environments. Palaeochannels in a given river migrate in the landscape through time such that present-day channels of a given river may not vertically overlie the palaeochannel(s) or the succession of 'palaeochannel deposits'.

The terms *'palaeodrainages'* for networks of palaeorivers, and '*palaeo-tributaries'* for tributary systems that flow into palaeorivers and palaeovalleys, are also used, where appropriate.

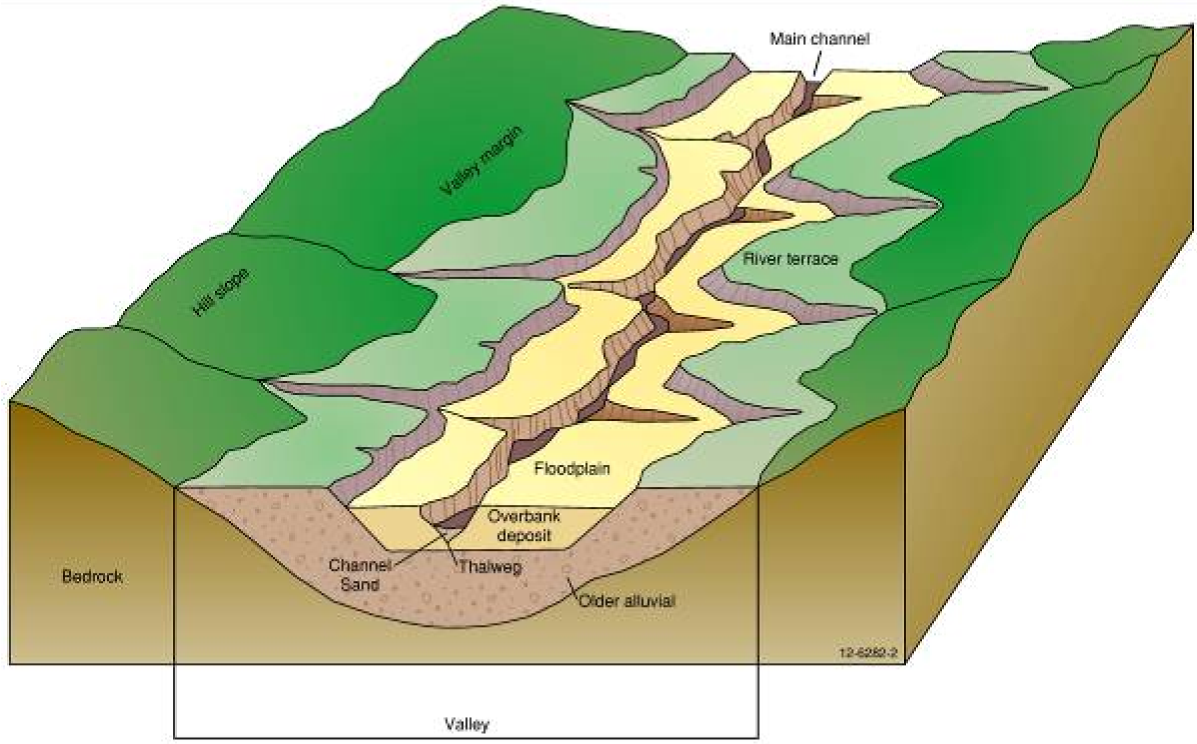

Figure 3: Block diagram illustrating valley and channel landform terms used in the *Palaeovalley Groundwater Project* (modified from Magee, 2009).

Although most palaeovalleys were formed by rivers, some may be of glacial origin, as are those described for the Paterson demonstration site in Western Australia (English et al., 2012b), or tectonic in origin, as are the Cenozoic basin and range drainage systems in central Australia (English, 2002; Woodgate et al., 2012; Wischusen et al., 2012). Some palaeovalleys, though not in the demonstration sites for the *Palaeovalley Groundwater Project*, have been partly or wholly infilled with volcanic rocks.

Table 1: Publications from the *Palaeovalley Groundwater Project*.

Publication	*Authors*	*Type and reference*
Palaeovalley Groundwater Resources in Arid and Semi-arid Australia – A Literature Review	JW Magee	Geoscience Australia Record 2009/03
Gawler-Eucla Demonstration Site Report – Palaeovalley Groundwater Project	SJ Lewis, AL Hanna, PL Kilgour, EN Bastrakov, JDH Wischusen & M von Behrens	Geoscience Australia Record 2012/05 (Geocat #73669)
Murchison Demonstration Site Report – Palaeovalley Groundwater Project	PM English, SL Johnson, EN Bastrakov, MK Macphail, PL Kilgour & M von Behrens	Geoscience Australia Record 2012/06 (Geocat #73670)
Paterson Demonstration Site Report for the Palaeovalley Groundwater Project	PM English, EN Bastrakov, JG Bell, M Woltmann, PL Kilgour & G Stewart	Geoscience Australia Record 2012/07 (Geocat #73671)
Ti Tree Demonstration Site Report for the Palaeovalley Groundwater Project	JDH Wischusen, EN Bastrakov, JW Magee, LJ Gow & PL Kilgour	Geoscience Australia Record 2012/08 (Geocat #73672)
Wilkinkarra Demonstration Site Report for the Palaeovalley Groundwater Project	MF Woodgate, J Holzschuh, JDH Wischusen, LJ Gow & PL Kilgour	Geoscience Australia Record 2012/09 (Geocat #73673)
The Palaeovalley Investigative Toolbox – Exploring and Assessing Palaeovalley Groundwater Resources in Arid Australia	LJ Gow, S Hostetler, PM English, JDH Wischusen, MF Woodgate, SJ Lewis, PL Kilgour, JG Bell, J Holzschuh, MK Macphail & AL Hanna	Geoscience Australia Record 2012/10 (Geocat #73674)
Thematic Map – Distribution of Palaeovalleys in Arid and Semi-arid WA–SA–NT (2012, Version 1)	JG Bell, PL Kilgour, PM English, MF Woodgate, SJ Lewis & JDH Wischusen	Geoscience Australia Thematic Map (Geocat #73980) – hard-copy and digital data publication

Note: The five demonstration site reports are each accompanied by a GIS geodatabase (digital format).

2. Demonstration site investigations

Fieldwork programs for the *Palaeovalley Groundwater Project* comprised multi-component investigations in five demonstration sites widely spread across arid Australia, these being Gawler-Eucla, Murchison, Paterson, Ti Tree and Wilkinkarra (Figure 2). The specific approach, datasets, interpretations and key outcomes of these investigations are described in a series of five reports published as Geoscience Australia Records (Table 1). This chapter provides a brief overview of these investigations to highlight significant findings from each site, and as context for the research approaches and outcomes relevant to the overall project.

Project activities across the arid zones of Western Australia, South Australia and the Northern Territory have mainly been directed towards:

- characterising representative, distinctive and/or broad-scale palaeovalley systems
- assessing methodologies that effectively detect and enable mapping of these aquifer systems at regional- to local-scales
- supporting groundwater resource investigations needed in the immediate or near future, e.g. for current or future mining operations or community water supplies.

The detailed evaluation of different study approaches and combinations of techniques in contrasting geographic, geologic and climatic regions has helped develop criteria for locating potable to hypersaline groundwater resources in Australian palaeovalley systems.

2.1 Gawler-Eucla

In South Australia, field operations focused on the geologic provinces of the western Gawler Craton and the eastern Eucla Basin (Figure 4). The Gawler-Eucla demonstration site covers an arid and sparsely populated area of ~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 obscure the Archean to Proterozoic bedrock. Despite the harsh and isolated environment this region has excellent potential for future mineral resource discoveries, with existing major mines (e.g. 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. On this basis the Gawler-Eucla region was designated as the primary study site in South Australia.

The Geological Survey of South Australia (GSSA) had conducted previous investigations (Hou, 2004, Hou et al., 2001, Hou et al., 2007) delineating major Cenozoic palaeovalley systems within the Gawler-Eucla region, including the Kingoonya, Anthony, Garford and Tallaringa palaeovalleys (Figure 5). Detailed stratigraphic studies based on multiple drilling transects confirmed that these palaeovalleys are predominantly infilled with fluvial sediments (gravels, sands, silts and clays) in the upper and middle reaches. Estuarine and shallow marine sediments are common in the lower palaeovalley reaches near the palaeoshoreline 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.

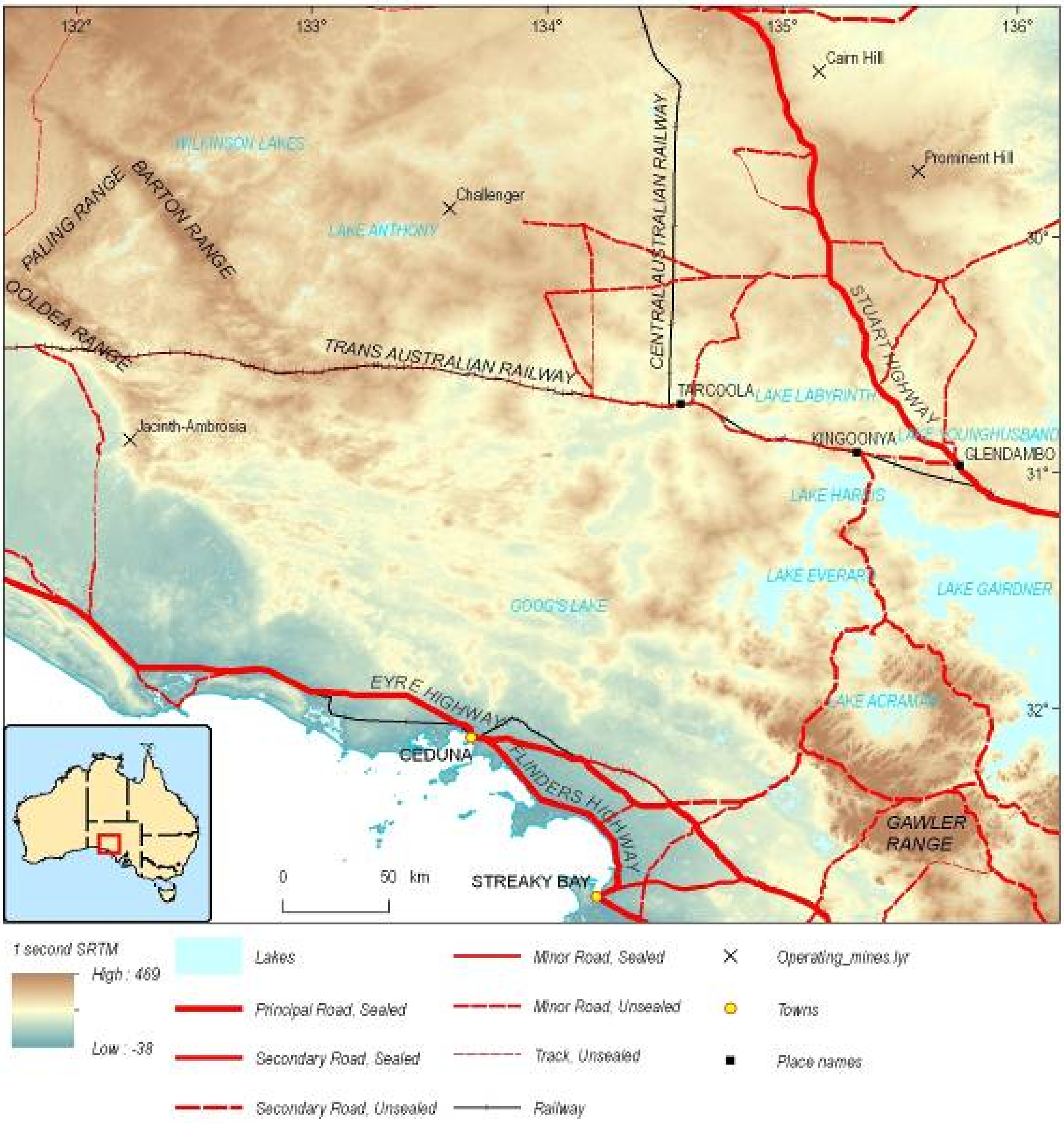

Figure 4: Gawler-Eucla demonstration site for the *Palaeovalley Groundwater Project.* The shaded background image depicts topographic variations of the land surface from the 1-arc second DEM derived from the SRTM dataset.

The Geological Survey of South Australia 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 (Figure 6), 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.

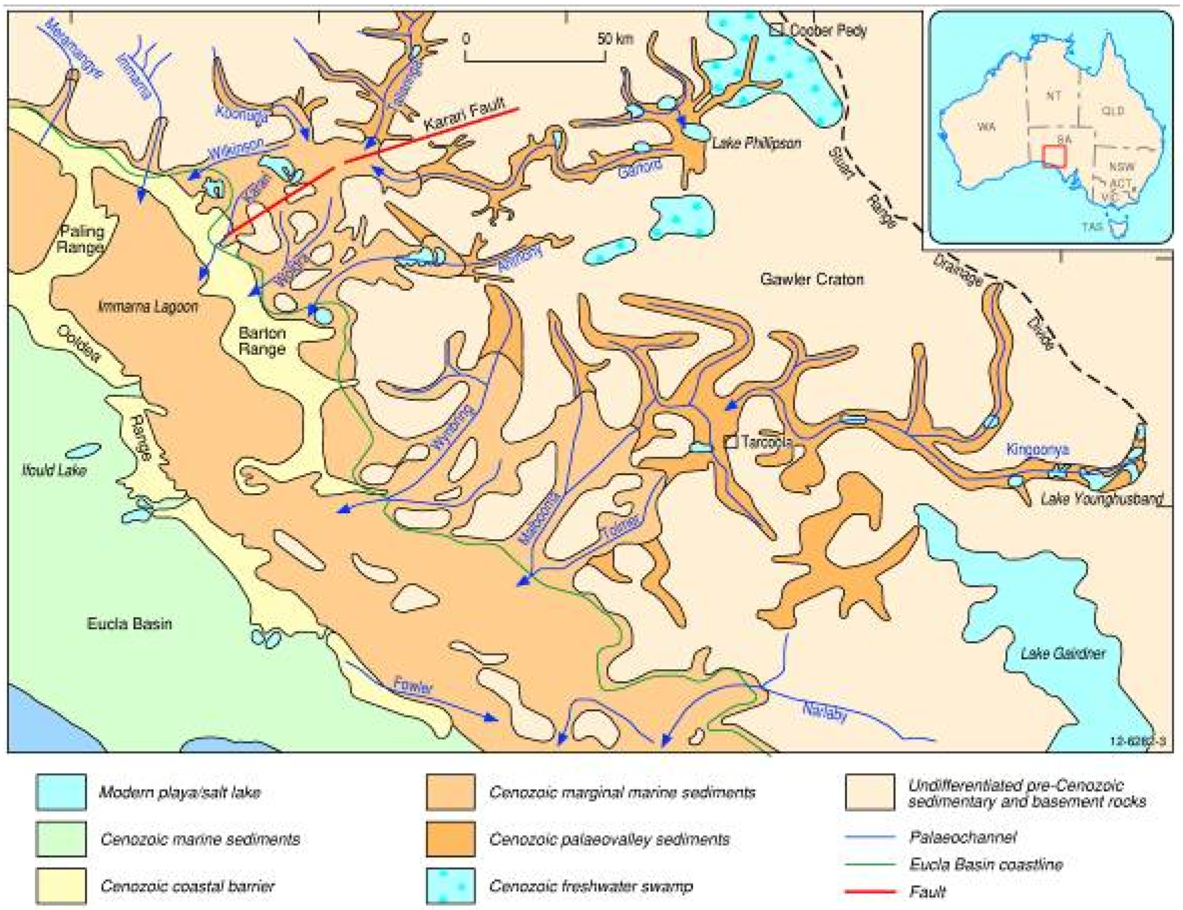

Figure 5: Palaeogeographic reconstruction of major palaeovalleys in the Gawler-Eucla region during the Eocene (modified after Hou et al., 2001).

2.1.1 Research objectives

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

- characterise the hydrogeochemical composition of groundwater in the Kingoonya Palaeovalley, including standard physical and chemical parameters such as pH, E_h and temperature, major and minor (trace) ionic species, stable isotopes (oxygen and deuterium) and radiogenic isotopes (carbon-14 and radon-222)
- 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
- determine the dominant physical and chemical processes that affect the groundwater system in the palaeovalley, including the likely source of dissolved ions
- compare new analyses with information available from the major palaeovalley groundwater users – the Challenger Gold Mine and Ambrosia-Jacinth Mineral Sands Mine
- 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.

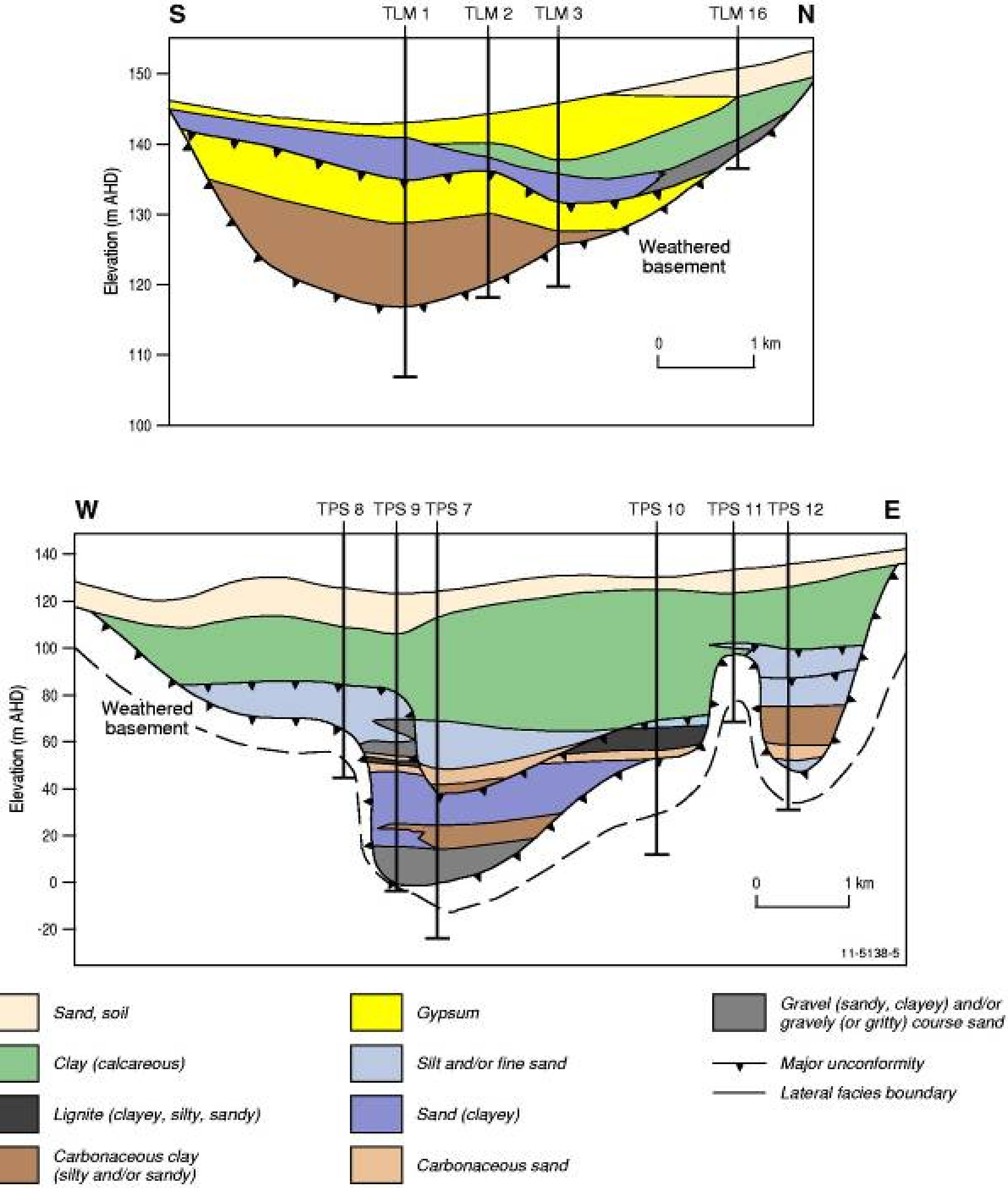

Figure 6: Geological cross-sections for the upper reaches of the Kingoonya Palaeovalley showing the main lithofacies and spatial relationships determined from detailed transect drilling (modified after Hou, 2004).

2.1.2 Field investigation program

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, hydrologic and remotely sensed datasets using 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 Geological Survey of South Australia, who provided pumps and sampling equipment. Difficulties involved in locating or sampling many bores limited the final collection to 27 new groundwater samples. Standard well-established sampling protocols were followed during field operations to collect the groundwater samples (Sundaram et al., 2009).

2.1.3 Hydrogeochemical characterisation

Groundwater from the Kingoonya Palaeovalley aquifer were analysed for ionic (Figure 7) and isotopic compositions at various laboratories, including Geoscience Australia, CSIRO, and the Institute of Geological and Nuclear Sciences (GNS) in New Zealand. Results show:

- 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
- 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
- predominantly oxidising groundwater, although the oxidation state ranges to slightly reducing and anoxic conditions (negative E_h)
- domination by Na as the major cation species, commonly at concentrations Na >(Ca+Mg+K), e.g. Figure 7
- 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
- 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
- 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
- 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 water
- sulfur isotope signatures are typically depleted relative to sea water, suggesting oxidation of reduced inorganic sulfur-bearing species contributes significantly to the overall sulfate load
- moderately to slightly depleted ^{13}C isotope data form a fairly well-constrained group that reflects buffering by dissolution of calcite in the aquifer
- bi-modal radiocarbon distribution indicating some component of ‘very old’ groundwater (>20 000 years old) from the deeper confined palaeovalley thalweg aquifer, and ‘modern’ recharge groundwater
- generally low levels of radon-222.

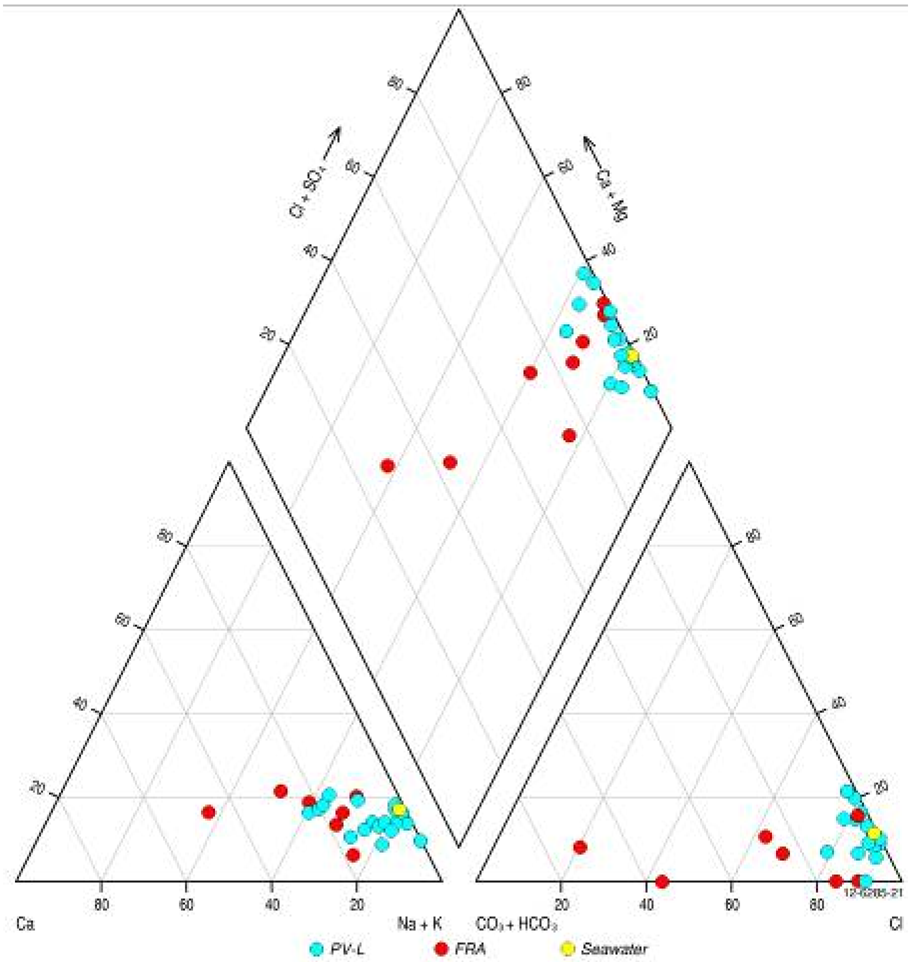

Figure 7: Piper plot of groundwater analyses from the Kingoonya Palaeovalley region. Red symbols distinguish fractured rock aquifers (FRA) from palaeovalley aquifers (blue).

2.1.4 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 (Lewis et al., 2012). 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 hydrogeologic conceptual model that illustrates salient features of the regional groundwater system and explains the dominant hydrogeologic processes (Figure 8).

Key aspects of the Kingoonya Palaeovalley conceptual hydrogeologic model:

- 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. 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.
- 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.

- 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.
- 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.
- 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.
- The groundwater system receives very limited input from direct and diffuse recharge, estimated at <0.5 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.
- Despite low levels of recharge there is clear evidence from radiocarbon dating that modern rainfall does infiltrate 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 (BP). 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.
- The very high salinity levels (commonly greater than sea water) 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.
- 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.
- 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 distributory channels where salt lakes are less common.

- The palaeovalley aquifer is, in places, hydraulically connected to the fractured and weathered bedrock aquifers. The palaeovalley itself was originally incised into the bedrock of the Gawler Craton, with structural features such as major faults playing a significant role in the development of the valley morphology. 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.

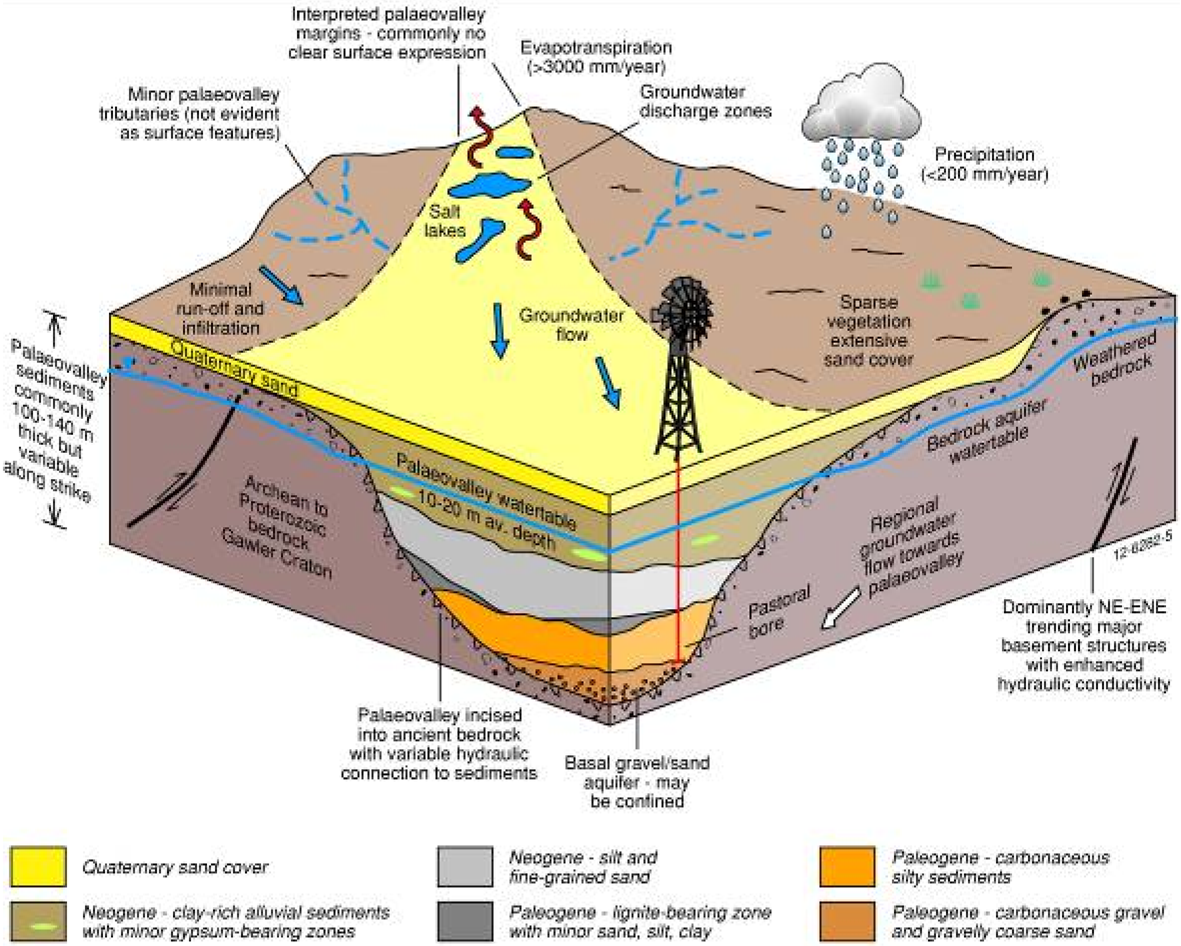

Figure 8: Conceptual model of the Kingoonya Palaeovalley viewed from the west.

The full report on this demonstration site is to be published as:

Lewis SJ, Hanna AL, Kilgour PL, Bastrakov EN, Wischusen JDH and von Behrens M 2012, 'Gawler-Eucla Demonstration Site Report – Palaeovalley Groundwater Project', *Geoscience Australia Record,* 2012/05, Canberra.

2.2 Murchison

Palaeovalley investigations in the Murchison demonstration site (Figure 9) were undertaken at four locations: Beringarra and Mt Padbury (Murchison River), Austin Downs (Sanford River) and Annean (Hope River). This was the first regional investigation of palaeovalleys in the Murchison Province, and the first focused on palaeovalley aquifer systems in the north-western Yilgarn Craton.

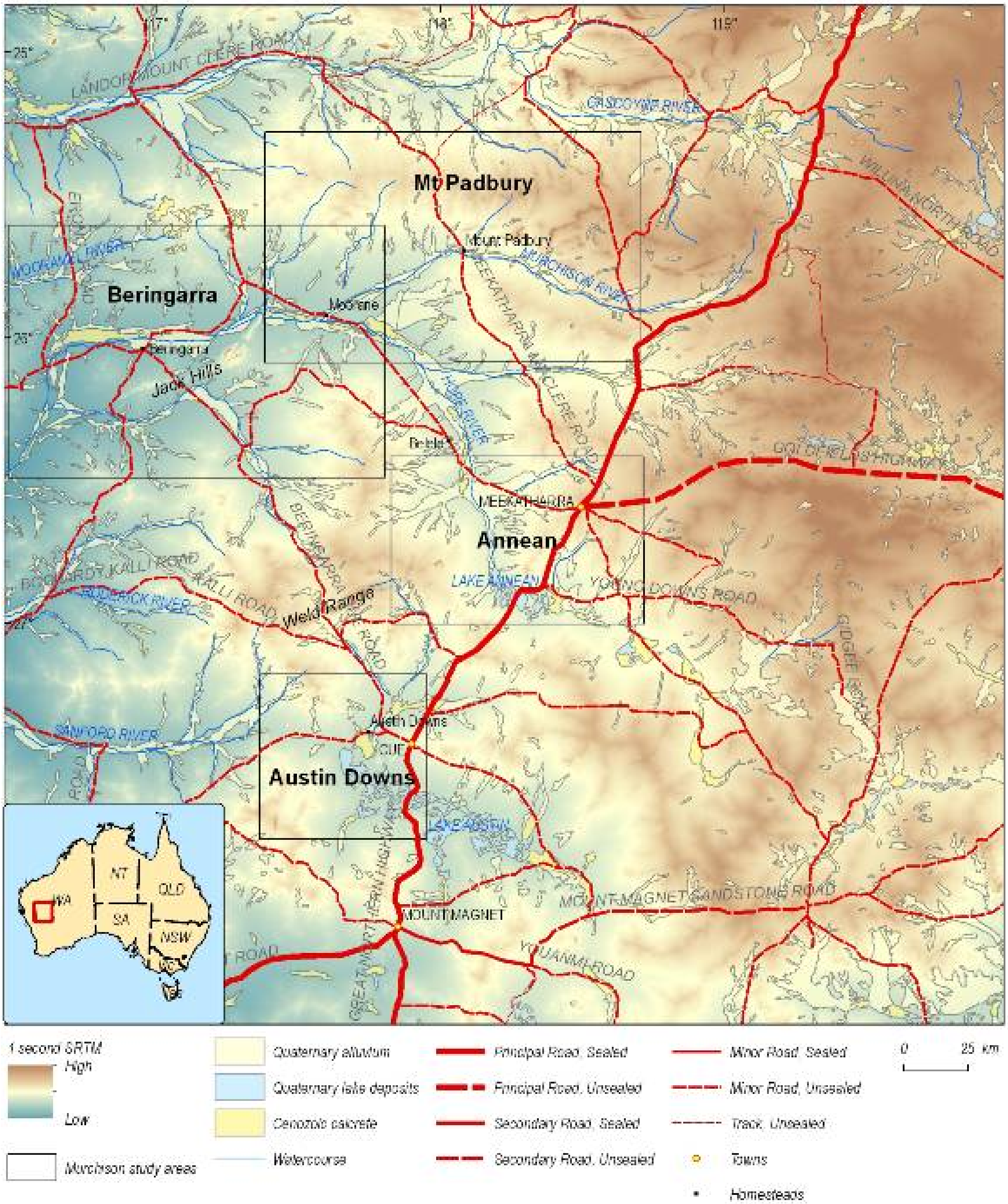

Figure 9: Murchison demonstration site for the *Palaeovalley Groundwater Project*.

The Murchison district depends on palaeovalley aquifers for water supplies to towns, pastoralists and mining operations. Most of the numerous bores (with windmills) are shallow (less than 20 m deep), accessing calcrete or near-surface alluvial aquifers. The first bores sunk to bedrock in the centre of palaeovalleys were for the present study. Scant information previously existed about depths of these palaeovalleys and their sedimentary infill to enable comparison with other Yilgarn palaeovalleys that have been subject to detailed hydrogeologic investigations. An improved understanding of the Murchison palaeovalleys is also a strategic priority for the Western Australian Department of Water, particularly for provision of water resources to expanding iron ore and gold mining operations.

2.2.1 Research program and objectives

The four main methods used to characterise the Murchison palaeovalleys were:

- analysis of digital elevation models (DEM) and their derived products
- ground gravity traverses
- drilling and installation of monitoring bores
- hydrogeochemistry.

Regional geological maps, geophysical (gravity, magnetic and radiometric) datasets and remotely sensed (e.g. Landsat) imagery were also used for the study. The Multi-resolution Valley Bottom Flatness index (MrVBF) (Gallant and Dowling, 2003), derived from high-resolution NASA Shuttle Radar Topography Mission (SRTM) DEM data (Figure 10), clearly depicted the palaeovalley networks in this region and was used to plan the ground geophysical surveys and drilling program.

2.2.2 Field investigation program

To determine the deepest section of each palaeovalley, 55 km of ground gravity surveying (130 stations spaced at 400 or 500 m intervals) were completed. Twelve investigative drill holes (totalling 1195 m) were sunk using mud rotary and reverse circulation techniques. Drilling continued to bedrock (mostly Archean granite–greenstone terrane) wherever possible.

Monitoring bores were installed in the deepest part of each palaeovalley (palaeo-thalweg) at the four study sites. Drill cuttings were logged to determine the stratigraphic and lithologic nature of each hole, and samples collected for water chemistry (including stable and radiogenic isotopes) and palynology (Figure 11 to Figure 14). The four new monitoring bores were surveyed and levelled, and data loggers installed for time-series measurement of standing water levels (SWL) and salinity.

2.2.3 Hydrostratigraphy

In the Murchison region palaeovalleys are incised into Archean bedrock to depths of 150–200 m below surface, compared with average depths of around 120 m in the north-eastern Yilgarn, 60 m in the south-eastern Yilgarn (Eastern Goldfields), 40–50 m in the south-western Yilgarn (Wheatbelt), and river valleys typically less than 50 m deep in the Pilbara-Hamersley coastal region. Geologic structures, possibly including faults and major basement contacts (e.g. Figure 11), appear to have influenced incision of the ancient rivers in the Murchison. Buried inset valleys are represented, suggesting multi-phase fluvial incision. In places, the palaeo-thalweg and present-day main river channels are offset by 2–3 km (Figure 11), suggesting tectonic tilting during the evolution of the palaeovalley systems. The depositional environment across the region is wholly terrestrial and dominantly fluvial, with subordinate lacustrine or swampy settings. The substantial valley incision, up to 200 m deep into crystalline bedrock in a valley less than 5 km wide, suggests high-energy fluvial depositional environments.

The sedimentary infill of the Murchison palaeovalleys is more sand-rich than in other parts of the Yilgarn, and this has significant implications for groundwater storage. Sediments commonly consist of coarse, immature sands indicative of local provenance, and may form alluvial aquifers with high porosity and transmissivity. Clayey sediments, where present, indicate either greenstone belt or weathered regolith provenance. Palynostratigraphic analysis of drill-chip samples indicates the sediments were deposited during the Pliocene to Pleistocene. This contrasts with palaeovalleys in the eastern and southern Yilgarn where

Eocene to Miocene sediments are under Quaternary infill (e.g. Commander et al., 1992). Pre-existing ancient basal sediments in the Murchison palaeovalleys may have been eroded by more dynamic river flow. This would suggest that past river gradients in the Murchison were steeper than the low-gradient, internally draining systems in east and south-east Yilgarn.

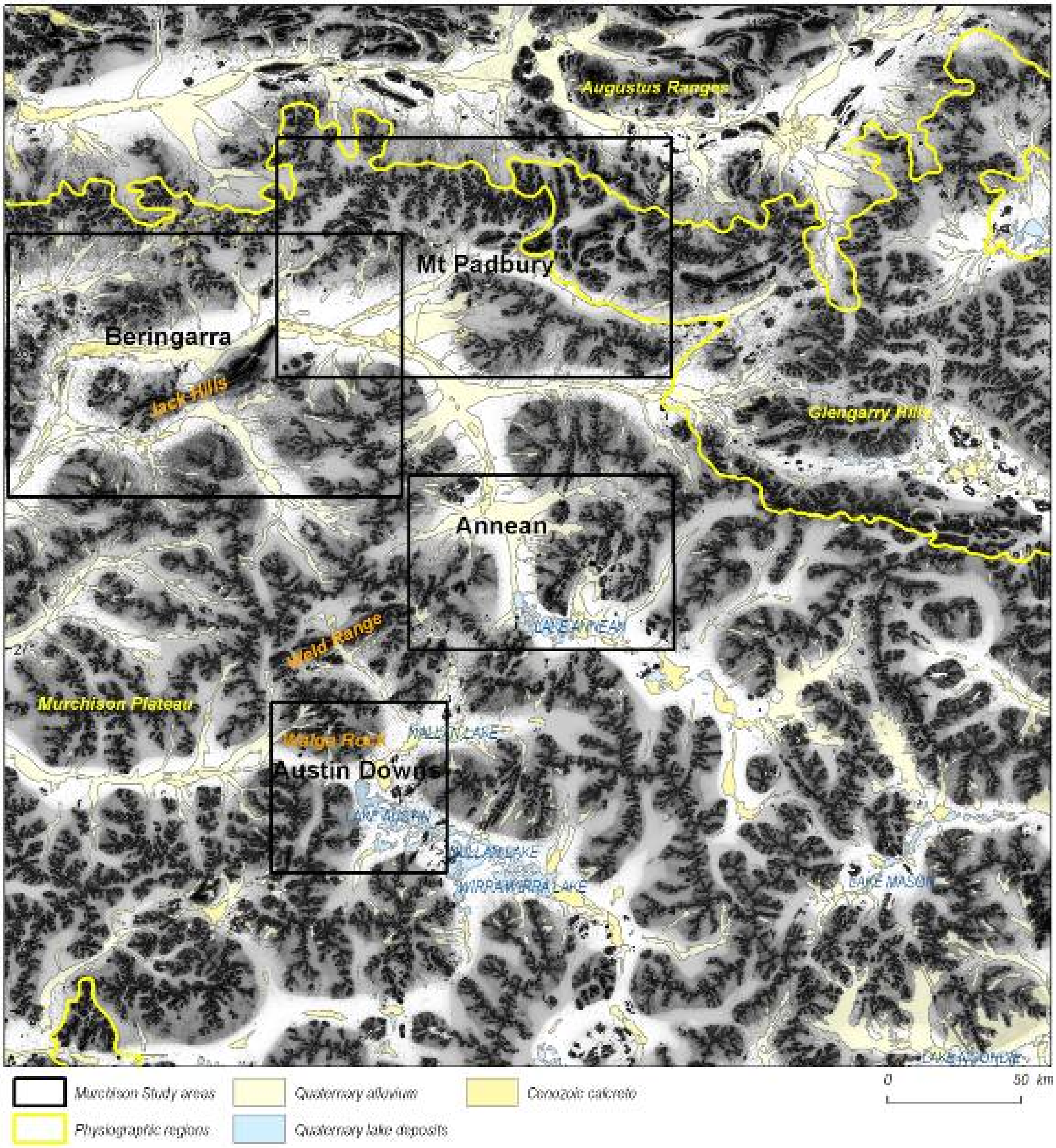

Figure 10: The MrVBF output for the Murchison region based on the 1-arc second SRTM DEM shows low and flat parts of the landscape (valley bottoms) in white and high and steep areas in black to grey. Physiographic regions from Pain et al. (2011).

Calcrete is an integral part of the near-surface stratigraphic profile in the Murchison palaeovalleys (Figure 10), many other parts of the Yilgarn, and further north in inland Western Australia and the Northern Territory. Groundwater resources drawn from calcrete aquifers have been the most heavily used for over 100 years in the Murchison Province. Many 'valley calcrete' bodies are silicified. Opaline silica aquifers are particularly desirable as sources of low-salinity water which can be accessed with relative ease at shallow depths. The degree of connectivity between deep and shallow palaeovalley aquifers has not yet been established and is an important consideration for future groundwater management.

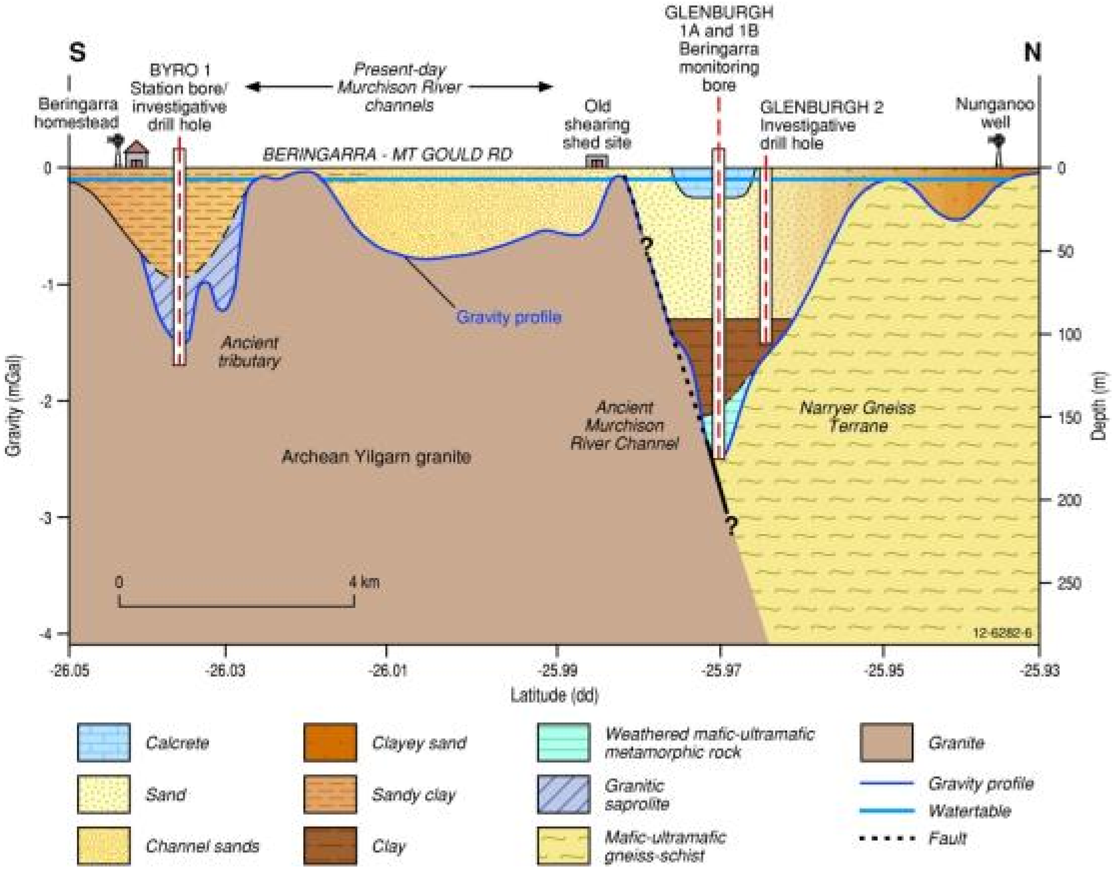

Figure 11: Interpreted Beringarra cross-section based on gravity profile and drilling data.

2.2.4 Hydrogeochemistry

Groundwater salinity in project bores ranges from fresh to highly saline, 650–130 000 milligrams per litre (mg/L) TDS, although is mostly 1100–4600 mg/L. The freshest water is from a shallow silicified calcrete aquifer. Hypersaline groundwater occurs at >100 m depth down-gradient from Lake Annean. In contrast, Lake Austin appears to be hydrologically closed as hypersaline groundwater emanating from beneath the salt lake does not flow down-gradient into the Sanford Palaeovalley. Palaeovalley groundwater in the Murchison is generally less saline than in the southern Yilgarn, possibly related to the rainfall regime and lithology. Widespread ‘stock quality’ water suitable for mining and pastoral activities and some potable supplies are present.

Groundwater compositions are dominated by sodium and chloride ions (Na, Cl), typical for arid-zone palaeovalleys (Chapter 4). Groundwater in many shallow bores exceeds the Australian Drinking Water Guidelines (ADWG) threshold of 50 mg/L for nitrate (NO_3), but not in the deeper project bores. Some groundwater in the deeper project bores exceeds the thresholds for fluorine (F), boron (B), manganese (Mn), lead (Pb) and arsenic (As). Groundwater from both pre-existing shallow bores and many of the new bores has high levels of uranium (U), some above Australian Drinking Water Guidelines thresholds. This is not uncommon for groundwater hosted in, or flowing from, Australian Precambrian (older than 542 million years) granite terranes that are notably rich in uranium (Champion and Sheraton, 1997).

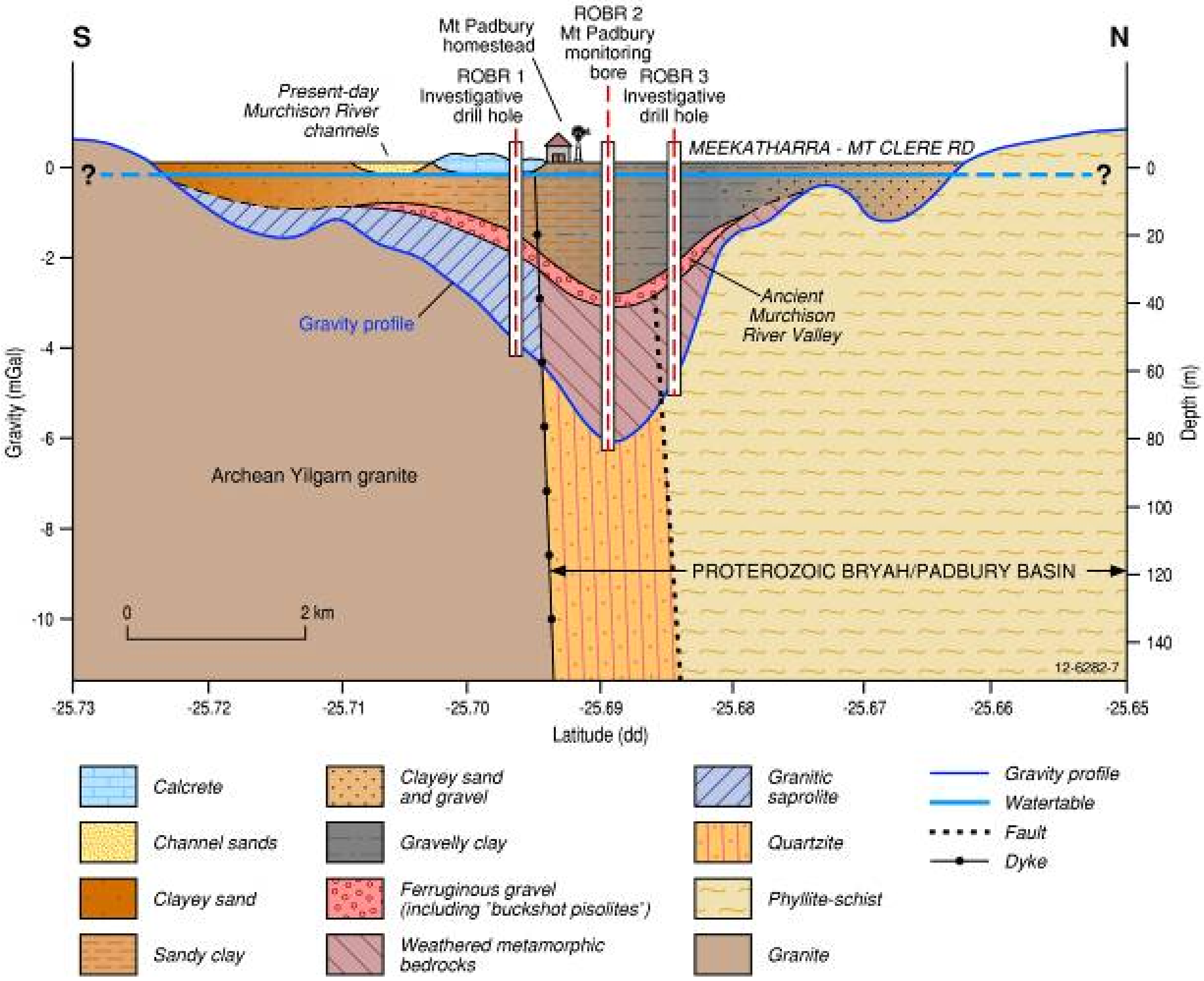

Figure 12: Interpreted Mt Padbury cross-section based on gravity profile and drilling data. The profile shows the main thalweg at this location inset into a broader valley.

Stable isotope data for groundwater samples show the new bores are enriched in the heavier isotopes. This indicates that evapotranspiration is the dominant process affecting groundwater systems. Radiocarbon (^{14}C) data indicate the presence of palaeowater in the new bores, with percent modern carbon (pMC) ranging from 30 to 1.37 pMC representing uncorrected ^{14}C ages of 9500 to 34 500 years BP. Recharge of the aquifers in the present climatic regime will be assessed from data loggers installed in the new monitoring bores, although it is predicted that periodic recharge occurs from rare high-magnitude rainfall events tracking east-south-east from the coast, from episodic river flow and semi-permanent pools in the main rivers.

2.2.5 Summary, conclusions and recommendations

Groundwater is more abundant in the Murchison than anticipated at the outset due to the greater-than-expected valley depths and the high proportion of sandy infill. Data are insufficient to estimate yields and overall volumes for specific palaeovalley reaches or sites. Watertables are shallow (2.5–6 m below ground level). Very substantial layers or lenses of highly permeable palaeochannel sands are up to tens of metres thick. This has been one of the most significant findings of the investigation, although it must be emphasised that the Murchison palaeovalleys are complex and heterogeneous and have thus far only been investigated at reconnaissance level. Extraction from these sandy aquifers may also induce leakage from overlying sediments, from up-gradient palaeo-tributaries and from weathered/fractured bedrock. Further work is required to establish the extent and magnitude of such recharge, and to determine analogies with better known palaeovalley systems in the Eastern Goldfields.

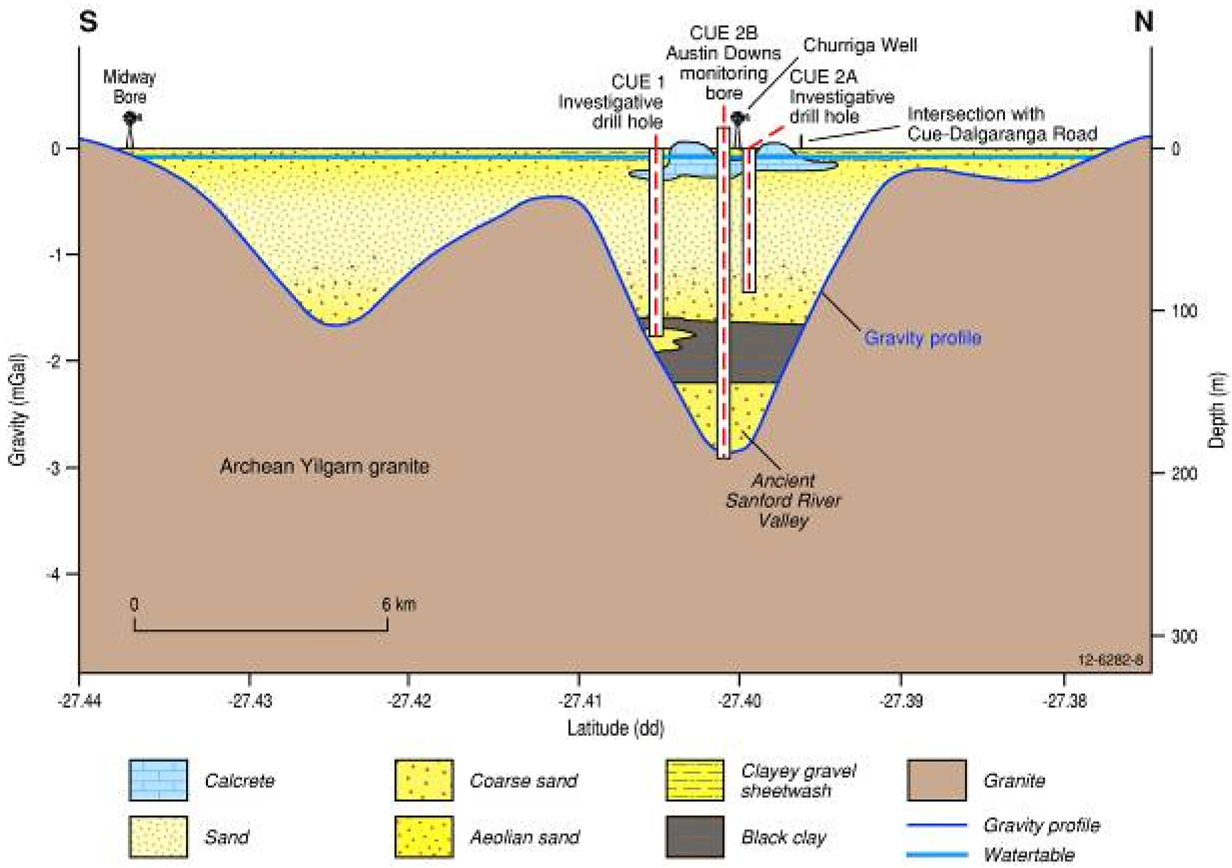

Figure 13: Interpreted Austin Downs cross-section based on gravity profile and drilling data.

Further drilling to bedrock is required to establish cross-section dimensions and stratigraphy of other Murchison palaeovalleys. Recovery of complete stratigraphic sections using sonic drilling or other coring techniques is highly recommended to improve understanding of palaeovalley infill sequences and sediments. Palynostratigraphic analysis of layers containing organic material should also be considered to better constrain the origin, age and depositional environments of regional palaeovalleys. In addition the next phase of groundwater investigation in the Murchison should focus on recharge, discharge and throughflow to improve understanding of groundwater dynamics, yields and storage.

The Austin Downs (Sanford Palaeovalley) and Annean (Hope Palaeovalley) sites are located downstream from salt lakes, Lake Austin and Lake Annean respectively. Groundwater in palaeovalley aquifers upstream (east) from these (and other) salt lakes is likely to be less saline than in downstream aquifers, not only because of the gradient relative to brine pools but in this case also because the prevailing wind is from the east and likely to transport aeolian salt deflated from the playa surface. Accordingly, headwater palaeovalleys and palaeo-tributaries east of the Great Northern Highway are prospective targets for good-quality groundwater, potentially benefiting Meekatharra, Cue and Mt Magnet.

This demonstration study has shown that the application of cost-effective ground gravity surveying and drilling techniques, combined with readily available DEM and regional geological and geophysical datasets, can be effective in characterising palaeovalleys for more detailed follow-up work. This study has also highlighted the complexity and heterogeneity of the Murchison palaeovalley systems, emphasising the need for additional investigations, particularly coring of complete stratigraphic profiles (to bedrock) across the full width of palaeovalleys, and careful palynostratigraphic analysis. Long-term monitoring of bores is also required, particularly if large groundwater volumes are to be extracted to support expanding mining activities, to improve understanding of any potential variability in the groundwater systems.

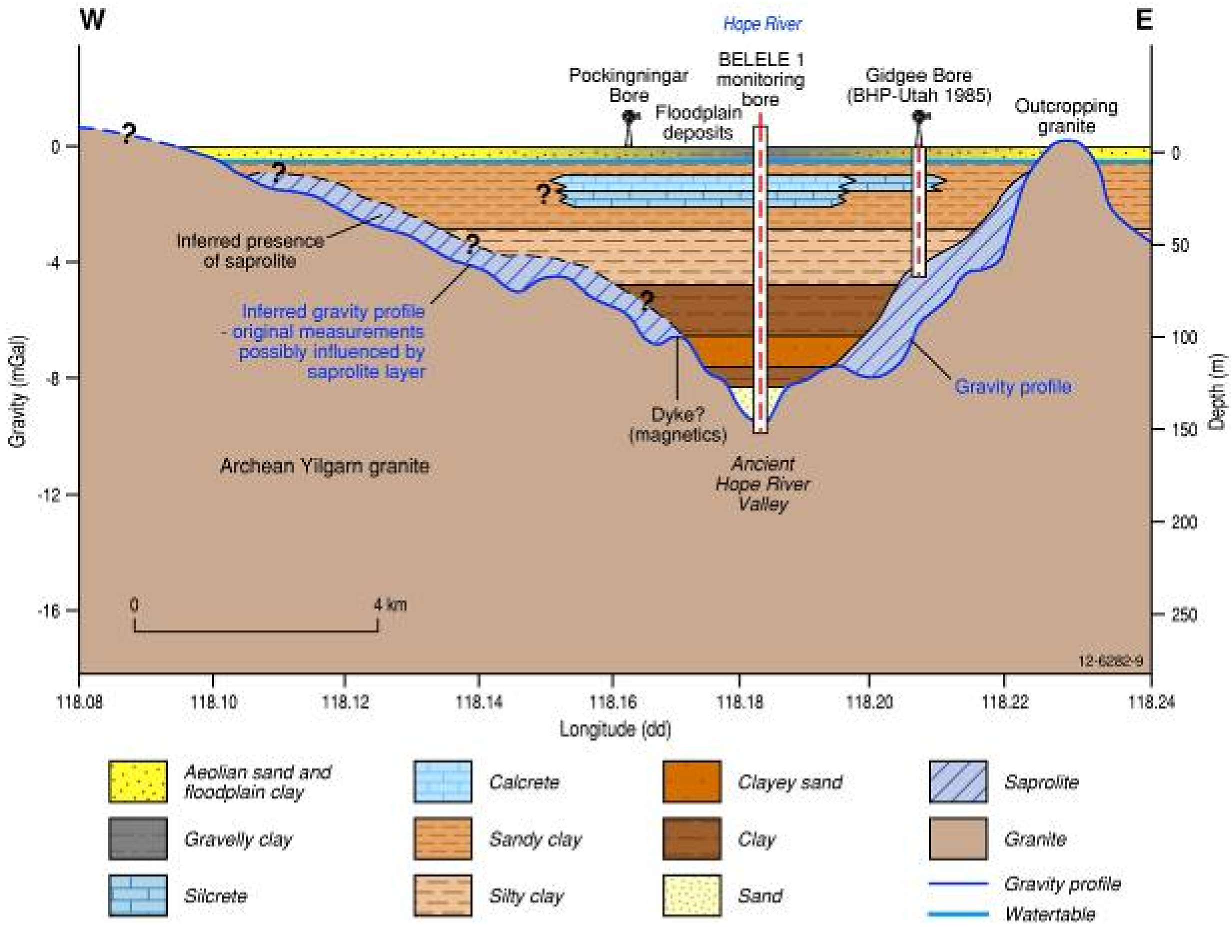

Figure 14: Interpreted Annean cross-section based on the gravity profile and drilling data.

The full report on this demonstration site is to be published as:

English P, Johnson S, Bastrakov E, Macphail M, Kilgour P and von Behrens M 2012, ‘Murchison Demonstration Site Report – Palaeovalley Groundwater Project’, *Geoscience Australia Record,* 2012/06, Canberra.

2.3 Paterson

The Paterson region (Figure 15) was selected as a demonstration site to take advantage of \$3 million worth of AEM data acquired at a range of flight-line spacing over 50 000 km^2 and processed by Geoscience Australia (2007–2010) for the Onshore Energy Security Program. The overall goal was to assess the utility of regional AEM for detecting palaeovalleys beneath extensive Great Sandy Desert dune fields and, wherever possible, mapping their constituent aquifers for water resource assessments (English et al., 2012b).

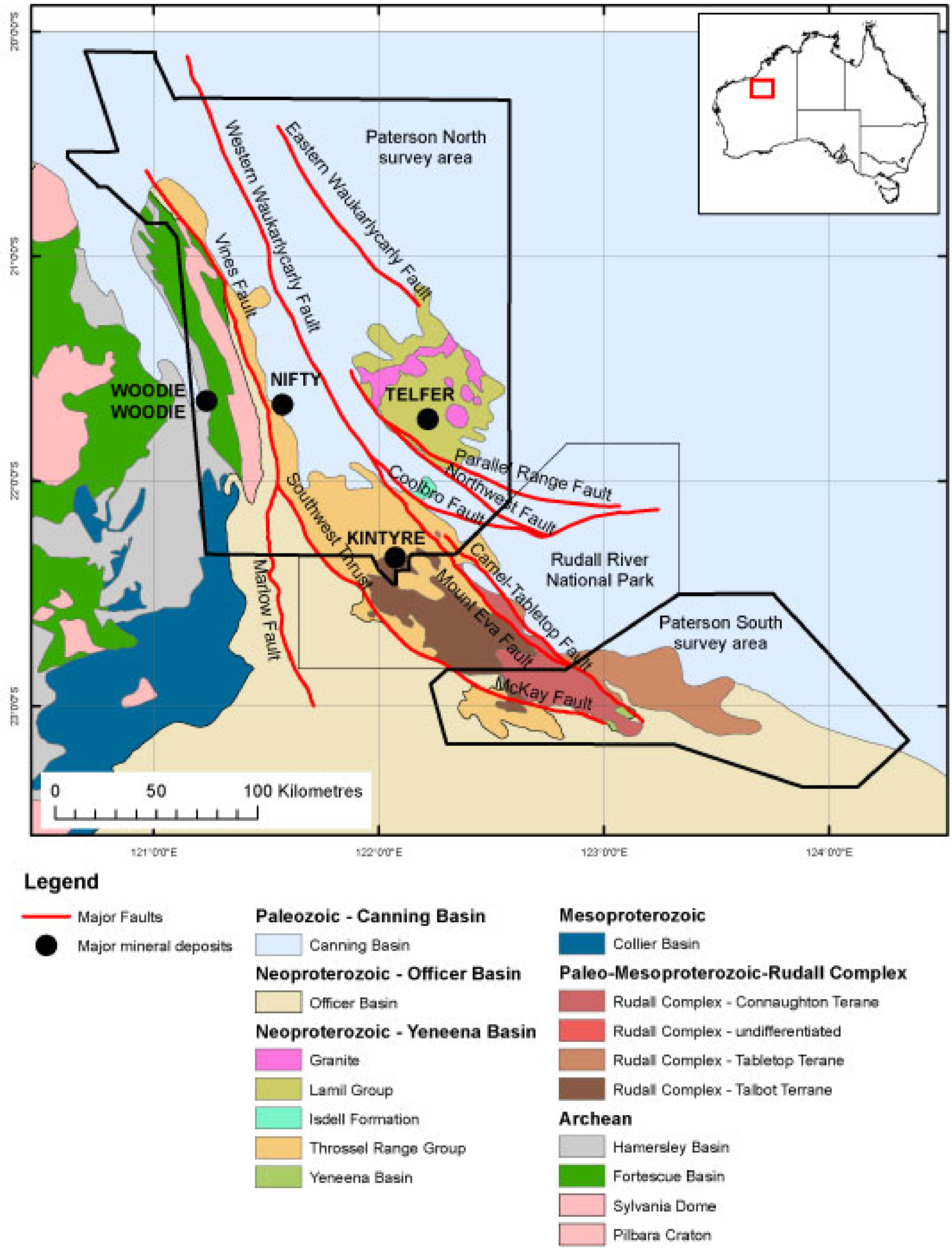

Figure 15: Simplified geology map of the Paterson region showing AEM survey areas, mineral deposits and major faults (modified after Whitaker et al., 2010).

The Onshore Energy Security Program AEM survey had been designed to stimulate multi-commodity mineral exploration in the highly prospective Paterson Province. This accelerated activity would increase demands for water resources to support exploration and mining operations, including the need for new borefields in dune-covered palaeovalleys. Some mines use bedrock aquifer groundwater resources, such as the Telfer Gold Mine and Woodie Woodie Manganese Mine, whereas others, such as the Nifty Copper Mine and Kintyre uranium deposit, depend on palaeovalley groundwater. The demonstration study focused on areas where palaeovalley groundwater resources are currently required or may be needed in the future, and also improved hydrogeologic understanding using AEM data and 3D conceptual modelling.

2.3.1 Research program and objectives

Previous work had focused on palaeovalleys at only a couple of mine-site borefields, although these were established without regional framework studies or hydrogeologic conceptualisation. Thus, a specific project objective was to represent integrated geoscientific datasets in 3D using computer-generated models (derived with GOCAD software) to aid conceptualisation and guide drilling. Investigations relied heavily on the Onshore Energy Security Program processing and interpretation of AEM survey data, and on known exploration drill-hole data (Roach, 2009; Roach, 2010), along with borehole data specifically provided by exploration or mining companies.

Four main methods used to characterise the Paterson palaeovalleys, additional to compilation of existing data, reports, maps and datasets, were:

- DEM and their derived products, e.g. MrVBF
- interpretation of AEM survey data
- generation of 3D models of integrated geophysical and stratigraphic datasets
- hydrochemistry.

Use of the MrVBF (Gallant and Dowling, 2003) helped overcome the obscuring effects of extensive linear sand dunes, and enabled detailed mapping of palaeovalley networks. Many palaeovalleys originated as Permian glacial valleys, particularly in upland areas of Archean to Proterozoic bedrock. The high-resolution SRTM DEM enabled plotting of topographic gradients within MrVBF-defined palaeovalley tracts (i.e. spot heights for the swales and interdunal corridors) to further elucidate likely flow directions (Figure 16). The distribution of near-surface palaeovalley calcrete and recent alluvium, post-dating sand dune formation, and of Paterson Formation outcrops (Permian glacial sediments) were integrated with the DEM imagery to aid interpretation of the AEM data.

The Paterson demonstration study focused on eight locations (Figure 17): Kintyre, Maroochydore, Goosewacker, Parnngurr, Nifty, Telfer Access Road (TAR bores), Canning Basin, and Oakover River Valley. These sites have diverse bedrock compositions, mineral commodities, palaeovalley types, and groundwater resource requirements. The regional AEM flight-line spacing also varied between sites, providing the opportunity to assess the relative usefulness of different AEM resolutions for mapping palaeovalleys (Figure 18 to Figure 20).

2.3.2 Palaeovalley examples

Kintyre

The main aquifer in the Rudall Uplands is the basal conglomerate facies of the Permian Paterson Formation, which infills glacial palaeovalleys incised into crystalline bedrocks of the Proterozoic Rudall Complex. Bedrock faults and shallow Cenozoic alluvium contain minor groundwater resources. Closely spaced AEM flight lines over the Rudall Complex resulted in high-resolution AEM data with clear depiction of palaeovalleys in 3D (Figure 18), particularly the more conductive glacial tillite clays and the valley thalweg, where conglomerate is most likely to occur. Offsets of the Paterson Formation are also evident across previously unmapped faults.

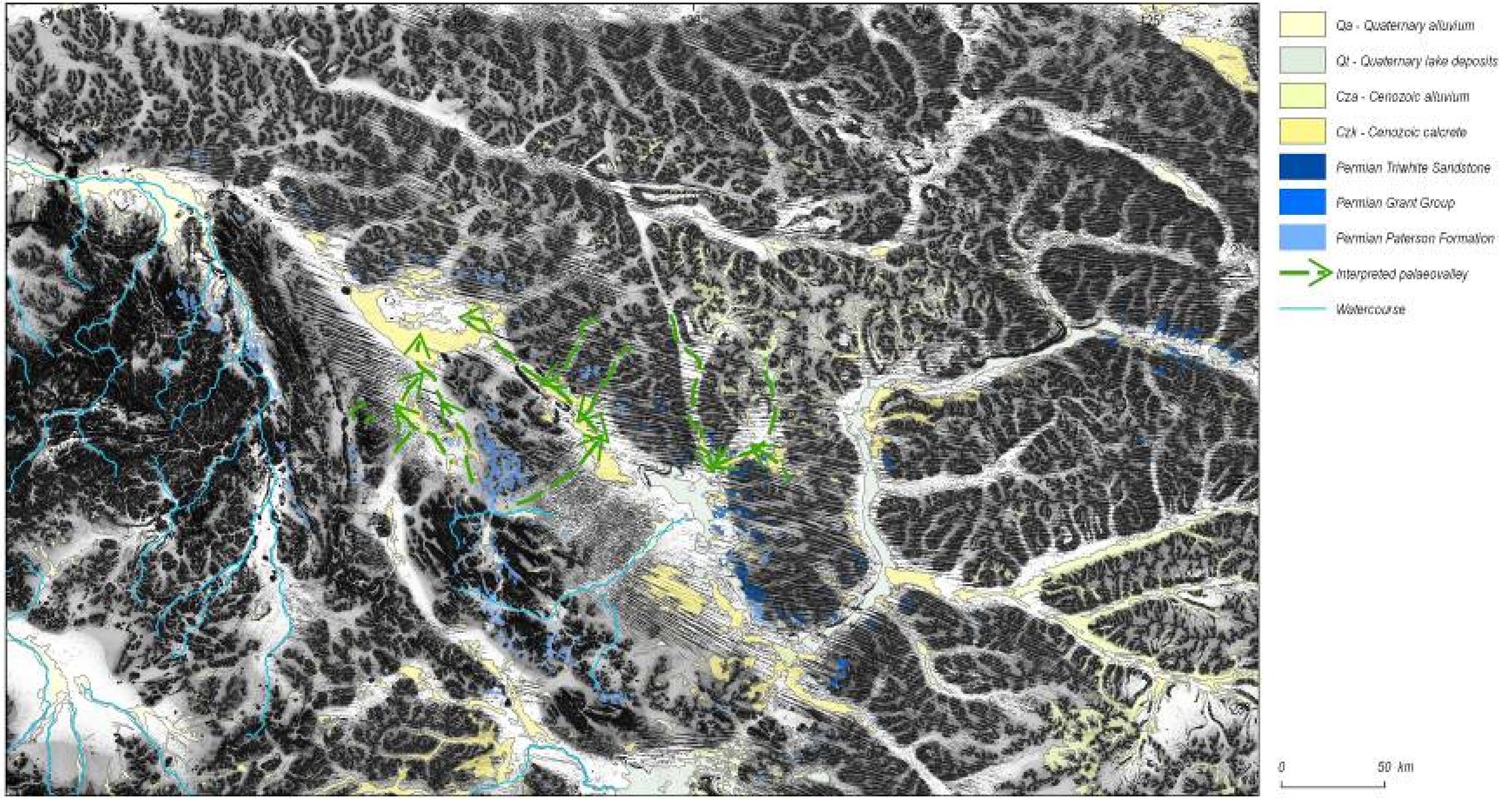

Figure 16: The distribution of 'valley calcrete' exposed in low-lying areas, shown on the MrVBF image along with salt lakes, Quaternary alluvium and gradients within interpreted palaeovalleys. The calcrete and Permian Paterson Formation palaeovalleys are far more extensive beneath dune fields.

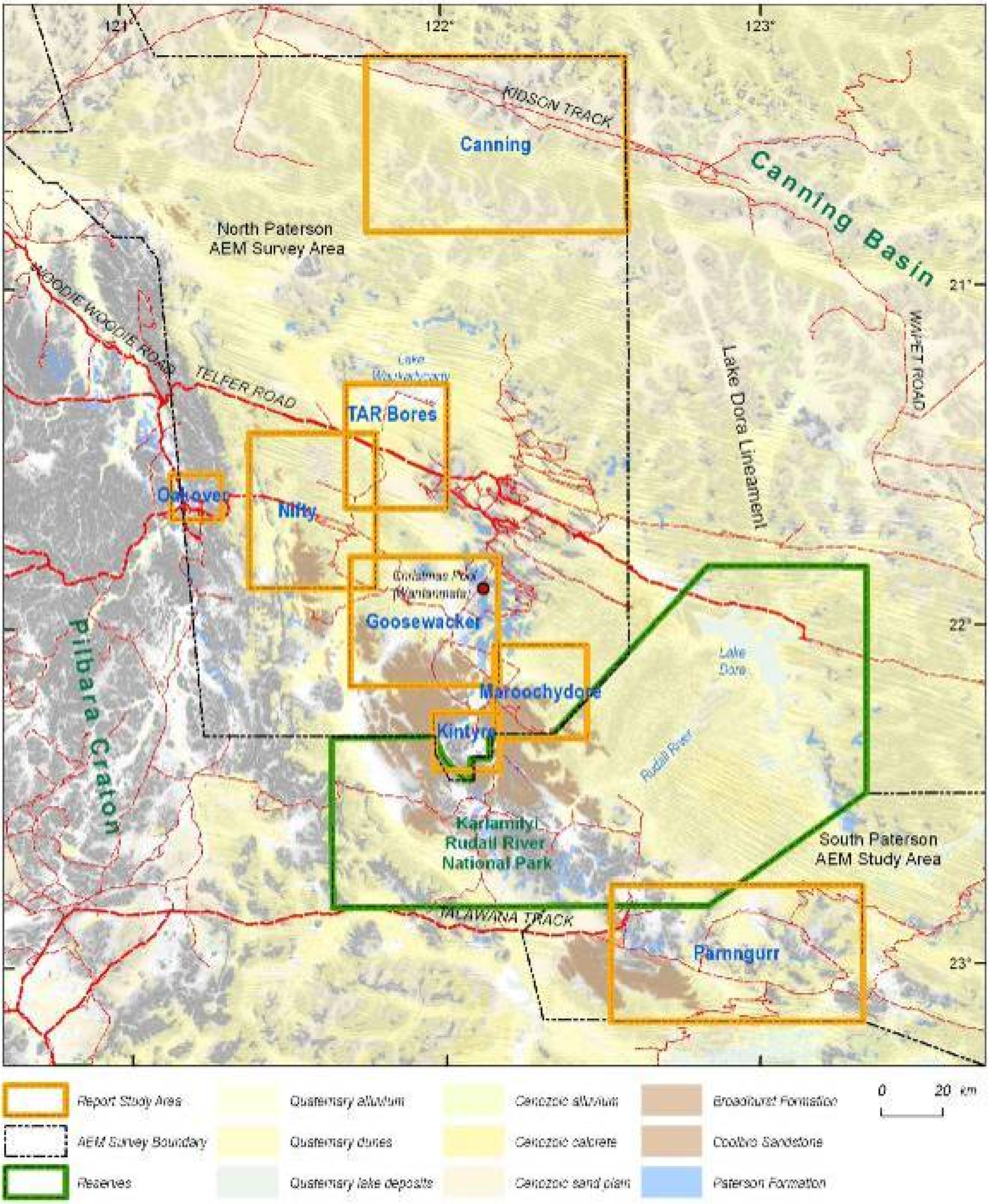

Figure 17: Paterson Province *Palaeovalley Groundwater Project* study sites (TAR, Telfer Access Road) overlain on the regional surface geology and the MrVBF image.

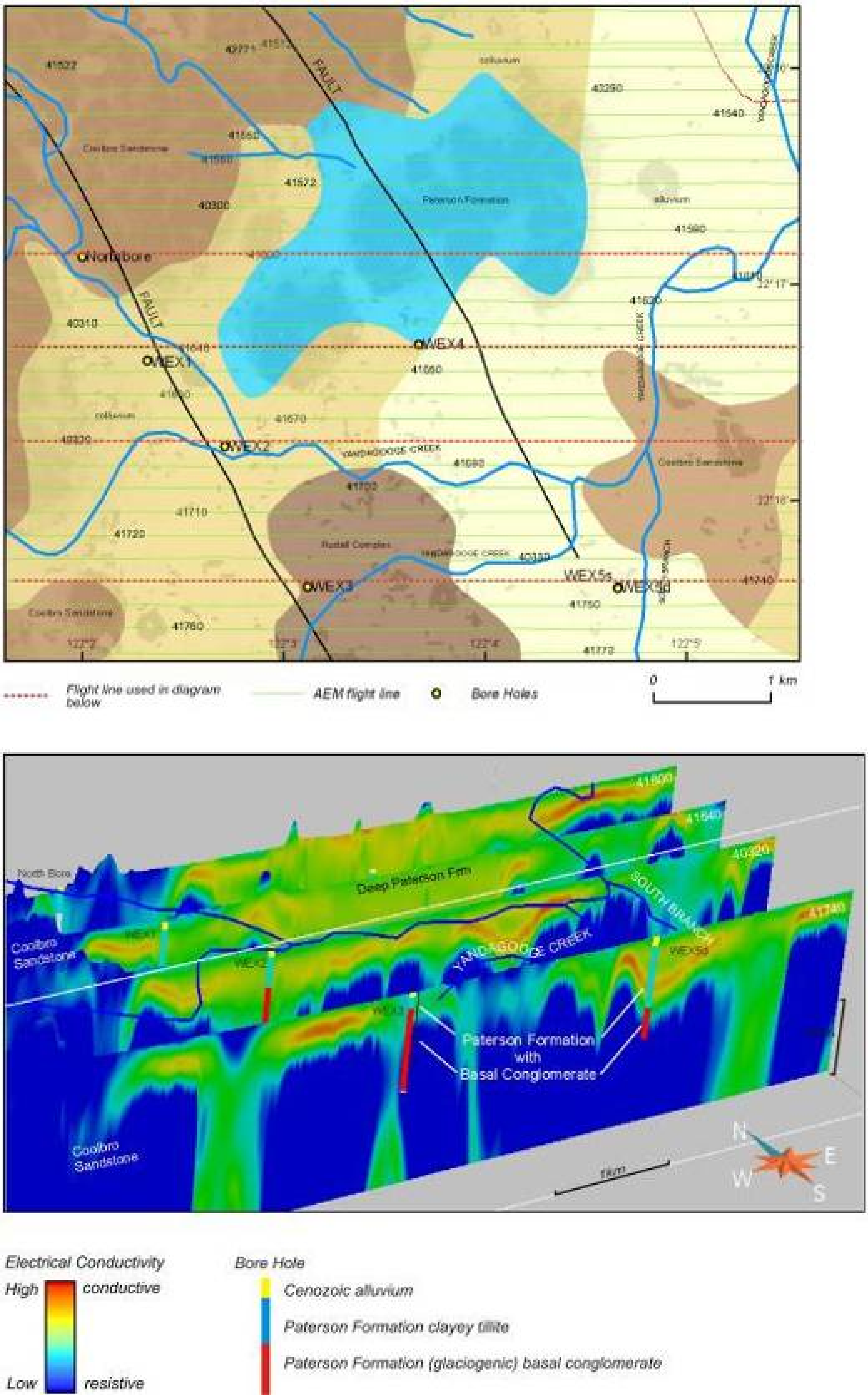

Figure 18: Geology map with AEM flight lines (top) and 3D model of the Kintyre area based on AEM conductivity sections, surficial geology and DEM data (lower). Vertical scale of AEM sections is approximately 200 m. Borehole stratigraphy is simplified from an unpublished company report (MWH Global, 2010) as follows: red – Paterson Formation conglomerate (glaciogenic), blue – Paterson Formation clayey tillite, yellow – Cenozoic alluvium.

Maroochydore

Maroochydore is a multi-commodity mineral deposit north-east of Kintyre within Proterozoic rocks of the Broadhurst Formation (Throssell Range Group, Figure 15). The Permian Paterson Formation blankets the plains abutting the Rudall Uplands, overlying the mineralised Broadhurst Formation, and is overlain by Cenozoic alluvium and Quaternary dunes. The integrated datasets reveal a very thick blanket of moderately conductive Paterson Formation rocks together with thick overlying Cenozoic alluvium (lower conductivity) beneath resistive sand dunes (Figure 19). The most prospective bore sites are about 6 km north of the exploration camp, close to the ephemeral Coolbro Creek, which receives episodic run-off from the adjacent Broadhurst Range. The Coolbro Fault, interpreted to have been reactivated in relatively recent times (English et al., 2012b) and coincident with the modern course of lower Coolbro Creek, makes for favourable bore siting and potential high yields of moderately fresh groundwater north of the camp (Figure 19). The moderate conductivity of the Paterson Formation and overlying Cenozoic alluvium suggests that these sediments have been well-flushed by fresh water associated with episodic high flooding of Coolbro Creek.

Nifty

Nifty Copper Mine is in a low-lying, densely dune-covered plain in the middle of the study area (Figure 17). Folded and faulted rocks of the Broadhurst Formation are blanketed, similar to the Maroochydore area, by the Permian Paterson Formation. The Paterson Formation is overlain by Cenozoic alluvium and Quaternary dunes that stand up to 17 m high at the western edge of the Great Sandy Desert. Some water for ore processing is supplied from mine dewatering. Potable water supplies are sourced from palaeovalley aquifers, both basal sands of the Paterson Formation and shallow alluvium.

Ground gravity traverses and follow-up drilling along dune swales east of the mine in early exploration (1991–1992) revealed a palaeovalley infilled with Paterson Formation rocks and overlying alluvium. The original interpretation suggested that the East Nifty Palaeochannel flowed to the south-east, along the axis of the Nifty Syncline (Figure 20). Integration of the original gravity profiles with Onshore Energy Security Program AEM conductivity slices and simplified stratigraphic columns enabled depiction of the palaeovalley in 3D (Figure 20), with the reinterpreted buried thalweg of the East Nifty Palaeochannel actually flowing towards the north-east. The palaeodrainage flow from the Coolbro Range to the Waukarlycarly Embayment and Lake Waukarlycarly is consistent with the regional gradient mapped from the SRTM and MrVBF data (Figure 16).

The AEM conductivity sections reveal numerous ‘glacial scours’ beneath the plain, additional to the East Nifty Palaeochannel, as well as clearly depicting near-surface Cenozoic alluvium beneath the dune field (Figure 20). These conductivity patterns are evident along the north-northwesterly strike of the mineralised Broadhurst Formation that extends through the Paterson Province. The integrated datasets, as represented in Figure 20, provide guidance for borehole siting along the strike of the mineralised bedrock zones and in adjacent areas.

South Paterson AEM survey area and Parnngurr

Karlamilyi National Park (formerly Rudall River National Park), in which Parnngurr community is located, was not flown in the Paterson AEM survey. The adjacent area to the south and east was part of the South Paterson AEM survey area, over the Rudall Uplands and adjacent parts of the Officer Basin. Flight lines were oriented north-east to south-west, in contrast to east to west flight lines over the North Paterson AEM survey area. In both cases the flight lines were perpendicular to the regional strike of bedrock structures.

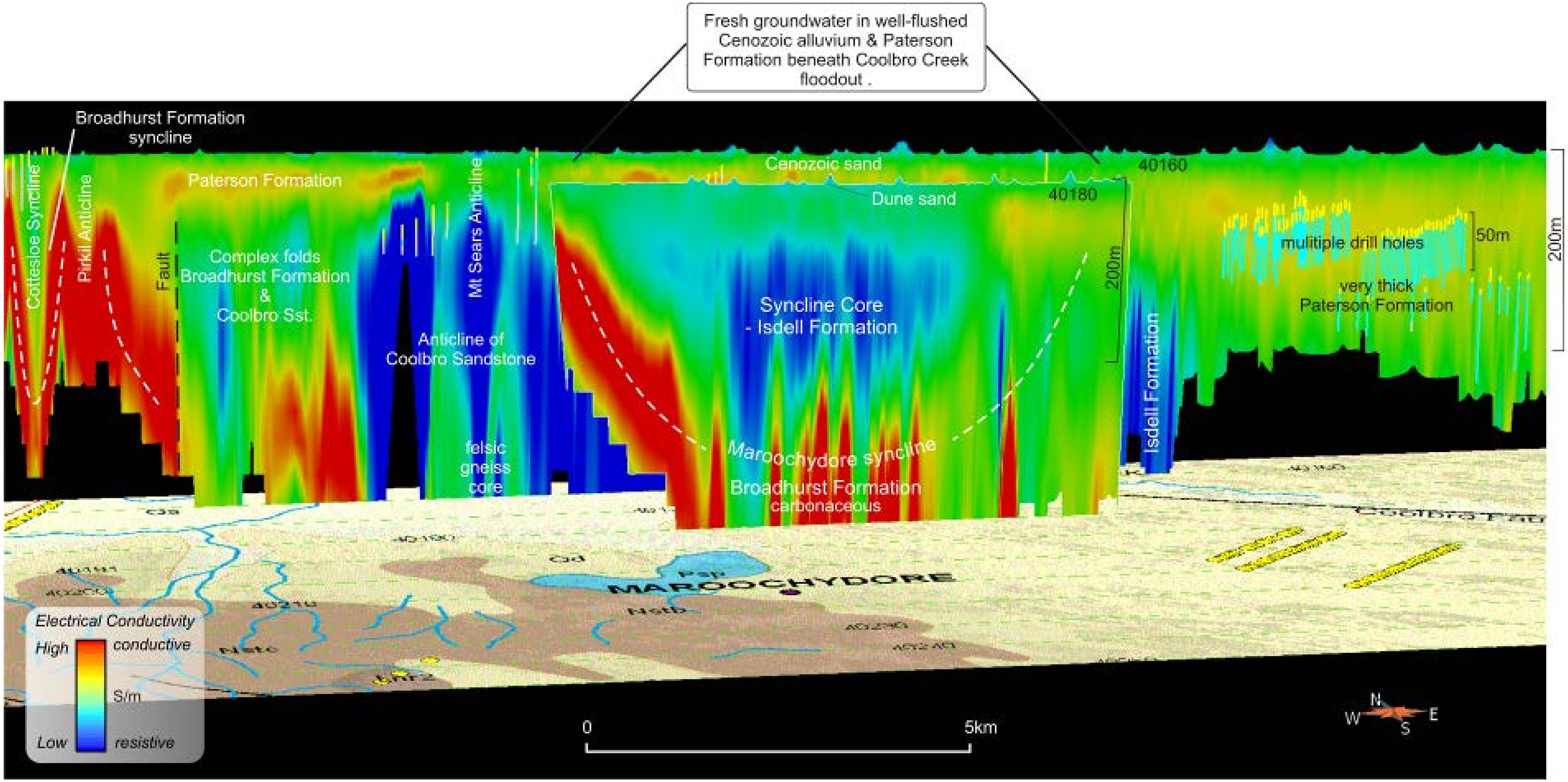

Figure 19: Oblique view of west–east AEM conductivity sections of the Maroochydore area with annotated interpretations. Drill-hole stratigraphy is simplified from exploration data compiled by Roach (2009).

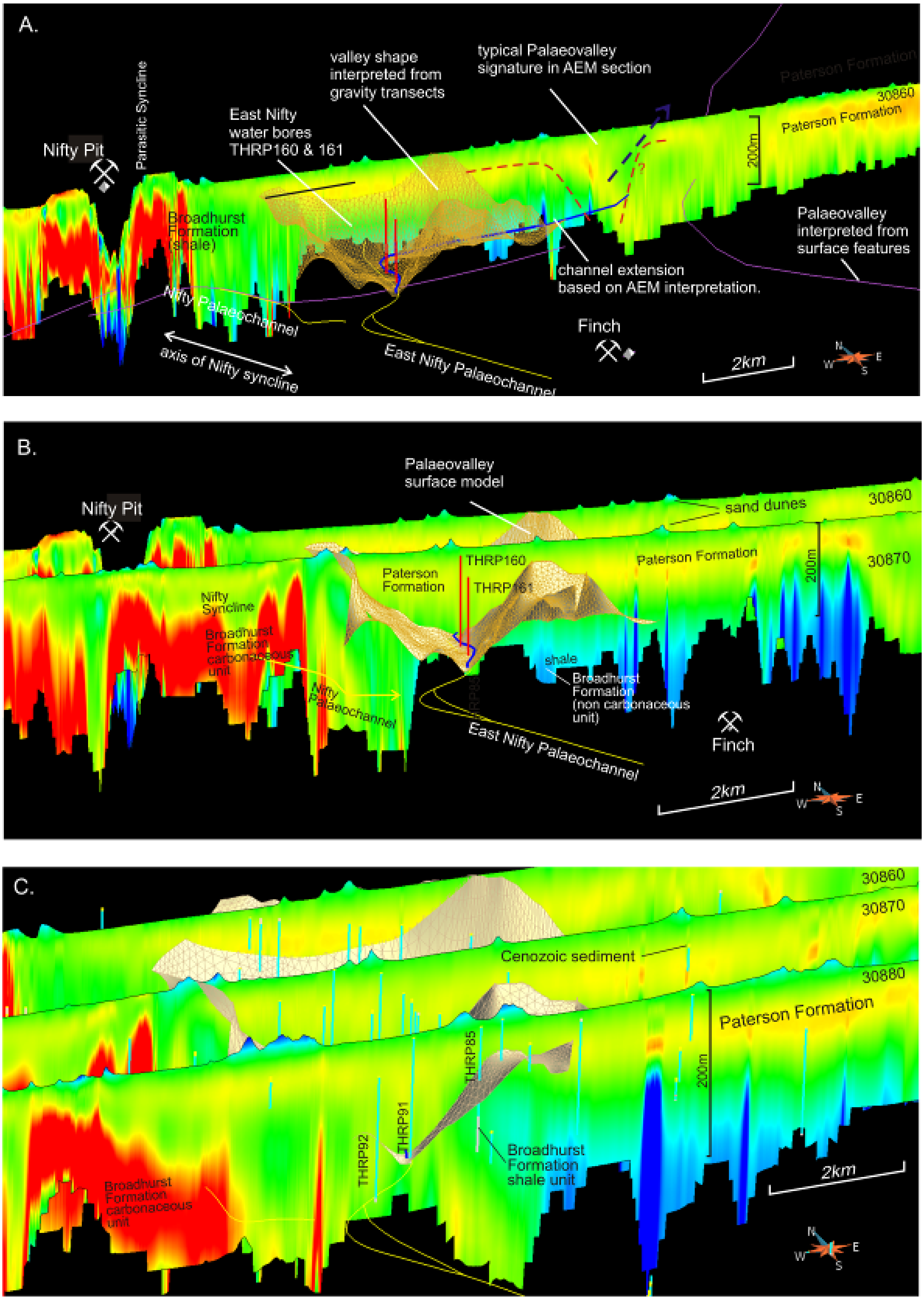

Figure 20: GOCAD model of the area east of Nifty Copper Mine, showing the integration of ground gravity profiles with AEM conductivity sections, simplified drill-hole data (vertical rods) and interpreted bedrock geology.

South and east of Parnngurr, the Proterozoic Karara Formation provides the most prospective bore sites to access groundwater resources for potential future use. Field observations, hydrochemical data and the AEM data suggest that the aquifer contains saline groundwater, particularly near Lake Disappointment, in the Little Sandy Desert (Officer Basin).

Parnngurr (Cotton Creek) is a small community of Martu traditional owners. The village is situated in the Rudall Uplands. Parnngurr has poor-quality water supplies because of metals leached from the nearby Mt Cotton mineral deposit, and possibly also microbial contamination because of poor reticulation (English et al., 2012b). Potable water resources for the community could be obtained from alluvium at Cotton Creek, 2.5 km to the west or north-west of Parnngurr (Front Cover Photo).

Other examples

The depth and elevation slices and conductivity sections from the AEM datasets have enabled clear depiction of dune-covered aquifers across the Paterson demonstration site. These aquifers occur in Proterozoic bedrock, Permian glacial palaeovalley deposits, and Cenozoic alluvium. Additional to Kintyre, Maroochydore and Nifty, the *Palaeovalley Groundwater Project* extended interpretation of AEM and other datasets to the areas shown in Figure 17. These study sites are described in English et al. (2012b) and include the following.

- Goosewacker Prospect is situated mid-way between Maroochydore and Nifty, and the Paterson Range. As for Nifty Mine, the area is well characterised in the AEM data because of tight folds of alternating conductive and resistive bedrock units overlain by a thick blanket of Paterson Formation sediments. The disposition of the Paterson Formation, including infilled palaeovalleys, is well depicted in the AEM data. Palaeovalleys infilled with Paterson Formation sediments are the most prospective aquifers if a borefield is required to develop the prospect into a mining operation.
- Waukarlycarly Embayment is a deep graben infilled with Canning Basin sedimentary rocks. Bores along the Telfer Access Road have been sunk into palaeovalley sediments within the Waukarlycarly Embayment to supply water for road maintenance and remote travellers. The Paterson Formation and overlying Cenozoic sediments and dunes are depicted in the AEM data, particularly compared to the resistive Mt Crofton Granite and surrounding formations in the Telfer area. Conductivity responses are relatively high because the Lake Waukarlycarly salt lake is nearby.
- Oakover Valley is at the western edge of the demonstraton study site and at the easternmost edge of the Pilbara Craton. The Oakover River flows from south to north, incised into Archean dolomite that are excellent aquifers and which are sharply depicted beneath more conductive Paterson Formation and Oakover Formation valley infill. The Oakover Formation is a distinctive Cenozoic palaeovalley unit of lacustrine sediments and calcrete.

- The southern edge of the Canning Basin was flown in the North Paterson AEM survey. Diverse Permian and Cretaceous sedimentary units overlie Paterson Province basement rocks and form extensive aquifers that contain large volumes of potable groundwater. In the Canning Basin, just beyond the extent of the AEM survey, the Percival Palaeovalley ('Canning Palaeoriver' of Beard, 1973) is a distinctive palaeovalley aquifer. The Cenozoic palaeoriver was incised through Cretaceous strata and associated ferruginous duricrust into Permian sediments. The Permian Triwhite Sandstone, an excellent aquifer, is exposed along the base of the valley flanks and groundwater emerges at springs around the edges of salt lakes (Commander, 1985). This contrasts with usual palaeovalley hydrostratigraphic scenarios where the main aquifer is basal alluvium or overlying sandy sediments that were deposited during waxing and waning of river flow. In the Percival Palaeovalley and possibly analogous others in the Canning and Officer Basins, Cenozoic fluvial aquifers are subordinate to the magnitude of Paleozoic-Mesozoic aquifers that valley incision has exposed.

2.3.3 Hydrogeochemistry

Groundwater salinity in bores sampled for the project range from fresh to brackish: 280 to 5700 mg/L TDS. The freshest water is from basal sand-gravel sequences of the Paterson Formation at Kintyre and Nifty, also from Cenozoic alluvium east of Nifty Mine. Groundwater compositions are sodium chloride (NaCl) dominated, typical of arid-zone palaeovalleys (Chapter 4).

Inorganic groundwater contaminants (fluorine, boron and arsenic) that may exceed Australian Drinking Water Guidelines thresholds are correlated with chloride ions, suggesting that evaporation may cause enrichment. In contrast, elevated uranium levels from Kintyre bores are not correlated and most likely relate to water–rock interaction.

Oxygen ($\delta^{18}O$) and deuterium (δD) isotopes for groundwater are enriched in the heavier isotopes. This indicates that evapotranspiration is a dominant process affecting groundwater systems, typical of the arid zone. Stable isotope data from the Paterson groundwater suite lie closer to the meteoric water line than palaeovalley groundwater from the Murchison demonstration site (English et al., 2012a), implying a lesser degree of evapotranspiration.

Radiocarbon (^{14}C) data reveal the presence of fossil water in sampled bores: percent modern carbon ranging from 84 to 2.6 pMC (uncorrected ^{14}C ages of about 1300 to 29 250 years BP). The youngest groundwater is from the Telfer Access Road bores which are in the low-lying Waukarlycarly Embayment where episodic cyclonic incursions may bring high rainfall, causing water to pond at the surface for considerable time. Two production bores at Nifty (THRP 160 and THRP 161), sunk into the East Nifty Palaeochannel (Figure 20), returned similar ages of 18 000–19 000 years BP. The oldest groundwater sample (approximately 30 000 years BP) was from a shale bedrock aquifer at Nifty Mine, sampled specifically for comparison with palaeovalley groundwater. Recharge appears to occur episodically from monsoon-related events that travel inland from Eighty Mile Beach, with major events arriving at approximately decadal timescales in the present climate regime.

2.3.4 Summary, conclusions and recommendations

Groundwater is abundant in the Paterson region, in palaeovalleys, diverse Proterozoic units, and the adjoining Canning and Officer Basins. AEM datasets have elucidated the depths of incision and architecture of glacially scoured palaeovalleys in exposed upland bedrock areas. AEM data generally depict bedrock aquifers beneath the Permian Paterson Formation and near-surface Cenozoic alluvial aquifers. The following conclusions are drawn from the study.

- AEM data are very useful for palaeovalley mapping beneath dune fields, detecting both Permian Paterson Formation and Cenozoic alluvium. The AEM data also aid mapping and characterisation of diverse bedrock aquifers, and geologic structures relevant to surface-water and groundwater dynamics. Fine-resolution (200–1000 m flight-line spacing) AEM data are useful for borefield siting, while coarse-resolution data (6 km flight-line spacing) are useful for reconnaissance surveys.
- Drilling and drill-hole data are required, along with a variety of other datasets, to effectively investigate palaeovalley aquifers and groundwater resources.
- AEM surveys flown for mineral exploration are useful for groundwater investigations, although surveys designed specifically to target groundwater (and taking account of likely aquifer depths, heterogeneity, resolution and other factors) will provide more useful and higher quality data.
- Existing geologic mapping and DEM are adequate exploration tools for aquifers such as calcrete and shallow alluvium, which can provide groundwater resources for smaller scale or short-term supplies, e.g. for pastoralists or temporary mineral exploration camps.
- Expensive AEM surveys may not need to be flown if sought water resources and/or funds are limited. Ground gravity surveys combined with drilling and geologic knowledge can be effective and economical for borefield siting. For example, early exploration in the Paterson region (e.g. Western Mining Company work at the Throssell Range Prospect, now called Nifty) demonstrated the effectiveness of ground-based gravity traverses, and ‘raw’ gravity data, to define the buried palaeovalley structure in dense dune fields. At Nifty, exploration drill holes subsequently defined the basal sands and gravels that continue to provide potable water supplies. Thus, although AEM is a desirable dataset, the likelihood that buried geologic elements display density contrasts as well as conductivity contrasts should not be ignored.
- Regional groundwater AEM survey datasets should be archived within a national database, to improve understanding of bulk conductivity ranges and anomaly patterns. This would assist in levelling and extrapolating datasets for widely separated regions of Australia. Such endeavours may include detailed analysis of the contribution of groundwater to bulk conductivities measured by airborne systems, as undertaken in recent salinity projects in Australia, e.g. Lawrie et al., 2010, Tan et al., 2012.

The Paterson demonstration study has shown that AEM survey data acquired for mineral and energy exploration can also assist in detecting and mapping buried palaeovalley aquifers and groundwater resources. However, AEM data must be integrated with regional geological and geophysical datasets, particularly drill-hole stratigraphic logs, to provide holistic interpretation. The Paterson AEM data highlights the complexity and heterogeneity of palaeovalley systems, but also their widespread distribution.

Based on fieldwork and groundwater isotope data acquired for the present study, it would appear that the Paterson is a relatively well-watered desert region. Although distinct palaeo-groundwater signatures occur, large volumes of reasonable-quality groundwater are stored in diverse aquifers, generally with some modern recharge. Management of palaeowater and monitoring of water levels is required in areas of heavy groundwater use. Replenishment of these aquifers (modern recharge) is favoured over decadal timescales by the nearby Western Australia north-west coast, and sporadic incursion of cyclonic weather systems.

The full report on this demonstration site is to be published as:

English PE, Bastrakov EN, Bell JG, Woltmann M, Kilgour PL and Stewart G 2012, ‘Paterson Demonstration Site Report – Palaeovalley Groundwater Project’, *Geoscience Australia Record,* 2012/07, Canberra.

2.4 Ti Tree

The Ti Tree Basin is in the Northern Territory about 200 km north of Alice Springs (Figure 21). This intracratonic Cenozoic basin is infilled with up to several hundred metres of alluvial and lacustrine sediments. The groundwater potential of the basin has been the focus of various government reports and policies since the early-1960s, with recent reviews by Knapton (2005; 2006a) and Magee (2009). The most comprehensive hydrogeologic investigations of the Ti Tree Basin aquifer were conducted by McDonald (1990) and Harrington (1999). A summary of relevant background information and geologic, hydrologic and geophysical data from the Ti Tree area was compiled in earlier progress reports for the project, for example Lewis et al. (2009) and Lewis et al. (2010).

Groundwater studies and management plans for the Ti Tree Basin have mostly concentrated on the relatively shallow Cenozoic aquifers. In 2012 these near-surface aquifers (accessed at depths less than 100 m below surface) supplied about 2.5 GL of groundwater for horticulture (e.g. table grape production), and a much smaller volume for community water supplies. The upper Ti Tree aquifer is estimated to contain ~8000 GL of groundwater (Knapton 2006a, 2006b).

Despite the strong reliance on groundwater in the Ti Tree Basin relatively little is known about deeper aquifers. This is despite information suggesting that in places, the Ti Tree Basin is infilled to depths of at least 320 m with sediments, including hydraulically conductive sand-rich layers. The deeper sediment sequences were encountered by the initial government drilling program (Edworthy, 1967) and some early mineral exploration work (O'Sullivan, 1973). Existing drillcore from exploration hole CRA TT1 in the central Ti Tree Basin has basement rocks at 305 m below surface and, within the basin sedimentary infill, a ~45 m thick zone below 208 m depth with clean, free-flowing sands. More recently, NuPower Resources Ltd also confirmed that sediments infill the southern Ti Tree Basin to depths of about 320 m. Their drilling encountered deep stratigraphic intervals with up to tens of metres of poorly consolidated sands (Higgins and Rafferty, 2009).

Palynostratigraphic analysis (Appendix 3) of lignite and carbonaceous sediments recovered from above the deep sand-bearing zones in nearby drill holes (Wyche, 1983) indicated possible Middle Eocene ages (Macphail, 1997). These dates implied that the deeper sand-bearing sequences in the Ti Tree Basin may be time-equivalents of Eocene sand aquifers known from palaeovalleys in Western Australia, such as the North Royal Formation (formerly Wollubar Sandstone) in palaeovalleys from the Eastern Yilgarn Goldfields (Commander et al., 1992). Determining the extent and nature of possible stratigraphic correlatives for the major Western Australian palaeovalley aquifers was a key recommendation arising from the initial project literature review on Australia's arid-zone palaeovalley systems (Magee, 2009).

Despite several drill holes having encountered deep sands in the Ti Tree Basin, none were constructed with suitable casing to allow evaluation of groundwater characteristics. Thus, prior to this study, there was no indication of groundwater quality or age for the groundwater resources of the deeper basin aquifer, or the potential for interaction with the shallower groundwater system.

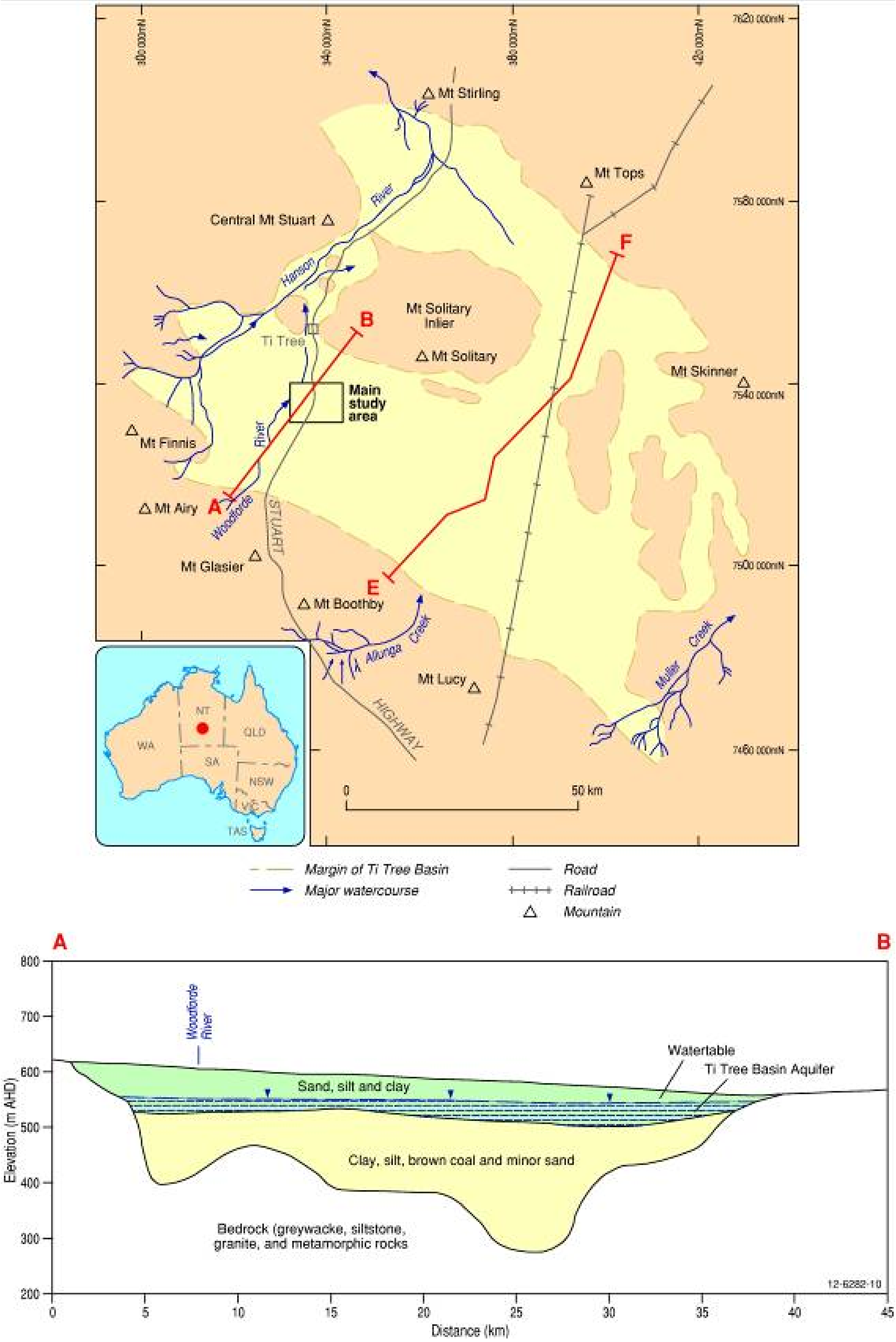

Figure 21: The main study area in the Ti Tree Basin. The Cenozoic basin, shown in yellow surrounded by bedrock, has the basic structure shown in cross-section A to B. The new interpretations for Line A to B and E to F from this project are shown in Figure 23.

2.4.1 Research program and objectives

Following initial data evaluation for the project[6] and endorsement of the proposed approach by the Technical Advisory Group, new research in the Ti Tree Basin focused on better understanding the nature of the deeper aquifer system. The key objectives of this study were to:

- construct new deep drill holes into basement Proterozoic rocks to intersect the entire Ti Tree Basin stratigraphic profile and to evaluate the distribution and quality of potential aquifers
- reinterpret the existing Ti Tree Basin drillcore (incorporating other prior datasets) to develop a new hydrostratigraphic framework across the basin
- collect representative groundwater samples from deep aquifer intervals to determine groundwater ionic and isotopic compositions, and gauge groundwater residence times (radiocarbon dating)
- develop a conceptual hydrogeologic model to explain groundwater distribution and processes in both the shallow and deeper parts of the Ti Tree Basin.

2.4.2 Field investigation program

The initial field investigation program focused on constructing a deep borehole, RN18356[7], adjacent to the original CRA TT1 drill hole (for which drillcore was available, thereby providing unequivocal stratigraphic control on target aquifer thickness and depth). The aim with this new drill hole was to evaluate the aquifer potential and groundwater characteristics of a prospective sand-rich horizon between 208 and 213 m below ground, as well as to better understand Cenozoic basin evolution more broadly in central Australia. Unfortunately, problems with installation of borehole casing after drilling prevented precise emplacement of screens. However, new information was obtained about the deep groundwater composition, as a representative groundwater sample was collected from a sandy siltstone horizon about 200 m below surface. Although drill-hole construction for RN18356 did not proceed as originally planned there was sufficient evidence to continue further investigation of the deep sand layers of the Ti Tree Basin.

Follow-up ground-based gravity and electromagnetic (SIROTEM) surveying along two ~10 km-long traverses (200 m station spacing) was undertaken to determine the location of the thickest sediment sequence (deepest basement) in the area. The ground geophysical work identified a distinct lower gravity anomaly about 2 km south of the CRA TT1 drill hole (characterised by lower relative gravity measurements). This gravity low was initially interpreted as the location of the thickest section of Ti Tree Basin sediments, potentially up to 500 m thick. To evaluate the geophysical anomaly and to obtain further deep groundwater samples, plans were advanced for a drill hole carefully designed from the lessons learnt from drilling RN18356. Drilling of the second deep Ti Tree Basin investigation hole (RN18594) showed that the basement intersection occurred at ~340 m below surface, indicating that the gravity low was probably due to density variations in the underlying basement rocks. Nevertheless, drilling at RN18594 permitted the installation of water-bore screens in this deeper sand-rich section of the Ti Tree Basin 265 m below surface, and the collection of further deep groundwater samples for analysis. The very high groundwater yields (greater than the 25 litres per second [L/s] airlift capacity of the drilling rig) obtained from this hole clearly demonstrated the excellent groundwater potential of this previously untested deep

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6 The realisation that potentially significant aquifer intervals occur at deeper stratigraphic levels in the Ti Tree Basin led to the suggestion that other major central Australian palaeovalleys (e.g., Central Mount Wedge Basin) may also host deeper aquifer systems with significant volumes of previously unknown (and untapped) groundwater.

7 RN refers to the Registered Number of the groundwater bore in the Northern Territory government water-bore database.

Cenozoic sand aquifer in central Australia. The salinity of the deep groundwater sample was 2600 mg/L TDS. The drilling method used in the construction of RN18594 proved sound and has already been used in other deep palaeovalley boreholes, for example RN18599 in the Mount Wedge Basin (the following section on Wilkinkarra details this work).

To provide basin-wide lithostratigraphic context for the new drilling data, Ti Tree Basin drillcore from 1970s CRA exploration was re-evaluated at the Alice Springs core storage facility (operated by project partners, the Northern Territory Geological Survey). Dr Carmen Krapf from the Geological Survey of Western Australia (GSWA) provided expert guidance to project staff to classify the major sedimentary facies of the Ti Tree Basin and determine the likely depositional environments. The availability of drillcore near the main project investigation area offered a rare opportunity to calibrate the new rotary air blast (RAB) drilling data. This new analytical work helped to classify four distinct hydrostratigraphic facies in the Ti Tree Basin (Figure 22). Several sedimentary horizons rich in organic matter were also sampled for subsequent palynostratigraphic analysis, with results confirming that the deeper sediments in the Ti Tree Basin were deposited during the Eocene (Macphail, 2011). These analyses further suggested that several of the overlying (younger) sedimentary facies are of Miocene age, although the high degree of deep *in situ* weathering and the relative geographic isolation of the central Australian region have weakened palynostratigraphic interpretations (Macphail, 2011). They reveal that multiple cycles of Cenozoic deposition formed the stratigraphic sequences in the Ti Tree Basin, a finding that correlates with the origin and evolution of palaeovalley infill sediments in parts of Western Australia and South Australia.

2.4.3 Hydrostratigraphy

Existing drillcore data, new drilling results and palynostratigraphic analyses indicate that the infill sediments of the Ti Tree Basin can effectively be considered a three-layer hydrostratigraphic sequence (Figure 22). From top to bottom, this comprises an upper aquifer with mottled sandy clays (Ti Tree facies 4), a confining layer of relatively low hydraulic conductivity dominated by lacustrine clays and fine-grained sediments formed in a low-energy depositional environment (Ti Tree facies 3 and 2), and, at the base of the sequence, a deeper aquifer system consisting of silty sands interspersed with zones of well-sorted, quartz-bearing sands (the basal Eocene sequence designated as Ti Tree facies 1).

The characteristics of this entire sedimentary profile are largely unknown elsewhere in the Ti Tree Basin as most drilling only targeted the upper aquifer system. Cored drill holes through the entire sequence to basement rocks are even rarer. The distribution of the three hydrostratigraphic layers has been evaluated however, with access to data recently acquired by NuPower Resources Ltd, including rotary drilling data for several deep holes and a regional AEM survey. The preliminary conceptual three-layer aquifer model is shown as a series of cross-sections (Figure 23). These sections indicate that the basal Eocene sediments of facies 1 are geographically isolated in the Ti Tree Basin and occur only in several deeper troughs within discrete northern and southern parts of the basin.

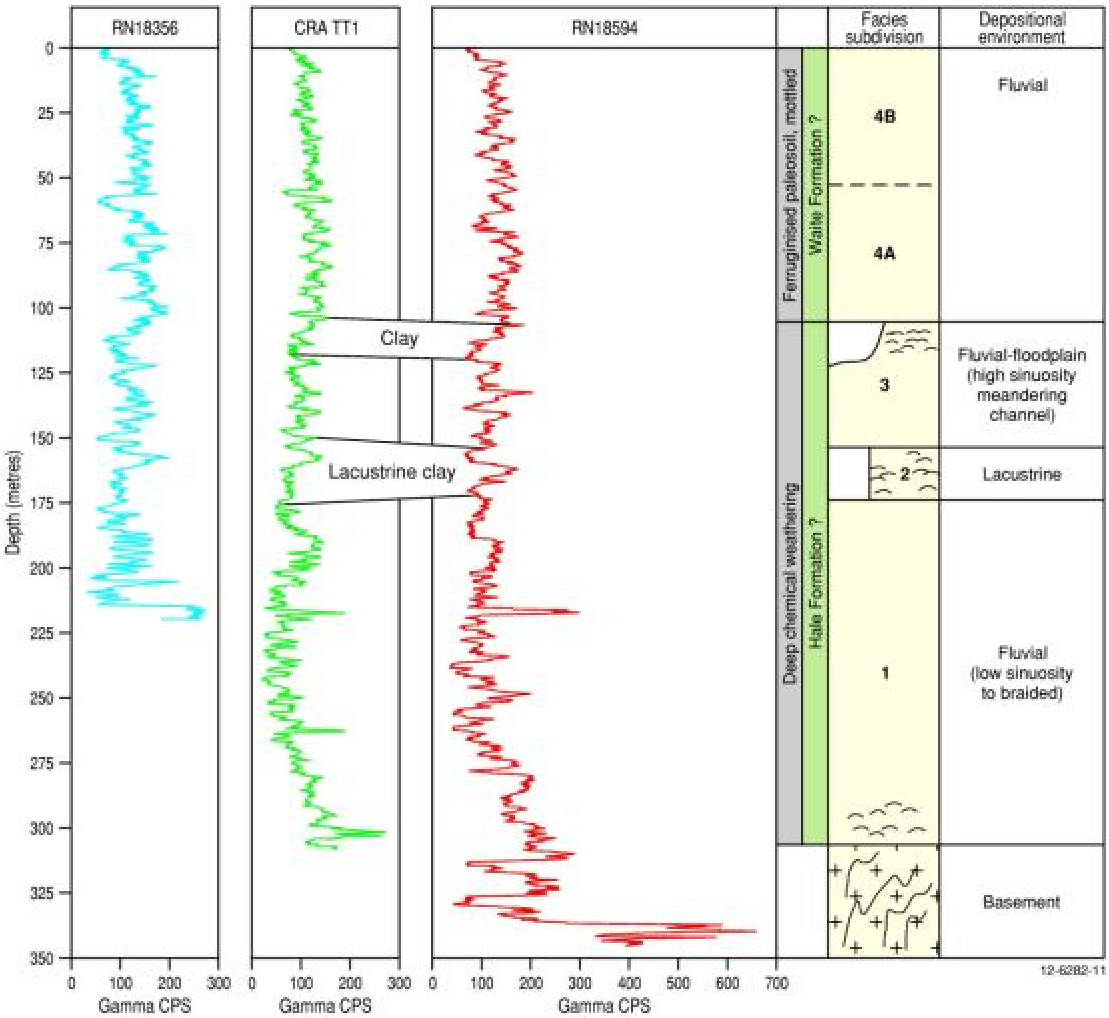


Figure 22: Comparison of downhole gamma logs for deep drill holes in the central Ti Tree Basin. The log for CRA TT1 was digitised from the paper record (O'Sullivan, 1973); RN18356 was drilled only 10 m away from CRA TT1, and matches closely. A schematic cross-section of the facies classification developed with Dr Carmen Krapf of Geological Survey of Western Australia is also shown for RN18594.

Stratigraphic correlation of the Ti Tree Basin with other palaeovalley systems in central Australia is difficult due to extensive deep chemical weathering, relatively poor preservation of microfossils, and the geographic isolation of many sites of Cenozoic deposition. This fact was also noted by Senior et al. (1995) in qualifying attempted Cenozoic correlations in central Australia:

> *… there is gross lithological similarity between the successions in the basins of the Alice Springs area, detailed correlation has been hampered by the weathering of many lithologies and the lack of fossils.*

Nevertheless, new palynological data acquired during this study suggest that the lower facies sequences in the Ti Tree Basin may be tentatively regarded as equivalents of the Hale Formation (Senior et al., 1995), whereas the upper aquifer layer probably correlates to the Waite Formation.

The new deep drilling program has confirmed the presence of significant sand-rich sediment sequences in deeper-than-expected parts of the Ti Tree Basin. Preliminary evaluation of the groundwater resources suggests excellent potential for high-yielding aquifers containing slightly brackish quality water. Furthermore, mineral exploration drilling (e.g. hole WF11 in Figure 23) in the south indicates that laterally extensive and thicker sand-rich sequences occur at depths parallel to the southern basin margin. This potential major extension to the aquifer sequence has yet to be tested for groundwater yield or quality. Spatially extensive and high-yielding, deep (~300 m below surface) groundwater resources containing potable to slightly brackish quality water may occur across significant areas of the Ti Tree Basin (based on their aquifer characteristics yet-to-be-proven similar to those encountered in drill hole RN18594).

In the northern Ti Tree Basin trough near RN18594 the slightly saltier groundwater in the deeper aquifer appears to have greater hydraulic head than the upper aquifer. This means that as the pressure is lowered (by extraction) in the upper aquifer, deeper and saltier groundwater may be drawn upwards to eventually mix with groundwater in the shallower aquifer. The magnitude of this interaction will depend on the vertical permeability of the separating aquitard layer. It is possible that even without reduction of head in the upper aquifer some deep groundwater is leaking into the upper aquifer layer. These results imply that any future work, necessary if the complete Ti Tree aquifer sequence is to be exploited and managed responsibly, should focus on groundwater heads and fluxes; in particular, a detailed understanding of the nature of connection between the upper and lower aquifer layers is vital.

2.4.4 Summary and conclusions

The key finding of the Ti Tree Basin investigative program is the increased likelihood of deeper, more extensive groundwater resources of slightly brackish quality water in high-yielding aquifers. These findings are of potential benefit to this major horticultural region of central Australia (DIPE, 2002). The development of a new conceptual three-layer aquifer model is also likely to be applicable to several other areas of central Australia (e.g. the Outer Farm Basin near Alice Springs) that contain relatively thick sequences of Cenozoic sediments (>300 m). Future management frameworks for these other regions should now also consider the possibility that deeper aquifer systems, possibly with different quality groundwater, may exist and be directly connected with the currently exploited shallower groundwater resources.

Other important conclusions that can be drawn from the Ti Tree Basin study:

- The extent, depth, thickness and salinity characteristics of the three-layer basin model suggest that at least some of the central Australian palaeovalley systems are, in a hydrogeologic sense, very different from the longer, more narrow and sinuous palaeovalleys typical of WA and SA;
- The hitherto unappreciated complexity of the Ti Tree Basin groundwater system discovered during this study acts as a cautionary tale for groundwater exploration and management elsewhere in the arid zone. It is likely many other palaeovalley groundwater systems will also prove similarly complex once assessed in greater detail.

Finally, the value provided by information in the long-forgotten Edworthy (1967) report, coupled with access to new exploration company data (deep drilling and AEM) in the southern Ti Tree Basin, clearly illustrates the benefit of assessing a wide variety of datasets for groundwater resource studies. This includes analysing data that are not traditionally considered as part of routine groundwater investigations, and applies even to those aquifers that have been relatively well studied.

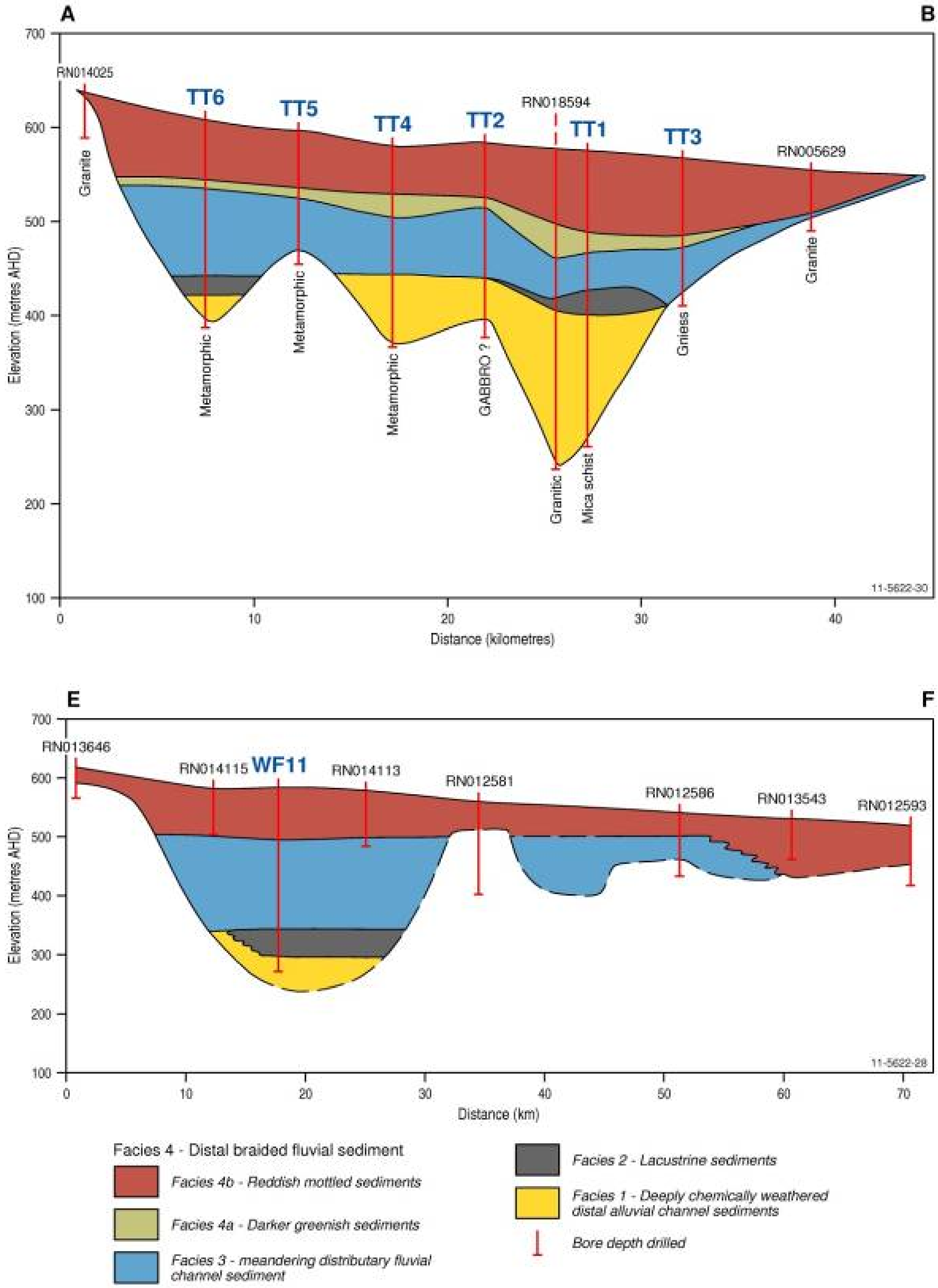


Figure 23: Regional cross-sections (A to B and E to F) for the Ti Tree Basin (note the differing scales of the images). Facies 4a is only distinguished from drillcore. The location of these cross-sections is shown in Figure 21.

The demonstrated relevance of mineral exploration data for groundwater assessments (and vice versa) indicates that jurisdictional government water departments and mineral resource departments should establish more formal working relationships to better inform and advise of relevant work programs and findings of interest to both parties. There are potentially significant outcomes and economic synergies in having clearer and more open communication between these separate government departments. For example, for the relatively minor costs of borehole casing and additional labour the deep NuPower Resources drill holes could have been established as monitoring bores to obtain groundwater quality and ongoing water level data for the southern Ti Tree Basin. However, as this opportunity was missed new water-bore infrastructure costing hundreds of thousands of dollars is now required to collect groundwater samples from this part of the deep aquifer.

The full report on this demonstration site is to be published as:

Wischusen JDH, Bastrakov EN, Magee JW, Gow LJ, Kilgour PL, Bell JG and Kelly T 2012, 'Ti Tree Demonstration Site Report – Palaeovalley Groundwater Project', *Geoscience Australia Record,* 2012/08, Canberra.

2.5 Wilkinkarra

Investigations in the Wilkinkarra demonstration site focused on three locations: the Kintore Palaeovalley, Nyirripi (Wilkinkarra) Palaeovalley, and the Central Mount Wedge Basin (Figure 24). These localities were predominantly 'greenfield' sites, with the main study objective to provide reconnaissance-scale data on key palaeovalley characteristics. No water bores had been drilled in the Wilkinkarra Palaeovalley so its depth, boundaries, stratigraphy and groundwater resources were essentially unknown. For the Kintore Palaeovalley a minor amount of information was available, such as the drilling data for the Western Water Study (Wischusen, 1998). The shallow parts of the Mount Wedge Basin (near Papunya community) had also been drilled and evaluated using ground geophysics (Lau et al., 1997), although the depth to basement, nature of sediment infill, and groundwater compositions for deeper sequences remained speculative.

2.5.1 Field investigation program

A range of ground-based geophysical techniques were trialled over areas where initial analysis of remote-sensing data (e.g. NOAA-AVHRR night-time thermal imagery) indicated the potential for palaeovalley systems. These surveys included micro-gravity traverses (~140 km of survey data acquired), seismic reflection (11 km completed), and time-domain electromagnetic surveying (~40 km transect completed). Following-on from the geophysical study 26 investigation boreholes totalling 1642 m were drilled using air and mud rotary methods (by the Northern Territory government drilling rig). Datasets acquired included stratigraphic and downhole geophysical logs (gamma), water chemistry analyses including stable and radiogenic isotopes, palynostratigraphic analyses, and time-series standing water levels.

2.5.2 Wilkinkarra and Kintore Palaeovalleys

Field investigations significantly improved delineation and mapping of both the Wilkinkarra and Kintore Palaeovalleys, and generated new insights on hydrostratigraphy and groundwater resources. Interpretation of these datasets suggested that the Kintore and Wilkinkarra Palaeovalleys were formed by incision of major river systems in pre-Cenozoic times, when the landscape had considerably greater relief than the subdued present-day terrain. In contrast, the Mount Wedge Basin was created, largely by tectonic activity, on the down-warped side of a major east–west mountain-front fault zone and subsequently infilled by a thick package of lacustrine and fluvial sediments.

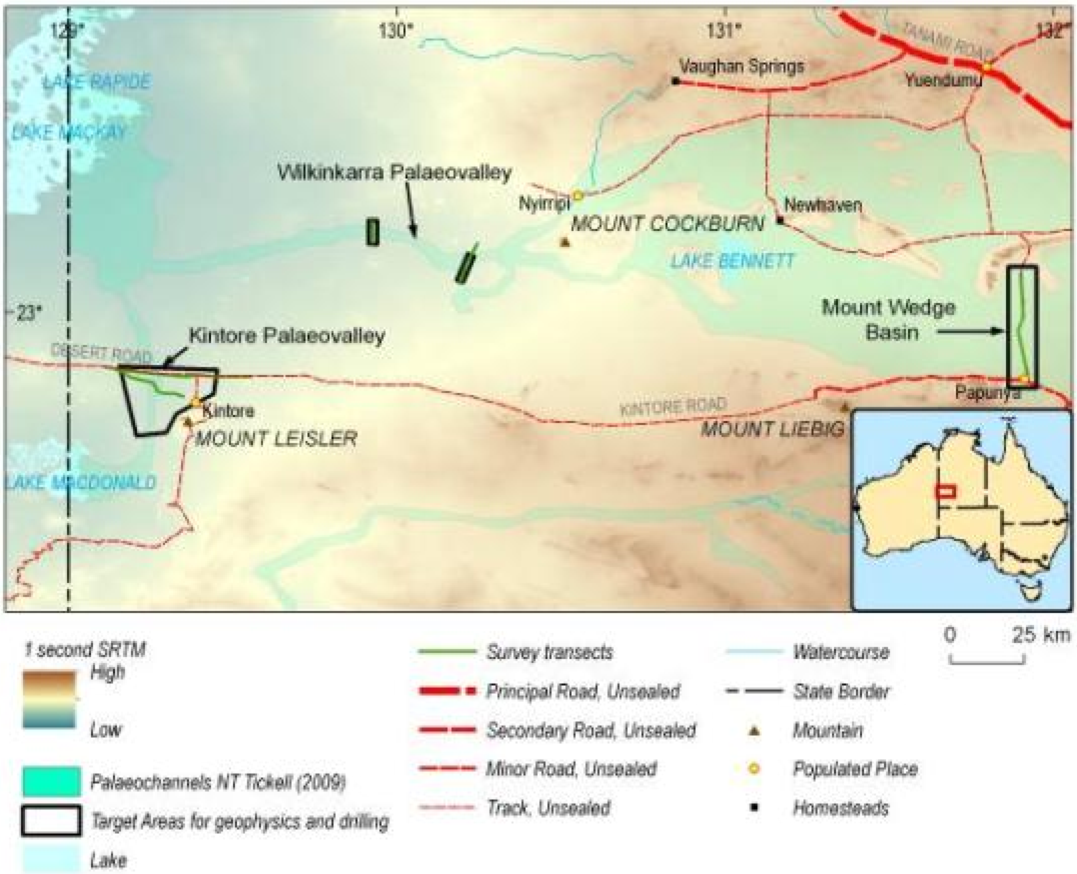


Figure 24: Location of Wilkinkarra demonstration sites (green lines are survey transects).

Drilling revealed that the Wilkinkarra and Kintore Palaeovalleys are broad and relatively shallow fluvial systems. The palaeovalley infill sediments were deposited on undulating and partly weathered basement rocks, deepening to approximately 130 m below ground level (Figures 25 and 26). The infill sediments are dominated by weathered and oxidised sandy alluvial facies, interbedded with fine-grained sediments such as clay and silt. Fining-upward sequences apparent in downhole gamma logs are typical of fluvial channel deposits. Black, silty clay containing organic matter was encountered at around 80 m depth below the surface in some of the Kintore Palaeovalley drill holes. Analysis of *in situ* fossil pollen spores indicated deposition likely occurred in the Middle to Late Eocene, suggesting restricted low-energy, swampy environments. Irregular calcrete deposits are widespread at or near the surface in both the Wilkinkarra and Kintore Palaeovalleys and commonly contain shallow potable groundwater.

Groundwater is abundant in both the Wilkinkarra and Kintore Palaeovalleys, with the watertables at relatively shallow depths (generally 3–5 m) below the surface. Groundwater is fresh to saline, salinity generally increasing down-gradient. Modern recharge to these palaeovalley aquifers is episodic, as indicated by time-series data collected over the course of an unusually wet period (2010–2011) from the two newly established monitoring-bore sites. The presence of fresh groundwater in this arid environment provides further evidence for modern recharge in these palaeovalleys.

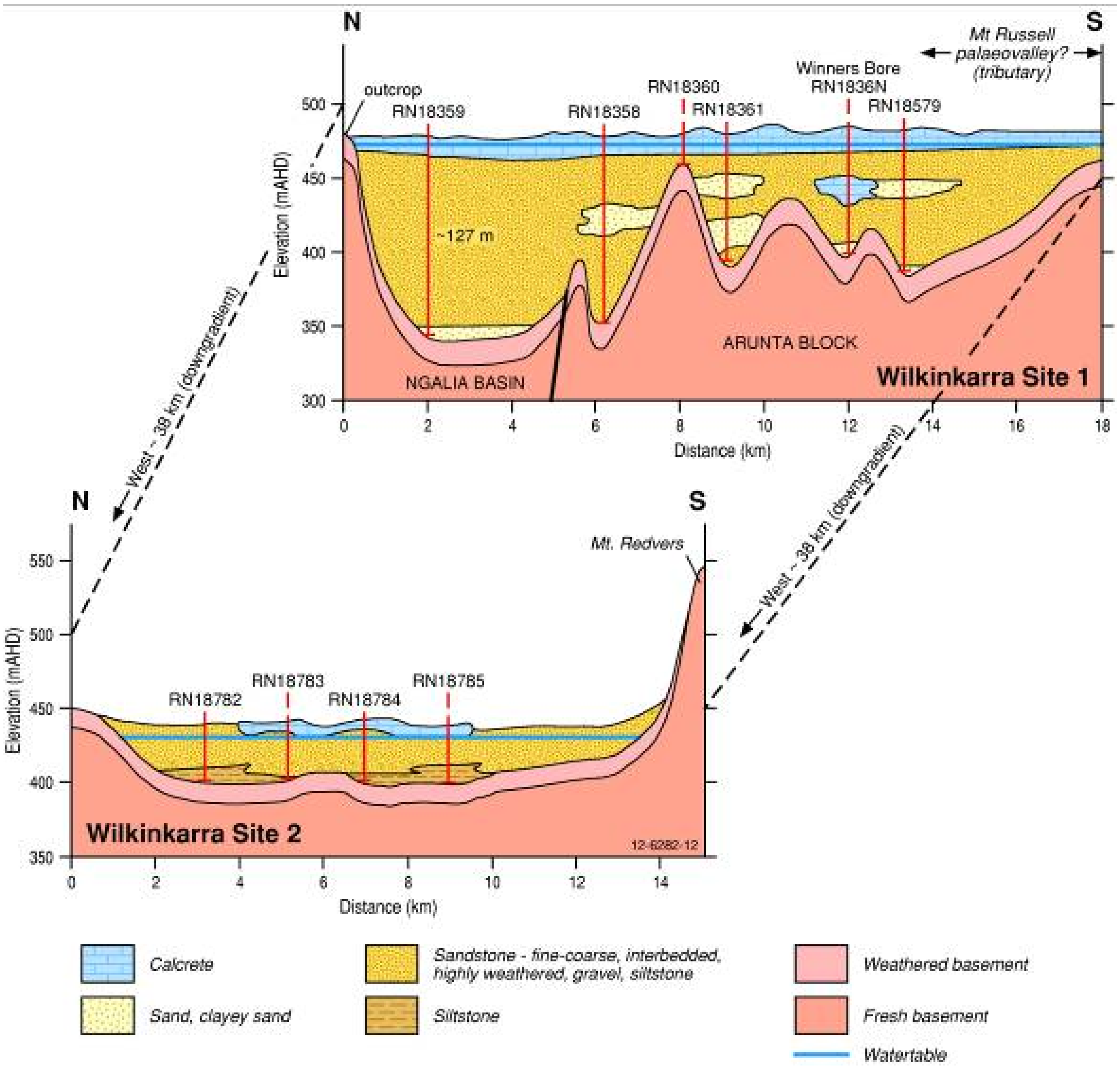


Figure 25: Schematic cross-sections for the Wilkinkarra Palaeovalley based on new drilling data. The investigative bores in the Wilkinkarra Palaeovalley are designated by their NT government water-bore database registered numbers (RN).

An important outcome of project investigations was the discovery of previously unknown fresh groundwater resources in both the Wilkinkarra and Kintore Palaeovalleys. These discoveries are potentially a significant benefit to the nearby communities of Kintore and Nyirripi; for example, the water resources could support horticultural activities as at Ti Tree. The palaeovalley aquifer is a possible future freshwater supply option for the local (within 5 km) people at Kintore community. Additional work undertaken by the project team led to the installation of a manually operated hand-pump (Winner's Bore) along a remote road that crosses the Wilkinkarra Palaeovalley, to be used for future emergency water supply situations, such as vehicle breakdowns (Wischusen and Lewis, 2010). The hand-pump represents both an immediate and durable benefit to the local community.

2.5.3 The Central Mount Wedge Basin

Seismic reflection data across part of the Central Mount Wedge Basin revealed the previously unknown structure of the entire infill sequence (Figure 27). The deepest basin identified from the seismic data, just north of Papunya community, was drilled to basement at 474 m below surface. This represents the thickest sequence of Cenozoic sediments discovered within any central Australian palaeovalley, and potentially the most significant accumulation of palaeovalley sediments within the entire Australian arid zone.

The stratigraphic composition of the basin comprises a thick (~350 m) and laterally extensive lacustrine sandy clay unit (the Mount Wedge Clay) overlain by coarser grained and strongly oxidised alluvial sediments (the Currinya Clay). The primary structures and sediment composition, as with those infilling the Kintore and Wilkinkarra Palaeovalley aquifers, are strongly overprinted by deep chemical weathering which hampers detailed facies analysis. Consequently, the stratigraphic profile of the Central Mount Wedge Basin is only correlated with sediments in the adjacent Lake Lewis Basin (to the east), although tenuous correlation with the Hale and overlying Waite Formation in other Cenozoic basins of central Australia may be possible with further work.

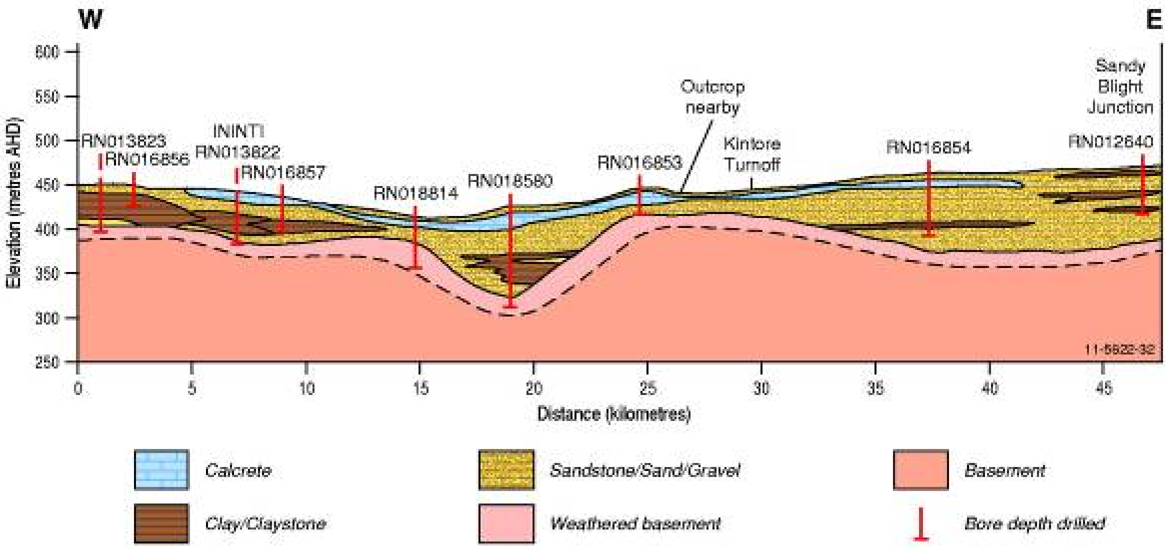


Figure 26: Schematic cross-section of Kintore Palaeovalley, showing finer grained sediments and the shallower infill sequence.

The watertable in the Central Mount Wedge Basin is consistently ~30 m depth below surface, although water quality varies spatially from fresh to moderately brackish. Groundwater is more saline in the deeper than the shallow aquifer, presumably due to longer residence times (confirmed by limited radiocarbon dating). This model suggests that groundwater recharge to deeper parts of the Central Mount Wedge Basin is significantly retarded by the thick clay-rich sequence that dominates the lower part of the basin. Groundwater generally flows north, with recharge via relatively porous montane alluvial fans and creek systems draining from the nearby uplifted Belt Range. Discharge is in salt playas to the north-west of Central Mount Wedge; consequently, the shallow aquifer salinity increases northwards (Figure 27).

2.5.4 Summary and conclusions

Multi-component field investigations in the Wilkinkarra demonstration site have clearly illustrated the usefulness of gravity, seismic,and electromagnetic surveys as well as drilling for reconnaissance exploration and mapping of palaeovalley systems. The successful delineation of palaeovalleys using geophysical techniques relies on distinct contrasts in physical (e.g. density or porosity) or electrical (e.g. bulk resistivity) properties between the palaeovalley infill sediments and the bedrock. This work has also shown that, as for most geoscientific investigations, drilling remains one of the most useful methods for acquiring information on the composition and structure of the subsurface. Drilling is also crucial for obtaining groundwater samples to evaluate water compositions and obtain residence time data.

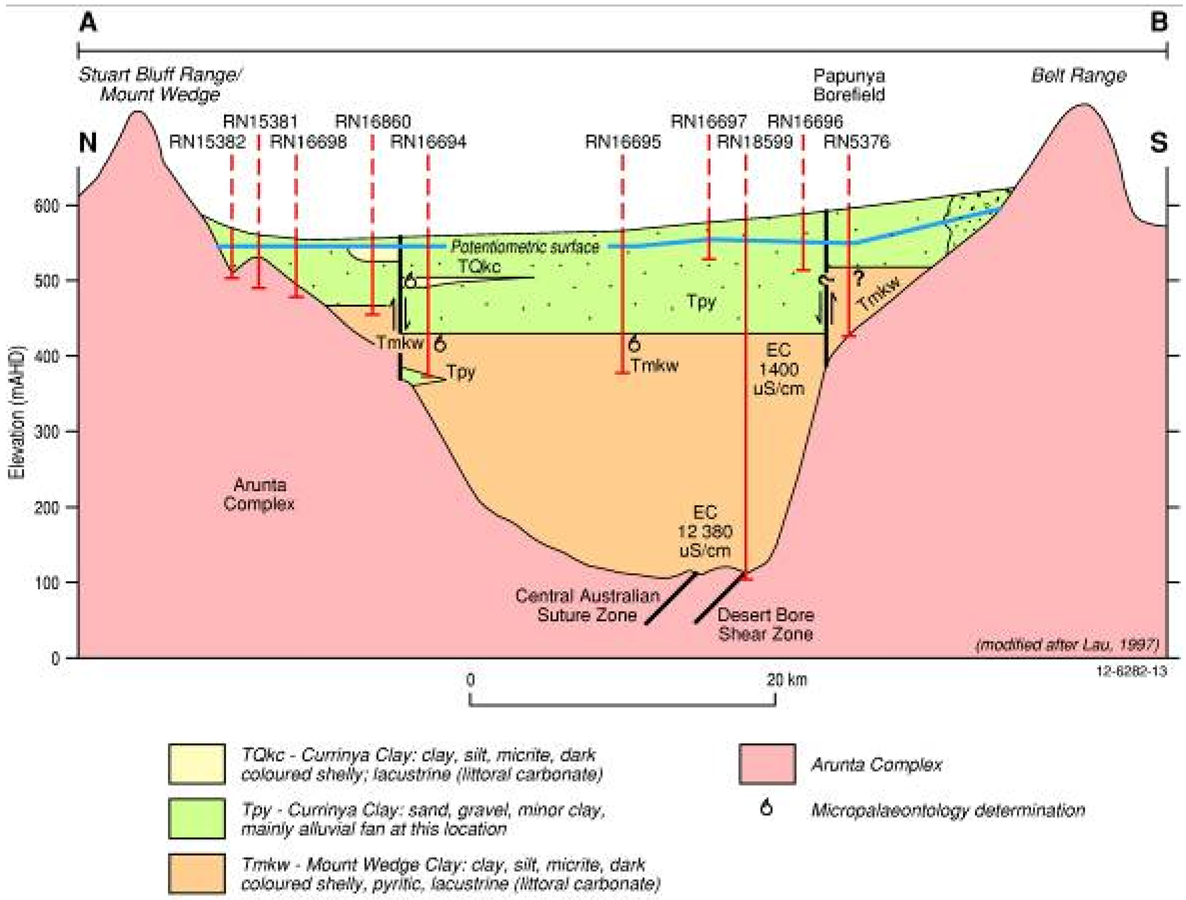


Figure 27: Schematic cross-section of the Central Mount Wedge Basin.

These field investigations have highlighted the variability of palaeovalley aquifers, especially for water quality (salinity) and sediment composition. Considerable heterogeneity exists between drill sites across all demonstration areas. The complexity of the palaeovalley systems renders difficult:

- stratigraphic correlation between sites
- reconstruction of depositional palaeo-environments
- prediction of freshwater location.

Nonetheless, investigations have significantly advanced our understanding of the distribution and groundwater characteristics of these palaeovalleys and also provided important insights for the broader understanding of arid-zone palaeovalleys in central Australia.

The full report on this demonstration site is to be published as:

Woodgate MF, Holzschuh J, Wischusen JDH, Gow LJ and Kilgour PL 2011, ‘Palaeovalley Groundwater Project – Wilkinkarra Demonstration Site Report’, *Geoscience Australia Record,* 2012/09, Canberra.

2.6 Summary of demonstration site investigations

Investigations carried out across the five demonstration sites were broad in scope and used a variety of methods in diverse terrains. The techniques employed at each site are summarised in Table 2, along with an explanation of the main research focus and the criteria or properties that the various methods aimed to evaluate. The table outlines the benefits of particular methods to address specific research questions relating to palaeovalleys and groundwater resources.

Table 2: Exploration and assessment approaches of field investigation programs at the five demonstration sites for the *Palaeovalley Groundwater Project*.

Study site	*Main research focus*	*Main field methods*	*Comments*
Gawler-Eucla	Hydrogeochemical evaluation of the Kingoonya Palaeovalley.	Groundwater sampling of bores identified in SA databases using GIS analysis.	Wide variety of analytical methods used to characterise groundwater, including major and minor ions, and stable and radiogenic isotopes.
Murchison	Regional reconnaissance study of 'greenfield' palaeovalleys, specifically to determine location in the landscape and cross-section, and evaluate the hydrostratigraphic profile and sediment composition.	1. Ground-based gravity survey transects over likely palaeovalley location (determined from terrain analysis); 2. Reverse Circulation and rotary mud drilling where gravity low appeared coincident with palaeovalley thalweg; 3. Construction of monitoring-bores and groundwater sampling.	Coincidence of gravity low and palaeovalley thalweg relies on density contrast between sediment infill and adjoining bedrock. Reliable depiction of density contrasts between unweathered bedrock and palaeovalley alluvium. Weathered bedrock has similar density to that of alluvium.
Paterson	Improved delineation of palaeovalley reaches near remote-area groundwater users (mainly mine sites), particularly beneath dense dune fields; determination of groundwater residence times in palaeovalley aquifers.	1. Regional airborne electromagnetic (AEM) survey completed for Onshore Energy Security Program required downhole conductivity logging and groundwater sampling in existing drill holes for data calibration; 2. Regional reconnaissance mapping and evaluation.	AEM data useful to map subsurface conductivity contrasts in geologic formations, including palaeovalleys with glaciogenic sediments (which can function as local aquifers). Zones of highly saline groundwater, particularly near salt lakes, tend to dominate AEM data.
Ti Tree	Preliminary characterisation of previously unknown deep groundwater resources, and revised hydrostratigraphic facies of the basin.	Drill multiple deep water bores and sample groundwater. Limited ground gravity surveying useful to site one borehole.	Mineral company and archival datasets enhanced interpretation of a previously well-studied site by elucidating significant and unanticipated palaeovalley aquifers. Drilling required to sample groundwater of deep aquifers.
Wilkinkarra	Regional reconnaissance study of 'greenfield' palaeovalley sites at Kintore and Wilkinkarra to determine cross-section shape, depth to basement, hydrostratigraphic profile, nature of sediments, and groundwater quality and residence times.	1. Ground-based gravity (and minor ground electromagnetic) surveys defined likely deepest part of palaeovalleys; 2. Rotary drilling to evaluate the structure and composition of sediments and to collect samples for palynology and groundwater analysis; 3. Seismic reflection survey completed at Mt Wedge Basin to site deep water bore to basal aquifer.	The combination of ground geophysics and follow-up drilling provides a wide range of very useful data to evaluate many features of poorly known palaeovalleys. Seismic data provides excellent characterisation of deeper palaeovalley basin-style architecture for bore siting to evaluate deep aquifers.

3. Palaeovalley regional mapping in Western Australia, South Australia and the Northern Territory

The new palaeovalley map covering most of arid and semi-arid Australia (Figure 28: Palaeovalleys of the arid and semi-arid regions of WA, SA and NT (reproduction of the map developed by Geoscience Australia for the *Palaeovalley Groundwater Project*

) is an important outcome that stemmed from the *Palaeovalley Groundwater Project*'s 4th Technical Advisory Group Workshop in Canberra (April 2010), agreeing that '*a consistent WA–SA–NT semi-arid and arid-zone palaeovalley map would be a highly beneficial outcome of the overall project*'. The acronym 'WASANT' was subsequently adopted, indicative of the region assessed for the palaeovalley map by this project. Geoscience Australia will publish the WASANT Palaeovalley Map (available in both hard- and digital-copy formats at http://www.ga.gov.au/cedda/maps/96) as a companion product of this report. This chapter provides an overview of the approach used to generate the thematic WASANT Palaeovalley Map, focusing on the application of the main input datasets and their respective limitations. Regional-scale variations in palaeovalley features are also discussed, and uses of the map suggested.

The WASANT Palaeovalley Map[8] was built on the legacy of pre-existing maps produced in Western Australia (Commander, 1989), South Australia (Hou et al., 2007), and the Northern Territory (Tickell, 2008). These state/territory-based thematic maps (prepared at either 1:2 000 000 or 1:2 500 000 scale), although not solely focused on palaeovalley systems, were the appropriate basis for updated representation of palaeovalleys using a consistent national-scale approach.

The Palaeovalley Map is the first attempt to draw together a range of existing geoscientific data and information relevant to palaeovalleys, combined with other national-scale datasets and expert knowledge. The map defines the spatial extent of regional palaeovalleys in the Australian arid landscape, especially where they occur beneath extensive desert dune fields. The resultant map is intended to enhance knowledge of Australian palaeovalleys as widespread and distinctive geologic elements, and potentially contribute to an improved understanding of palaeovalley aquifers and their groundwater resources. However, the map does not replace more detailed palaeovalley mapping that may exist in some areas.

3.1 Mapping objectives

The WASANT Palaeovalley Map adopted a consistent approach across the entire arid to semi-arid study region at 1:4 500 000 scale. This required not only a coherent methodology but also a consistent definition of the term 'palaeovalley', especially the distinction between palaeovalleys and palaeochannels (see Section 1.7, based on Magee, 2009). Previous broad-scale maps in Western Australia, South Australia and the Northern Territory which had included palaeovalleys or related landforms (outlined above) were designed with different objectives. They also used different development methods and, consequently, lacked a standard approach or set of input data.

Palaeovalley refers to the entire depositional zone in the relict valley system, bounded by hillslopes on either side. In contrast, palaeochannel is the buried thalweg(s) of the

8 Also referred to as 'the WASANT Map' or the Palaeovalley Map'.

palaeovalley system (Figure 3). Some earlier maps focus on depicting palaeochannels whereas others have mapped the broader fluvial depositional zone. In most cases, the WASANT Palaeovalley Map represents palaeovalleys as the entire depositional zone between adjoining slopes.

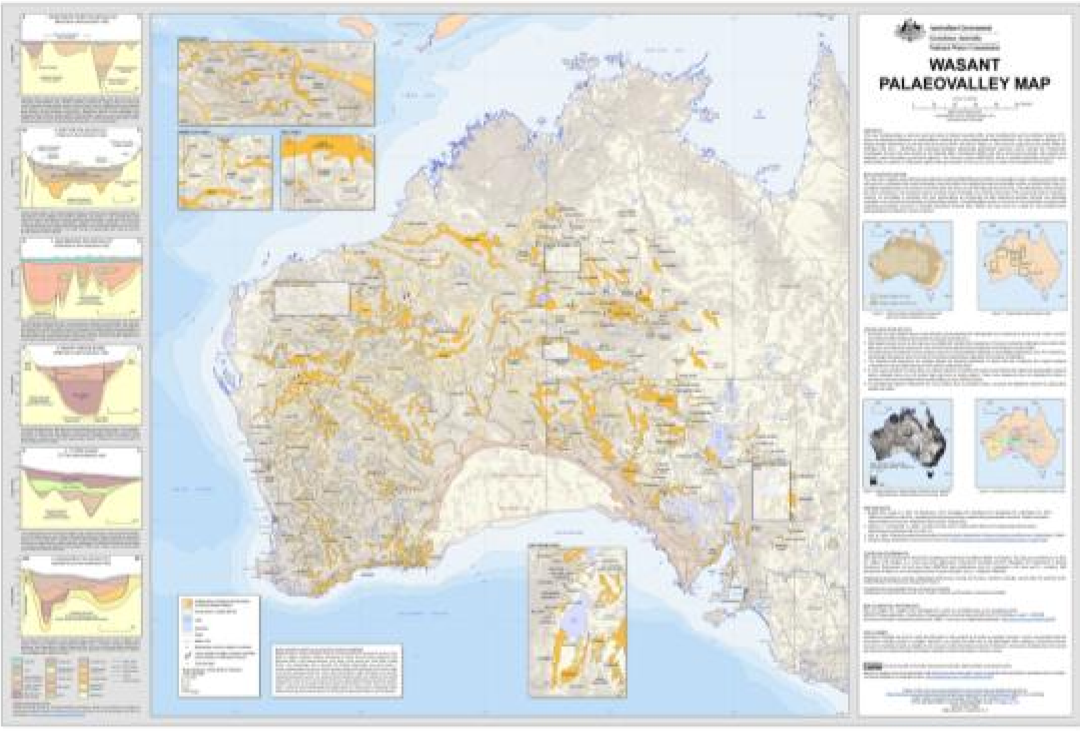


Figure 28: Palaeovalleys of the arid and semi-arid regions of WA, SA and NT (reproduction of the map developed by Geoscience Australia for the *Palaeovalley Groundwater Project*

In line with the overall *Palaeovalley Groundwater Project*, the WASANT Palaeovalley Map would cover the arid and semi-arid areas only, as defined by the Köppen-Geiger climate classification scheme (Chapter 1). This excludes parts of northern Australia, some coastal areas, and south-western Western Australia. As palaeovalleys do not always terminate at the edges of the arid or semi-arid zones, mapping of discrete palaeovalleys was extended outside this boundary in several regions. This allowed for improved understanding of overall palaeodrainage systems. However, contemporary drainage lines with mapped Quaternary alluvium (Qa) on published geology maps have not been included, except where there are supporting data or expert knowledge to substantiate the presence of an underlying palaeovalley.

3.2 Time and budget constraints

The WASANT Palaeovalley Map was developed and produced within the final 6 months of the 4-year *Palaeovalley Groundwater Project*. This constraint meant that the mapping approach relied mainly on the use of GIS to compile available datasets and local geologic or hydrogeologic knowledge. The scope of the mapping exercise did not allow for incorporation of drilling data (except in the Northern Territory) or other forms of 'ground-truth' to validate the GIS outputs. Such work is recommended as part of any future refinement of the map, as they provide valuable data related to sedimentary infill depths to further assess the results of initial palaeovalley mapping.

3.3 Development of the Palaeovalley Map

Palaeovalleys are complex hydrogeological systems with limited surface expression in the arid regions of Australia. They are commonly buried under dunes and sand sheets with the deep thalweg zone, potentially the most prospective aquifer, difficult to locate without the use of geophysics and follow-up drilling.

There are, however, some surface features which may provide clues to the location of buried palaeovalleys. These include the presence of:

- low and flat-lying valley base landforms suggesting areas of sediment deposition
- chains of salt lakes, which are the remnants of former active fluvial systems and commonly zones of groundwater discharge
- secondary surface rock types formed by processes of chemical deposition, such as calcrete, ferricrete and silcrete.

These terrain features, which may assist in detecting palaeovalleys, were used to develop the Palaeovalley Map. The key mapping inputs and development processes used to generate the map are further discussed below.

3.3.1 Existing mapping data

Existing maps from each jurisdiction were used to guide the development of the WASANT Palaeovalley Map. These maps were also used to gauge the usefulness of various national-scale datasets for mapping palaeovalley systems through visual comparison of data, for example displaying GIS data on adjacent computer monitors. The maps listed below were the most useful as they all contain palaeovalley-related features in one form or another[9]:

- Hydrogeological Map of Western Australia, 1:2 500 000, published by the Geological Survey of Western Australia (Commander, 1989)
- 1:250 000 hydrogeological maps of the southern part of the WA Goldfields (Figure 29) and more (not depicted) of the Wheatbelt to the south coast have been published by the Geological Survey of Western Australia, the Waters and Rivers Commission and the WA Department of Water (http://www.water.wa.gov.au/Publications/Find+a+publication/default.aspx)
- Palaeodrainage and Tertiary Coastal Barriers of South Australia, 1:2 000 000, Geological Survey Branch, SA Department of Primary Industries and Resources, (Hou et al., 2007)
- Groundwater of the Northern Territory, 1:2 000 000 scale, published by the NT Department of Natural Resources, Environment and the Arts (NRETA), Palmerston, NT (Tickell, 2008).

As an example, the Hydrogeological Map of Western Australia depicts ‘shallow aquifers’ which, in many arid and semi-arid parts, correspond closely with the location of palaeovalleys. However, these ‘shallow aquifers’ are not palaeovalleys *per se*, as they include several large areas of Quaternary alluvium (Qa) present on the west coast, as well as in modern river systems not associated with palaeovalleys, such as the Fitzroy River.

9 In the present report these compilations and publications are commonly referred to as ‘state/territory palaeovalley maps’, ‘state/territory-scale palaeovalley maps’ or ‘pre-existing palaeovalley maps’.

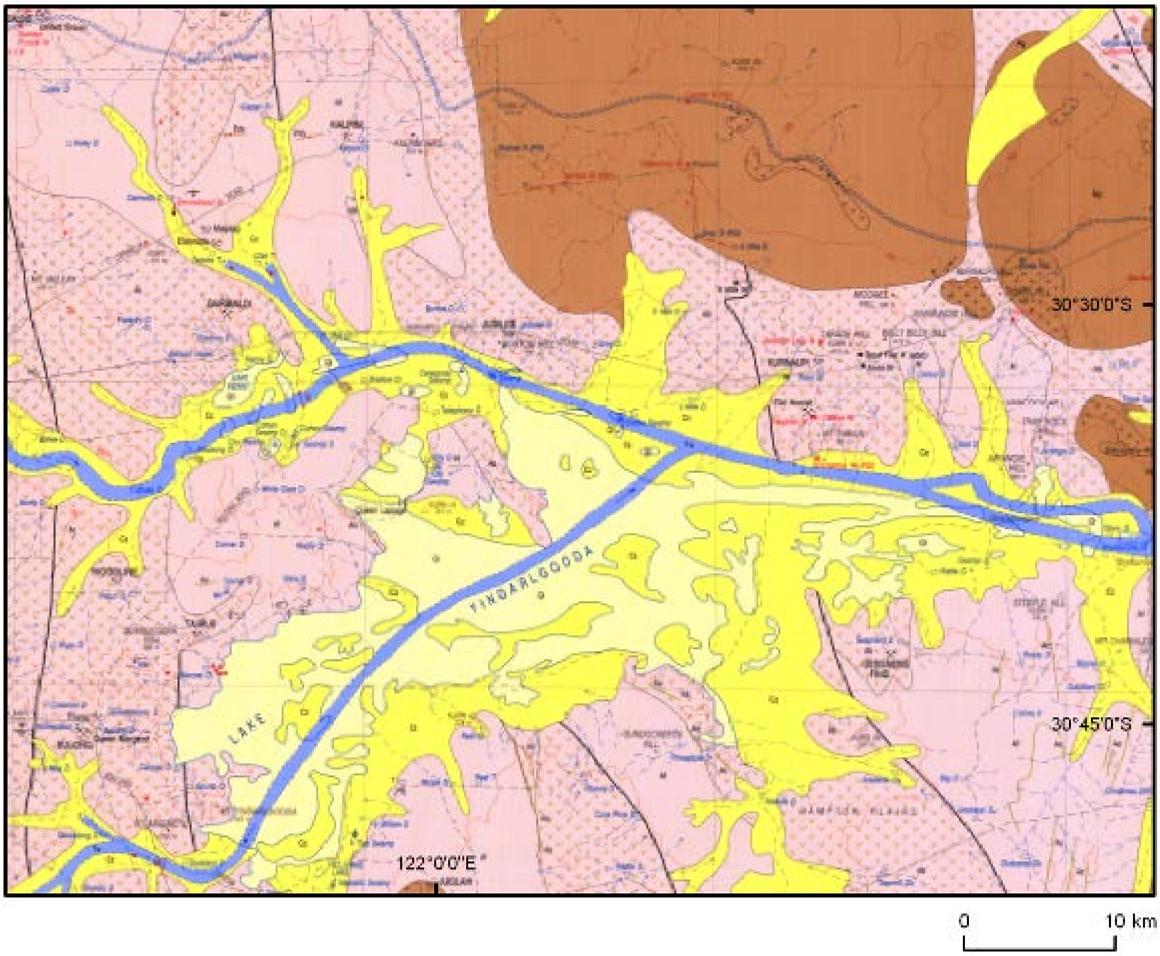


Figure 29: The Kurnalpi hydrogeological map in the Goldfields region of WA (reduced from 1:250 000 original scale). The blue lines are palaeochannels interpreted from detailed drilling (red dots), and the yellow zones depict sediments related to the main palaeovalley system. The Archean to Proterozoic bedrock (granite–greenstone) is in pink and brown.

3.3.2 Remote-sensing imagery

Diverse, remotely sensed imagery, satellite-borne in particular, were evaluated as mapping tools in the early development stages of the WASANT Palaeovalley Map. Previous work by Hou et al. (2007), and reviews of remote-sensing platforms for the *Palaeovalley Groundwater Project* (e.g. Magee, 2009, Gow et al., 2012, and respective chapters in project Milestone 4 and Milestone 7 reports) showed that night-time infra-red (NTIR) data acquired by several satellite systems may assist in defining palaeovalleys. These satellite sensors detect temperature variations in the sediments and surrounding bedrock, caused mainly by differences in moisture content, mineral composition and surface texture (Statham-Lee, 1995). The radiant surface temperatures recorded by the sensors are products of kinetic temperature and the ability of the sediments/rocks to absorb and re-radiate thermal energy (known as emissivity). Thermal contrasts between palaeovalley sediments and bedrocks are generally greatest pre-dawn, as night-time cooling is an important control on the amount of radiant temperature detected (as well as the amount of insolation and the material's thermal properties, Hou et al., 2001). In NTIR imagery, darker tones represent cooler areas (potential palaeovalleys) and lighter tones are warmer. Image interpretation can be complicated by wind shear (Baohong Hou, GSSA, pers. comm., 2012). Further information on all satellite systems used in this project is compiled in the Palaeovalley Investigative Toolbox (Gow et al., 2012).

Selected broad-scale, remotely sensed imagery data were initially processed and scrutinised to determine their suitability for national-scale palaeovalley mapping of the WASANT. This included NOAA-AVHRR[10] and ASTER[11] data, with respective resolutions of 1 km and 15–90 m. This work showed that satellite-derived imagery with large pixel or grid cell sizes (covering relatively wide areas) may reveal parts of larger palaeovalley features such as trunk palaeovalleys. However, finer scaled palaeovalley features such as upland tributary systems are difficult to depict using the NOAA-AVHRR dataset. Detailed analysis of pre-dawn data from multiple areas across the WASANT showed poor correlation of NOAA-AVHRR imagery with previously mapped palaeovalleys (as depicted on the existing maps listed above), mainly because of the relatively coarse resolution of this dataset (Figure 30).

Preliminary assessment of higher resolution imagery from the ASTER satellite was also conducted (Gow et al., 2012). Despite the enhanced resolution available with ASTER data and the ability to collect multiple data bands including thermal infra-red, it was unsuitable to use for the entire WASANT area because:

- numerous (several hundred) images are required due to the much smaller swath of individual scenes
- the optimal timing and conditions for data acquisition to define palaeovalleys is pre-dawn, cloud-free, and following significant rainfall events, i.e. greater than 50 mm. These conditions are rare in arid Australia.

Thus, the time (work hours) required to search available archives or wait to acquire new data from specific regions, coupled with acquisition costs and limited investigation area per scene, were beyond the scale and scope of the current project. However, the acquisition of ASTER data (especially with thermal infra-red bands) for specific local-scale palaeovalley investigations in arid Australia is recommended as the enhanced resolution is capable of providing important information on palaeovalleys.

3.3.3 Digital elevation models and derived products

The national-scale DEM developed from SRTM data was used extensively to generate the WASANT Palaeovalley Map, either directly or through application of the derived MrVBF (Gallant and Dowling, 2003). The national DEM is currently available at 1-arc second (approximately 30 m) resolution and is particularly useful for depicting the present-day drainage divides, or watersheds, between palaeovalleys (Figure 31). Across much of the continent the modern divides correspond with ancient drainage divides of the Cenozoic (neotectonism notwithstanding) and provide an indication of the catchment areas of given palaeovalley systems. This is relevant to the recharge of palaeovalley aquifers in the modern climate. The high-resolution DEM dataset was also used to revise and refine the extents of previously mapped palaeovalleys. It enabled identification of confluences and disruptions in valley courses, at least with respect to imagined river flow in these now arid landscapes. The DEM also elucidated features such as abrupt terminal zones which occur on some palaeovalley systems, for example the south-flowing palaeovalleys of the southern Yilgarn Craton which are truncated by marginal marine basin sediments deposited by Eocene to Miocene transgressions of the Eucla Basin.

The MrVBF of Gallant and Dowling (2003) can be used to differentiate various landscape components, especially low and flat-lying valley floors from steep slopes and hilltops (refer to Gow et al., 2012 for further information on MrVBF). Most WASANT palaeovalleys are located beneath wide and flat modern valley floors. Commonly, the adjacent and relatively steeper

10 NOAA-AVHRR is the acronym for the National Oceanic and Atmospheric Administration – Advanced Very High Resolution Radiometer.

11 ASTER is the acronym for the Advanced Spaceborne Thermal Emission and Reflection Radiometer.

hillslopes on either side of the valley consist of bedrock outcrop or colluvium mantling bedrock, typical of desert regions world wide. The flat valley bottoms are very commonly blanketed by sand dunes or other surficial material within the WASANT area. However, the MrVBF output substantially mitigates the blanket-like effect of dune fields, improving definition of flat alluvial depositional valley floors, as well as the adjacent slopes. Comparison of the MrVBF dataset and existing state/territory-scale palaeovalley mapping showed excellent correlation between low and flat valley bottoms and the previously defined palaeovalley margins for Western Australia (Commander, 1989), South Australia (Hou et al., 2007), and the Northern Territory (Tickell, 2008), for example Figure 32.

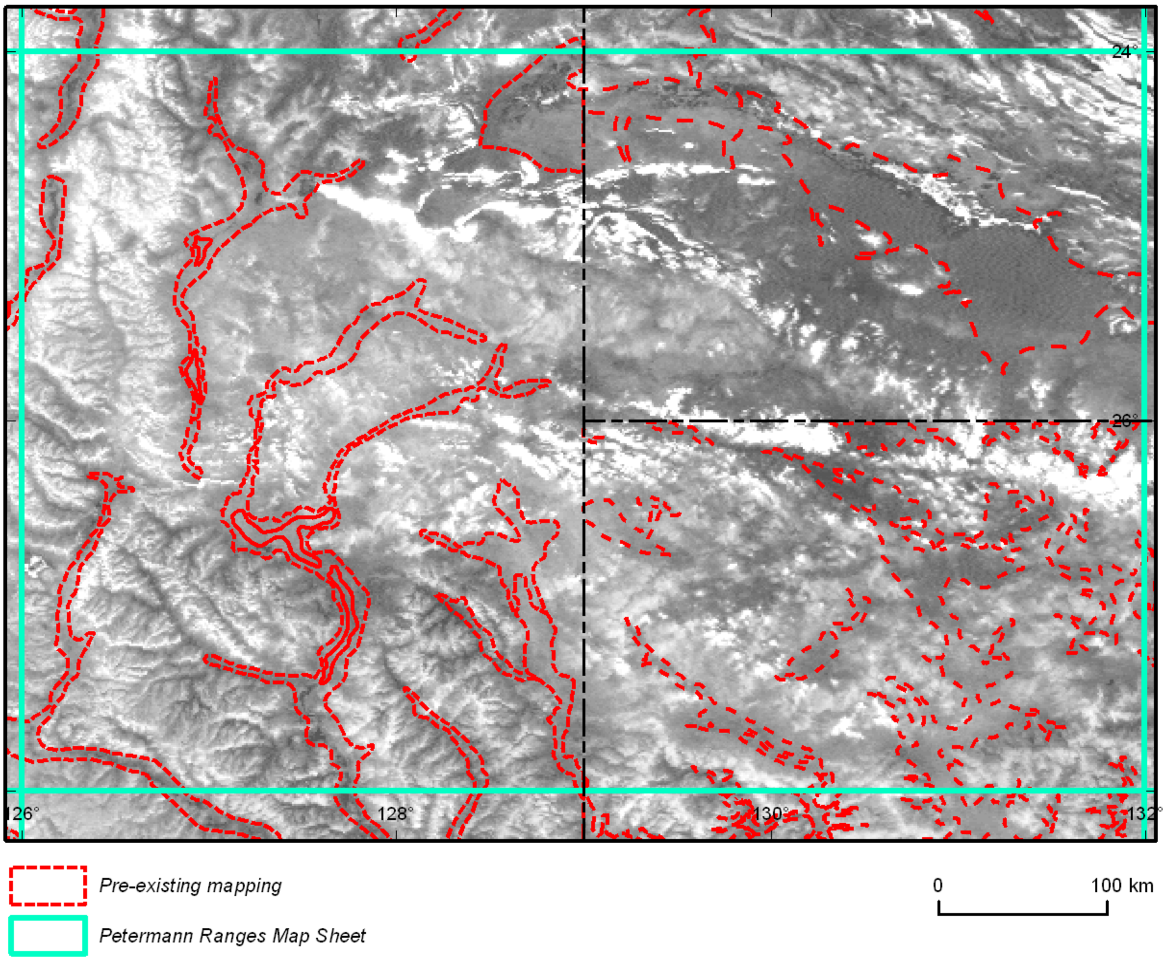


Figure 30: NOAA-AVHRR (pre-dawn) thermal image showing the Petermann Ranges 1:1 million-scale mapsheet at the border of WA–SA–NT. Darker tones may correspond with relatively cooler palaeovalley sediments having shallow watertables. The red dashed lines represent palaeovalley features published on WA, SA and NT maps.

Evaluation of the MrVBF outputs generated from both the 1-arc second (30 m grid cell size) and 3-arc second (90 m grid cell size) SRTM data was completed across all demonstration sites for the *Palaeovalley Groundwater Project*. Detailed analysis of the MrVBF dataset highlighted its suitability as a foundation dataset for the WASANT Palaeovalley Map, particularly as it can be consistently applied across all geologic and geographic regions.

Application of the MrVBF DEM

A conceptual model was first established to determine how to apply the MrVBF DEM to assist with interpreting and depicting palaeovalleys over the WASANT study area. This helped develop consistent guidelines for the mapping procedure to ensure coherent and robust outputs that were as scientifically valid as possible at such a broad scale.

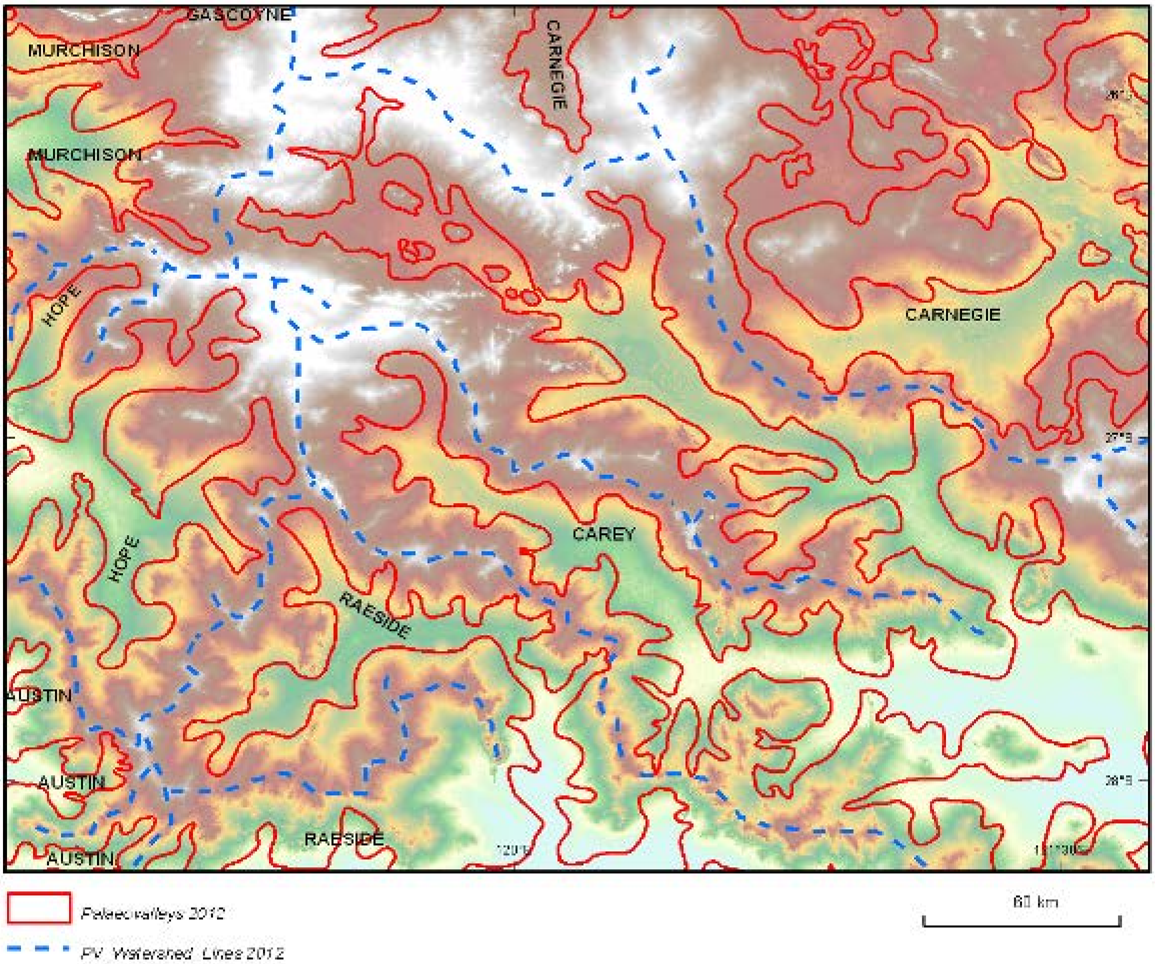


Figure 31: Example of present-day watershed divides developed from the national 1-arc second DEM (high elevations in white and red, low elevations in pale green and blue). The dark blue dashed lines display high points in catchments between valleys. Some may indicate watersheds developed when the original rivers were active.

The series of published 1:250 000 hydrogeological maps of the Western Australian Goldfields (referenced above) were used to evaluate the effectiveness of the MrVBF imagery for mapping palaeovalleys at relatively fine scale. The published hydrogeological maps show the palaeovalley depositional zone, basal palaeochannels (thalwegs, derived from drill-hole data), bedrock outcrop and borehole sites.

Several of the Goldfields 1:250 000 hydrogeology maps were scrutinised using MrVBF imagery within GIS by importing and georeferencing the maps (Figure 33). This allowed for direct comparison of palaeovalley features with the regional geology and various landmarks, as respective datasets could be overlain and compared. Initial variations were noted with the style used for individual 1:250 000 hydrogeology maps. For example, some depict alluvium and colluvium outlines extending further along tributary side valleys than other maps, suggesting some degree of individual interpretation by respective authors. As the published Goldfields maps were the result of many years of detailed field mapping, ground geophysical surveys and drilling over relatively small areas, it was possible to represent the buried thalweg channels at the base of the palaeovalleys. This work showed that within bounding valleys the thalweg zone is located variably with a meandering course that is, in places, close to the edge of or outside the present-day flat valley bottom zone (Figure 33). These variations, disclosed through reliable field investigations and detailed data-points, reinforced the view that attempting to map or represent the buried basal palaeochannel, or thalweg, or to predict its course, is generally not possible remotely, least of all at the national scale.

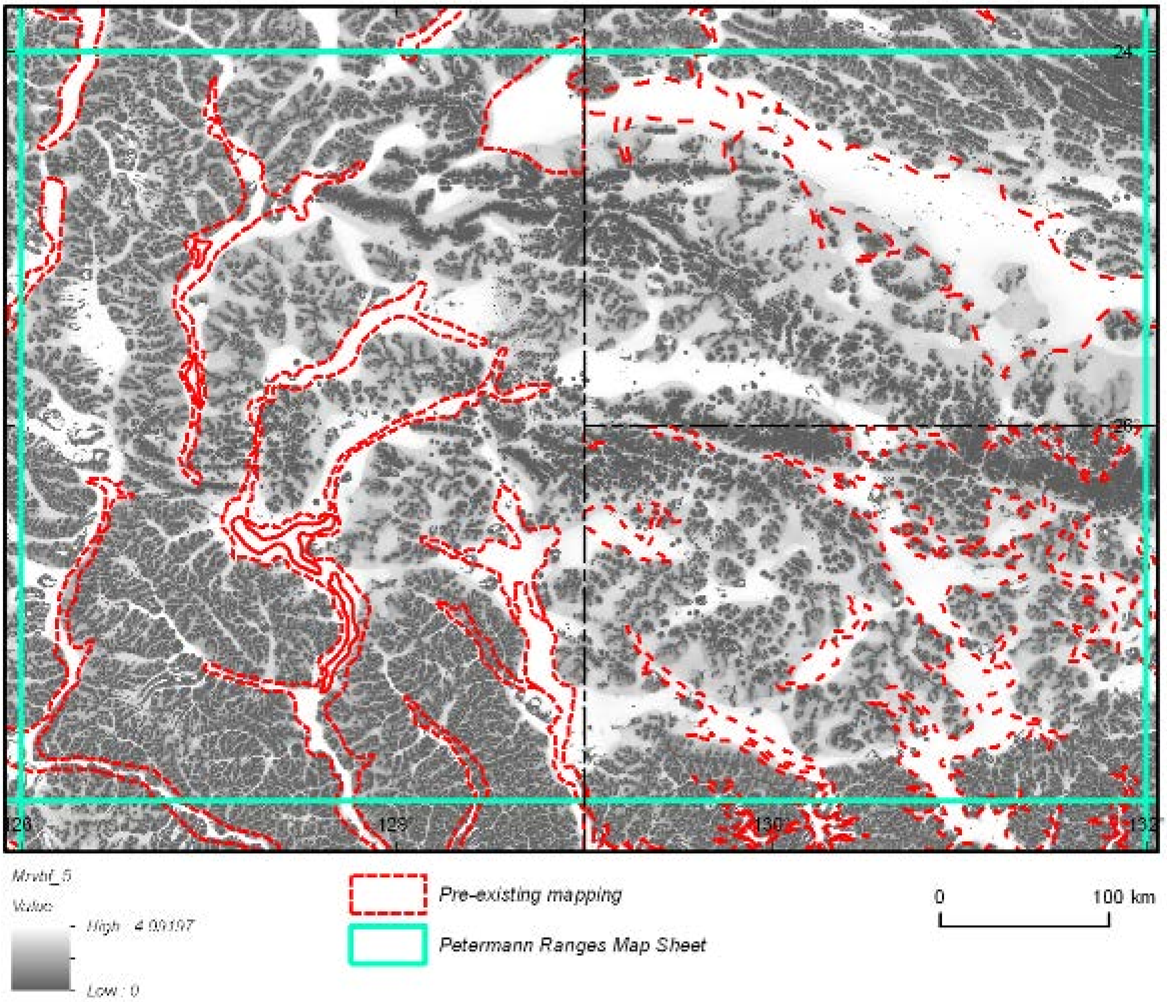


Figure 32: The 1:1 million-scale Petermann Ranges map sheet showing pre-2012 palaeovalley-related mapping (red dashed lines) superimposed on the regional MrVBF image.

Flat valley base used for mapping

Comparison of the different shades of topographic-based gradations in the MrVBF scheme and mapped zones of alluvium and colluvium on the Goldfields 1:250 000 hydrogeology maps showed that the palaeovalley margins needed to be modified. In particular, valley boundaries were extended to the edge of the white valley basal zone, or into the first or second order tier of the grey-scale MrVBF scheme, depending on slope and landform features. Importantly, in some cases, local knowledge or reference to detailed previous mapping, where available, meant that palaeovalley boundaries were extended into areas classed as 'steep or high' (darker shades) in the MrVBF scheme. These anomalies indicated that consistent and precise correlations between remotely acquired data and the actual course of a buried palaeovalley (as determined by drilling or geophysics) are not realistic or achievable due to subtle landform and terrain variations. The detailed evaluation of the MrVBF dataset showed that, for the most part, it is a reliable and useful tool for representing palaeovalley systems at the regional, state/territory or national scale, even though it cannot be used to predict or map the position of the buried thalweg aquifer.

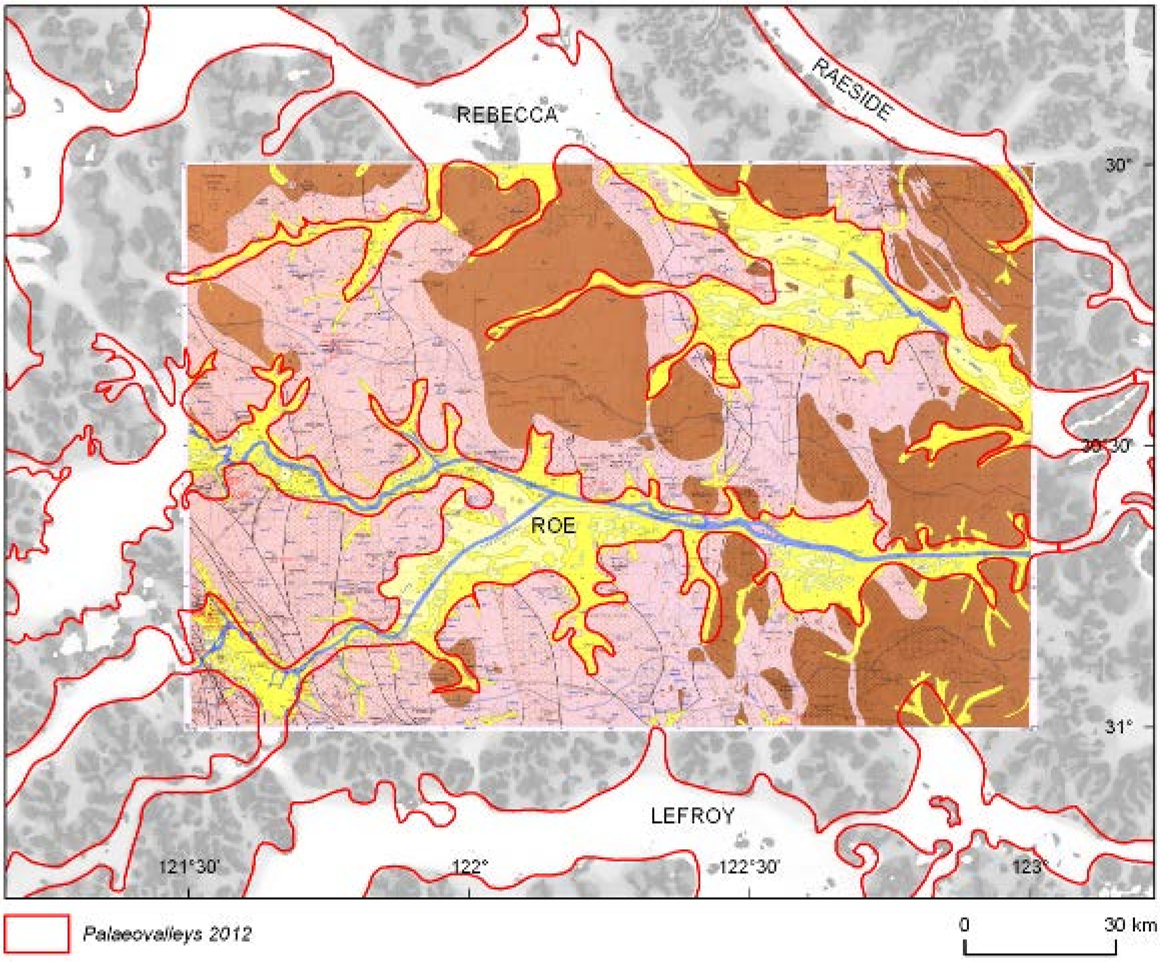


Figure 33: Comparison of the Kurnalpi 1:250 000-scale hydrogeological map with the flat valley bottoms identified from the national MrVBF (red lines and grey background). The Raeside, Rebecca, Roe and Lefroy Palaeovalleys are shown.

Extending the concept to the entire map

Following initial testing and evaluation the MrVBF technique for mapping flat valley bottoms was extended beyond the Goldfields region to the rest of arid Western Australia (Figure 34). Detailed hydrogeological mapping does not exist for most parts of Western Australia, so the 'shallow aquifers' defined on the 1:2 500 000 Hydrogeological Map of Western Australia (Commander, 1989) were used as a guide. This approach provided a consistent state-wide mapping methodology and allowed particular regional inconsistencies between the state-scale map and the MrVBF dataset to be identified. It also permitted integration of other datasets and piecemeal information (where available) to provide more comprehensive mapping. Following application for all of Western Australia, the MrVBF approach was extended to South Australia and the Northern Territory study regions.

Regional variations in MrVBF

Differing geomorphology across geological regions is revealed in MrVBF DEM and has influenced the style of palaeovalleys, such that distinct patterns typify certain regions of WASANT (Figure 35). For example, Hamersley Province valleys that contain palaeovalley aquifers are relatively narrow and difficult to define using MrVBF. Many of these palaeovalleys occur within the darker shades of the MrVBF scheme, where palaeovalleys would not usually be mapped at the regional scale unless reliable 'ground-truth' data exists. In this area, remote mapping of palaeovalleys was more readily achieved using the original 3-arc second SRTM DEM with scenes zoomed to differentiate areas of maximum relief and maximum resolution of topographic features (with the MrVBF only displayed as a transparent overlay). The MrVBF, although generally very useful, cannot be universally applied to map palaeovalleys across all regions. Rather, it provides a consistent initial frame of reference to use in tandem with other key datasets.

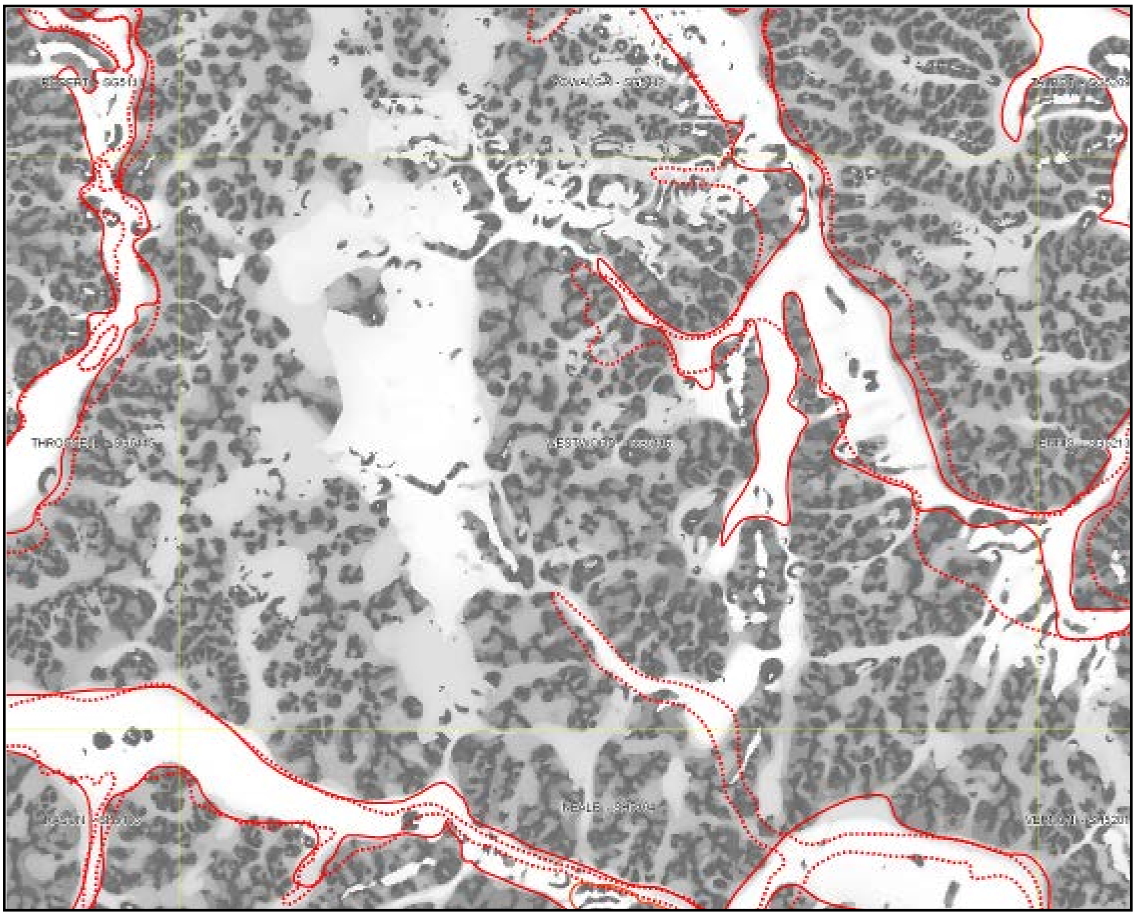
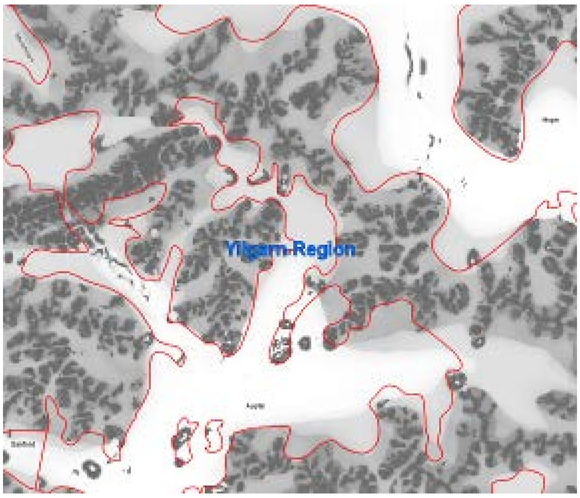


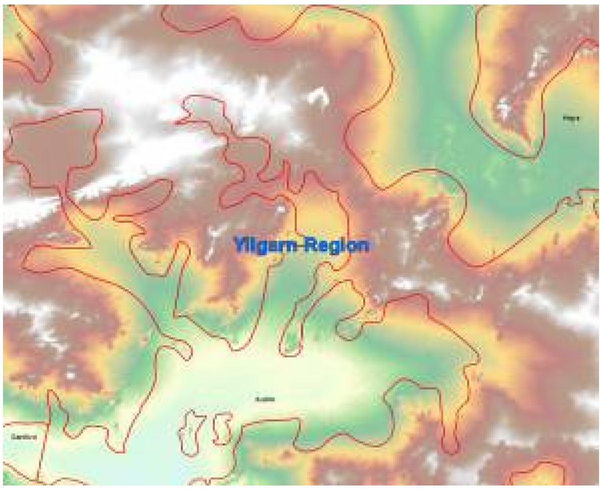
Figure 34: The MrVBF image (grey background) for the Westwood (SG5116) 1:250 000-scale map sheet in remote WA. The solid red lines show interpreted palaeovalleys and the red dotted lines 'shallow aquifers' from the Hydrogeological Map of Western Australia.

3.3.4 Applying other data sets and information

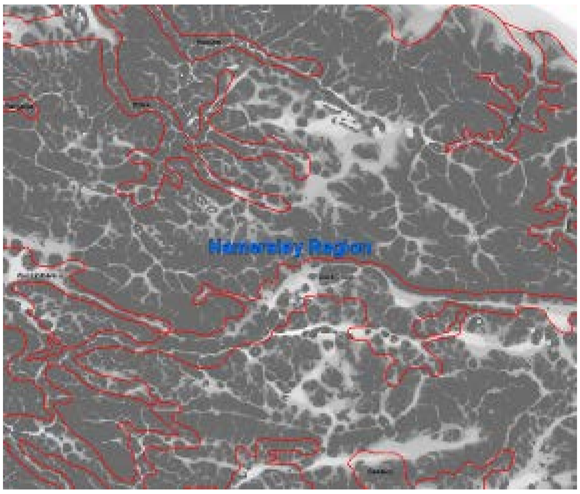
Application of the MrVBF dataset across the WASANT region provided significant insight into the distribution and nature of palaeovalleys across arid Australia. These initial mapping efforts were then refined using other national-scale datasets which included:

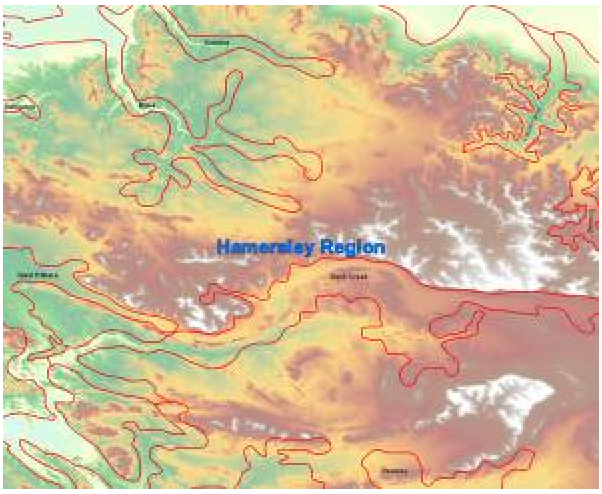
- distribution of bedrock geological units (generally pre-Cenozoic rocks)
- distribution of surface geological units, especially Quaternary alluvium and calcrete.





Yilgarn region MrVBF *Yilgarn region DEM*





Hamersley region MrVBF *Hamersley region DEM*

Figure 35: MrVBF images from WA contrast the wide open Yilgarn valleys with the relatively narrow and dissected features of the Hamersley region. The images are 100 km across.

Bedrock geology

A 'mask' of all bedrock outcrops was produced from existing Geoscience Australia geologic datasets by using GIS to generate 'exclusion areas' where palaeovalleys are unlikely to occur (Figure 36). Ancient palaeovalleys have been incised into bedrock and may exist as bare rock, within eroded gorges. However, such locales do not contain depositional facies (potential aquifers) and are only of interest to the *Palaeovalley Groundwater Project* where alluvial deposits persist upstream and downstream. Thus, the 'bedrock mask', in combination with the 'high and steep' graduations of the MrVBF dataset, effectively demarcated the intervening landscape as sites in which palaeovalley sediments may occur. These extents were further defined by integrating palaeovalley outlines traced (where available) from existing hydrogeological maps.

The bedrock mask enabled editing of the broad-scale 'surficial aquifer outlines' so that there was no overlap with defined outcrops. 'Islands' of bedrock persist within some surficial aquifers and palaeovalley tracts, as either actual inliers of bedrock or artefacts of the mapping procedure. The detailed ‘ground-truthing’ needed to verify these potential scenarios, was beyond the scope of the regional mapping assessment method.

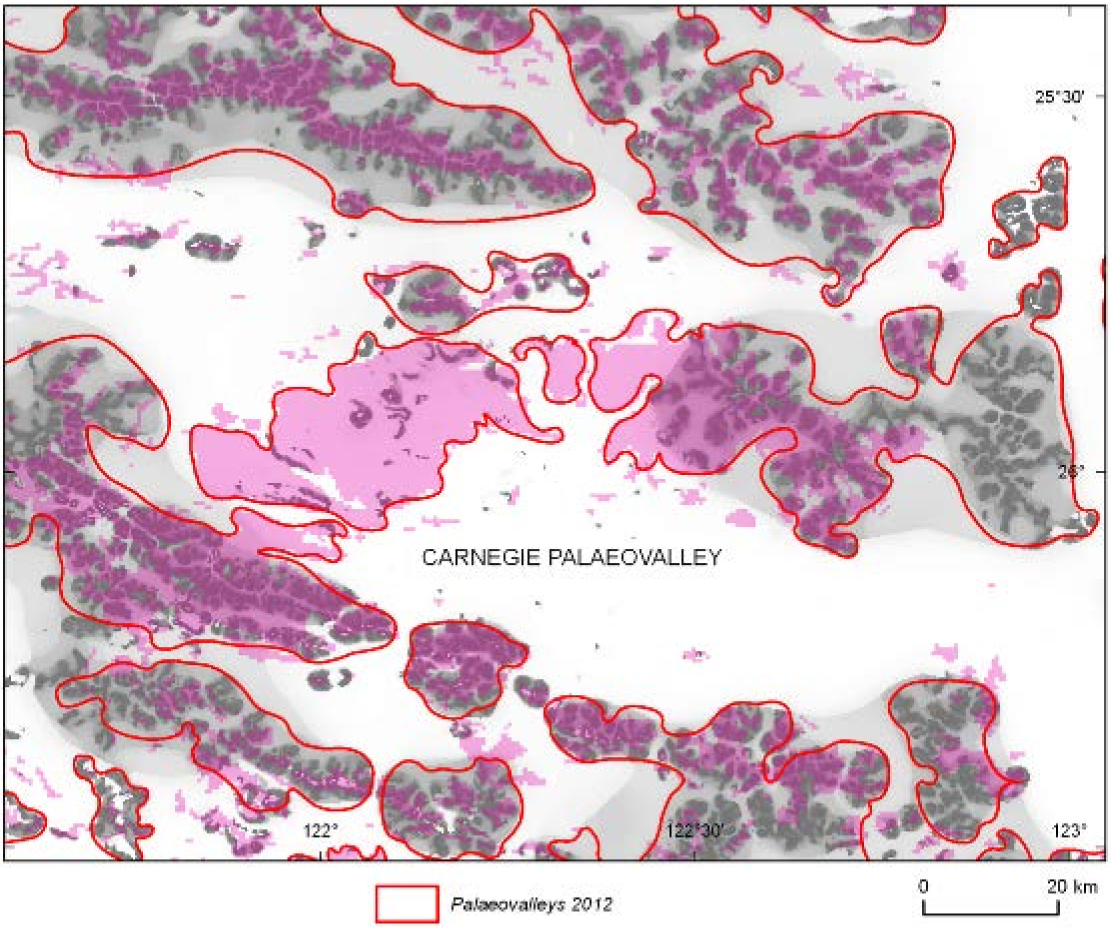


Figure 36: Areas of (pre-Cenozoic) bedrock outcrop (coloured pink, from parts of the Stanley and Kingston 1:250 000-scale maps in WA) show that palaeovalley sediments do not occur in the middle as originally interpreted from the MrVBF mottled grey background image.

Surface geology

Calcrete polygons (*Czk*) from the Geoscience Australia 1:1 million-scale national surface geology map helped to define WASANT palaeovalleys. ‘Valley calcrete’ deposits are very widespread in inland arid Australia and are typically located in palaeovalley floors. They form part of the ‘shallow aquifer’ classification of Commander (1989). The distribution of calcrete, for the most part, correlates well with the low, flat areas of the MrVBF dataset. Minor calcrete deposits occur in higher landscape areas, and such outliers were commonly excluded from the palaeovalley polygons in the WASANT Palaeovalley Map. Calcrete deposits also form mesas, particularly the older Miocene calcrete bodies. Such landforms may form within or outside defined palaeovalleys, depending on the extent of erosion. In either case, mesas are above the contemporary watertable and are not groundwater targets in the modern environment, although they may be zones of modern recharge. They also provide an indication of ancient watertable levels.

Quaternary alluvium (Qa) is common within palaeovalley systems but in higher reaches also occurs outside of the flat valley bottoms. This may relate to perched palaeovalleys which contain thick alluvium, as at the Kintyre Prospect of the Paterson region in Western Australia (Figure 37). In other cases recent alluvium is likely to be a thin veneer on bedrock, with minimal aquifer potential or lateral extent. These minor alluvial deposits did not influence the depiction of palaeovalleys on the WASANT Palaeovalley Map (although they remain in the digital geodatabase compiled for the project).

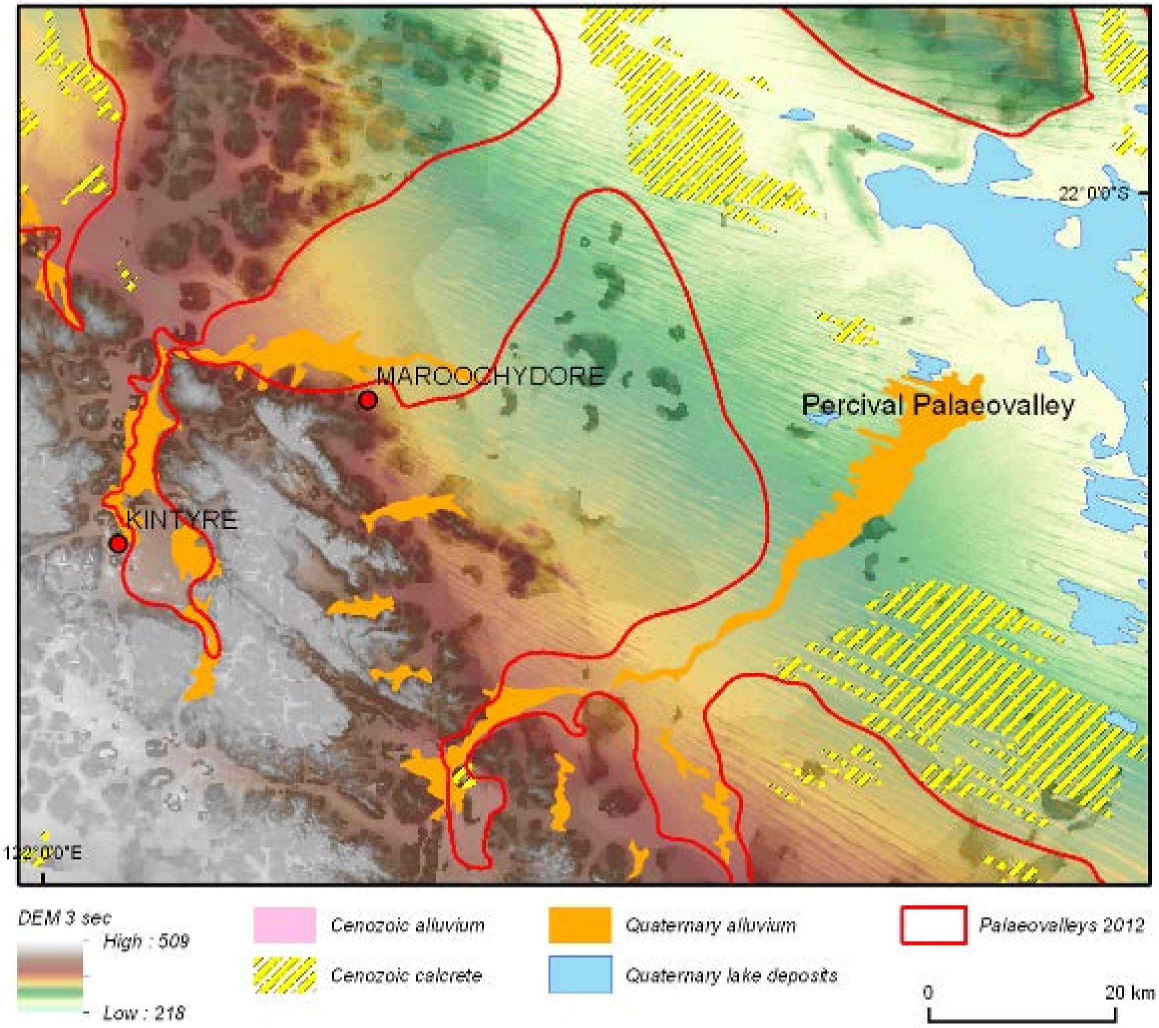


Figure 37: Quaternary alluvium (orange) in upland tributaries incised into bedrock (former glacial valleys) reveals a much more substantial Percival Palaeovalley than anticipated in this setting. The broad red outline of the low-lying parts of the palaeovalley represent the buried distribution of very thick glaciogenic sediments (Paterson Formation), revealed in AEM data, beneath dense dune fields.

3.3.5 Limitations with the MrVBF

May include non-palaeovalley areas

The MrVBF 'low and flat areas' represent the modern surface landscape that provides an indication of where valleys occur. There are many circumstances where low and flat zones shown on MrVBF imagery are clearly not related to ancient valleys or drainage systems. For example, flat areas of impervious bedrock covered with a sandy veneer could have a signature similar to a trunk palaeovalley. The converse occurs also, where former palaeovalley sediments become elevated in the landscape because the flanking slopes, whether bedrock or colluvium, have eroded away to create 'inverted relief' (referred to further below). The need to validate the initial MrVBF output with independent datasets is outlined above using geological maps. Ideally, subsurface data, especially drill-hole logs, are required to prove the existence of palaeovalleys.

Potentially significant palaeovalleys may not be detected

Palaeovalley systems outside areas depicted on the MrVBF-derived Palaeovalley Map include the Robe Formation (formerly known as the Robe Pisolite) in the Hamersley Province of Western Australia. In particular, the channel iron deposits (CID) of the Robe Formation may form a distinctive palaeovalley unit in elevated landscape settings or buried beneath younger alluvium in the base of palaeovalleys. As a DEM-based derivative, the MrVBF maps these CID as high and steep landscape features (Kepert et al., 2010).

Isolated high and steep landscape elements (darker gradations in the MrVBF schema) that have not been mapped as bedrock outcrops, may also represent relict or inverted palaeovalley strata in other parts of arid Australia. Such putative palaeovalley deposits may, or may not, directly overlie alluvial aquifers that have not been mapped as palaeovalleys because of the elevated topographic position and lack of substantiating data. Examples of topographically inverted palaeovalley deposits (commonly formed due to post-depositional silicification of the valley-fill sediments) are mapped in the Mirackina and Poole Creek palaeovalleys in South Australia (Hou et al., 2007). In the Rudall Uplands of the Paterson region of Western Australia, indurated rocks of the Paterson Formation occur as mesas and hilltops, although AEM data substantiate many decades of exploration drilling that have shown that most of these glaciogenic rocks occur in topographically low areas beneath younger sediments (Figure 37).

Glaciogenic sediments of the Permian Paterson Formation in the Paterson Province of Western Australia occur as both valley-fill sediments and mesas. The former are important regional aquifers, whereas the latter are elevated tens of metres above valley floors, perched atop hills of crystalline bedrock. Thus, topographic position is relevant with respect to aquifer mapping. Even in places where such sedimentary deposits can be mapped, they may not always function as aquifers because of their elevation relative to watertables, their landform and/or their composition, if they have been subjected to silicification or other forms of alteration. Geologic mapping is required in the case of elevated outcrops, whereas geophysics and/or drilling are needed to define the Permian palaeovalley infill which may be obscured beneath younger material (Figure 37). Remotely acquired topographic analysis alone will not provide detailed understanding of the aquifer sequences.

Applying new information blurs the consistent approach

The MrVBF DEM provides a useful starting point for interpreting palaeovalleys. It is a consistent nationwide dataset and integrates well with other national-scale data such as geologic maps and surface drainage maps, and also with satellite imagery. Detailed analysis using GIS tools has proven particularly useful for compiling the WASANT Palaeovalley Map as various datasets could be stacked, overlain and made semi-transparent to enhance data interpretation. Even so, considerable local-scale knowledge from previous detailed investigations (using drilling or geophysics) has been required to further develop the Palaeovalley Map. This is because of inherent anomalies or limitations in interpretation of national-scale MrVBF. For example:

- Some low, flat areas have not been depicted as palaeovalleys. This is common in low-lying, elongated bedrock areas, even though they may be covered with a veneer of shallow aeolian or alluvial sediments. Such features occur typically in limestone provinces such as the Fortescue Valley in WA. In other areas, low and flat zones define tracts of contemporary alluvium not related to palaeovalleys, such as west coast and Fitzroy River deposits in WA.

- In some areas palaeovalleys have been depicted in relatively high and steep areas (dark graduations) of the MrVBF image. The fact that these are identified as palaeovalleys, with likely aquifers, is predicated on existing local-scale information, such as drill-hole logs or expert knowledge (e.g. the Kintyre Prospect), or is a regional variation on how the MrVBF is representing local topographic gradients and relatively narrow bedrock-defined palaeovalley systems, e.g. in the Pilbara.
- Inverted palaeovalleys or palaeochannels, such as the Robe Formation in the Hamersley Province, are not mappable using low and flat graduations in the MrVBF scheme.
- The scale of the Palaeovalley Map does not accommodate finer detail or resolution of local-scale anomalies that may exist. Excellent aquifers may occur in very narrow and poorly distinguished palaeovalleys. Conversely, poor or non-existent aquifers may occur in large palaeovalleys that are highly conspicuous in broad-scale datasets.

3.3.6 Summary of inputs for the WASANT Palaeovalley Map

The following data provided the main inputs into developing the WASANT Palaeovalley Map.

- Published palaeovalley and hydrogeological maps, and related GIS datasets
- MrVBF (especially the Level 5 or 6 intermediate outputs) derived from the national 1-arc second and 3-arc second high-resolution DEM, based on the SRTM dataset
- Geoscience Australia 1:1 million-scale surface geology map
- A selected subset of the surface geology map containing polygons for lakes, Quaternary deposits, colluvial deposits, calcrete and the Robe Formation
- A GIS mask to occlude areas of outcropping bedrock and high steep areas of the MrVBF classification
- Drainage maps and drainage basin maps
- Infrastructure and topographic datasets: roads, populated places, state/territory borders, coastlines, etc.
- Mines and mineral deposits dataset
- Local knowledge from state/territory hydrogeologists including peer review, workshopping, and exchange and editing of interim mapping products and maps.

3.3.7 State/territory-specific mapping variations

Western Australia

The 1:2 500 000 Hydrogeological Map of Western Australia (Commander, 1989) was compiled largely from 1:250 000 geology maps and expert hydrogeological knowledge, without the benefit of high resolution DEM or advanced GIS techniques. All aquifers are represented on the 1989 map, including bedrock systems, sedimentary basins, and various surficial aquifers, along with the distribution of some geologic units classified as aquicludes. Palaeovalleys are part of the ‘surficial aquifers’ classification, along with calcrete, modern alluvium and coastal deposits. High-yielding aquifers within the surficial aquifer category include large exposures of valley calcrete. The distribution of surficial aquifers provided a useful guide for compilation of the Western Australia part of the WASANT Palaeovalley Map, with the additional DEM and various datasets. In the present compilation, Quaternary alluvium and coastal deposits were not necessarily regarded as palaeovalleys unless supporting information provided evidence for the presence of deeper sedimentary deposits.

The very great extent of the Western Australian arid and semi-arid zone and the enormous number of palaeovalleys therein precluded interrogation of Western Australian drill-hole and water borehole logs for the WASANT Palaeovalley Map. Tens of thousands of drill-hole and borehole logs have been archived in databases maintained by the Geological Survey of Western Australia (WAMEX) and the Western Australian Department of Water (WIN database). It is recommended that the next phase of palaeovalley mapping in Western Australia include interrogation and inclusion of these data to validate the 2D representation of palaeovalleys compiled for the WASANT Palaeovalley Map. This will constrain the third dimension (depth) of the palaeovalleys and greatly improve definition of aquifers.

South Australia

The 'Palaeodrainage and Tertiary Coastal Barriers of South Australia' (compiled by Hou et al., 2007) was published at 1:2 000 000 scale with associated GIS datasets. The development of this South Australian map used available geologic data, DEM, airborne radiometrics, Landsat Thematic Mapper, NOAA-AVHRR, ASTER NTIR images, geophysical data (particularly AEM), integration of drill-hole data and knowledge of continental sedimentation and sedimentary history. The stratigraphic information for palaeovalleys was relatively detailed because most available drill-hole data were included. These datasets were integrated with the MrVBF and national DEM data for the WASANT Palaeovalley Map compilation. The South Australian palaeovalley deposits are classified as either Mesozoic, Paleogene or Neogene sediments (Hou et al., 2007), but due to the broader scale of the WASANT Palaeovalley Map were amalgamated into a single GIS layer for correlation with the MrVBF. This enabled consistency with the palaeovalley representation for Western Australia and the Northern Territory. The Cretaceous Bulldog Shale, although it commonly functions as an aquiclude, was included within some WASANT Palaeovalley Map polygons as it may infill some Mesozoic or older palaeovalleys incised into bedrock.

Northern Territory

The Groundwater Map of the Northern Territory (Tickell, 2008) includes an inset map showing the distribution of Cenozoic palaeochannels and basins, mostly in central Australia. To ensure consistency with the other jurisdictions for the Palaeovalley Map, the data from the original Northern Territory Groundwater Map was further refined by other datasets (Table 3). In particular, palaeovalleys in the Northern Territory were verified by existing water-bore drilling logs available in the Northern Territory government registered water-bore database (maintained by the Department of Natural Resources, Environment, the Arts and Sport, NRETAS).

The Northern Territory drilling data provided important information to validate the interpretations made on the basis of the remote-sensing imagery. This work showed that detailed evaluation of existing borehole logs can improve confidence in palaeovalley mapping generated from national-scale datasets such as the MrVBF and the surface geology maps. Drill-hole density and the quality of drilling logs vary considerably across the arid zone, such that careful scrutiny of available drilling datasets is required. Future revisions of the WASANT Palaeovalley Map should integrate drill-hole and water-bore data to improve the robustness of the mapped outputs.

Table 3: Data sources for the Northern Territory component of the WASANT Palaeovalley Map.

DATA	*COMMENTS*
Water-bore logs in NRETAS database	Bore logs of variable quality. Included some mineral exploration bores.
NT groundwater Map	The palaeovalleys were originally mapped by Tickell (2008) for NRETAS.
Multi-resolution Valley Bottom Flatness index (MrVBF)	The MrVBF algorithm identifies flat and low-lying areas in the landscape and helped highlight relict palaeovalley features in the arid zone. These data were reclassified to depict the lowest, flattest 50% areas.
Binary outcrop mask	Highlights all basement outcrop zones from geological mapping, effectively excluding their being classified or interpreted as palaeovalleys.
1:250 000 surface geology mapping	The calcrete, ferricrete, Quaternary alluvium and salt playa layers were of particular use.
3-arc second DEM	Provides additional topographic insights, especially with datasets such as MrVBF and surface geology draped semi-transparently.
Reports and maps	Previous studies reviewed included: 1. All Cenozoic basins: Senior et al. (1994) 2. Aremra Basin: Senior et al. (1994) 3. Great Artesian Basin: NRETAS bore log interpretations 4. Tanami: Domahidy (1990) 5. Ti Tree Basin: Higgins and Rafferty (2009) 6. Uluru region: Jacobson et al. (1989) 7. Western Desert: Lau et al. (1997) and Wischusen (1998) 8. Yaloogarrie Basin: Stewart (1976)
Reclassified thermal satellite data – NOAA/AVHRR	Worked better in some areas than others, but is an additional tool to evaluate areas with scant drilling data.
Landsat	Some used for WASANT study; Tickell (2008) applied Landsat imagery.
WA and SA palaeovalley mapping	Assisted greatly in mapping palaeovalleys at the state/territory borders.
Anecdotal information	Expert local knowledge obtained by conversing with hydrogeologists, researchers, mineral explorers, etc.

3.4 Application of the WASANT Palaeovalley Map

The WASANT Palaeovalley Map displays the distribution, style and form of palaeovalleys in arid and semi-arid parts of Western Australia, South Australia and the Northern Territory. As discussed above, this map has been largely compiled using a combination of remote-sensing and GIS analytical methods, with some ground validation in specific regions where drill-hole logs and water-bore reports are available (mostly for the NT and earlier work in SA). The large extent of Western Australia, the very large number of palaeovalleys within the state and the limited timeframe for the *Palaeovalley Groundwater Project* precluded accessing drill-hole and borehole logs for Western Australia for the present exercise. Important considerations for using and applying the WASANT Palaeovalley Map are as follows.

- The map does not show the presence or distribution of palaeovalley groundwater resources *per se*. The map provides a regional-scale approximation of palaeovalley boundaries that include near-surface calcrete deposits and presumed to encompass the buried thalweg aquifer. The mapped extent also incorporates palaeovalley sediment deposits that are not aquifers, such as fine-grained clay deposited in lacustrine or swamp settings, and mud-rich sediments in overbank or floodplain deposits. Although useful groundwater resources are found in most palaeovalley systems, they are not necessarily associated with all palaeovalley segments on the map. Unless the requisite information is already available (unlikely for most arid regions) more focused investigations are required to accurately determine the most prospective groundwater zones within the palaeovalley. As demonstrated by the site investigations for this project (Chapter 2), such detailed studies usually involve a combination of techniques including analysis of remotely sensed data, geophysics, and drilling to sample the infill sediments and groundwater resources (Gow et al., 2012 has details of investigative methods).
- The map does not provide specific information on or representation of groundwater quality because of the heterogeneity of groundwater salinity in palaeovalley aquifers. However, some insights into water quality can be made on the basis that palaeovalley segments near salt lakes are likely to contain saline or hypersaline groundwater. At the other extreme, groundwater in minor tributary systems and in some headwater trunk valleys is likely to be less saline as these palaeovalley segments occur closer to upland bedrock areas that commonly act as freshwater recharge zones. For example, the mountain-front alluvial fan aquifers of central Australia typically contain fresh groundwater, close to range run-off areas that receive higher rainfall due to orographic effects (English, 2002). Salinity gradients are steep, as hypersaline groundwater occurs at salt lakes 50 km from the ranges. Fresh to brackish groundwater in palaeovalleys extends for tens of kilometres between the recharge and discharge zones, and relatively fresh groundwater occurs in calcrete aquifers above the salt lakes. Heterogeneous groundwater salinity at this scale cannot effectively be represented in a national-scale map.
- The map does not depict local groundwater flow directions although the regional flow trend is generally evident, or can be predicted, from the drainage pattern. It will roughly follow the topographic gradient and direction of flow of the precursor river and tributaries. Anomalies may occur where neotectonic disruption or tilting of the prior landscape has altered flow directions or closed hydrologic systems, or has caused capture of headwater systems from one valley to another.
- The WASANT Palaeovalley Map should be treated as a conceptual interpretation of palaeovalley distribution, given the difficulty and uncertainty in mapping palaeovalleys with remotely acquired data (unless drilling data is available and incorporated). The map will provide a useful guide to interpret groundwater exploration targets in many geologic provinces, especially if dune covered. However, detailed ground-based investigations (mapping, geophysics, drilling and sampling) will always be required to definitively characterise individual palaeovalleys and to site new borefields.

3.5 Highlights and suggestions for further development

Particular project-wide highlights evident from developing the WASANT Palaeovalley Map:

- The use of existing WA-, SA- and NT-based datasets provided a basis for calibration and testing of various methods to produce the new Palaeovalley Map based on a consistent and updated national approach using high-resolution datasets.

- Adequate storage and maintenance of national datasets for use in GIS-based projects is of great value. In particular, without access to Australia-wide high-resolution DEM, MrVBF, geology and drainage maps (among other datasets) this regional-scale mapping project would not have been possible.
- The role of Geoscience Australia in fostering the input and collaboration of state and territory partners has ensured consistency across borders and acceptability of the finished product across jurisdictions.

Suggestions for further development of the WASANT Palaeovalley Map:

- The WASANT Palaeovalley Map produced for the *Palaeovalley Groundwater Project* should be further developed and updated in a future project. Great potential exists for editing, refining and adding results of new work, particularly inclusion of borehole and geophysical data to provide 3D perspective.
- The methods used to produce the WASANT Palaeovalley Map could be readily extended across other areas of Australia and would provide a very useful approach to develop a national hydrogeological map which improves on the existing 1987 national map[12].
- Future regional palaeovalley mapping may benefit from integration of airborne magnetic data, detailed geologic maps and structural geology to more fully explain regional palaeovalley patterns and modes of occurrence.
- It would be useful to improve understanding of how and where water moves within the palaeovalley systems (or where it is relatively stagnant in hydraulically closed systems). As mining and development of palaeovalley systems increases in the future, enhanced knowledge of palaeovalleys as aquifers will ensure improved management practices and foster sustainable extraction.
- National-scale estimates of the quantity and quality of water in the major palaeovalley systems would provide relevant information to guide water resource planning and management.

3.6 Conclusions

The Palaeovalley Map is the first national-scale attempt to integrate a wide variety of topographic, geologic and hydrologic data to generate a map of palaeovalley systems across arid and semi-arid Western Australia, South Australia and the Northern Territory. This map is a major step in describing the extent and character of palaeovalleys in Australia. Development of the map required a new methodology to be designed and validated to ensure that the final mapped output provided a realistic and spatially robust depiction of remote palaeovalley systems. The map could be extended across the eastern states and beyond the arid zone, providing the basis for an updated national hydrogeology map that would subsequently incorporate bedrock and basin aquifers, faults and other structures, as well as water-quality data. The approach adopted for the WASANT Palaeovalley Map could also be extended to broad-scale hydrogeological mapping efforts in arid and semi-arid lands elsewhere in the world.

12 Jacobson, G and Lau, JE, 1987. Hydrogeology of Australia.
https://www.ga.gov.au/products/servlet/controller?event=GEOCAT_DETAILS&catno=32368

4. Towards an improved understanding of palaeovalley groundwater systems in arid Australia

Improved understanding of palaeovalley groundwater systems across diverse geographic regions of the arid zone is a major outcome from the *Palaeovalley Groundwater Project*. The purpose of this chapter is to highlight the main findings from the multi-component investigation program, under the themes of:

- Spatial distribution and variability
- Origin and evolution
- Stratigraphy and sediment sequences
- Groundwater resources
- Hydrogeochemistry.

4.1 Spatial distribution and variability

The WASANT Palaeovalley Map (Chapter 3) was generated as a key output from the *Palaeovalley Groundwater Project*. Palaeovalleys are an integral component of inland Australia's near-surface environment, albeit with many obscured by desert dune fields in more recent geologic times. The techniques applied to compile the WASANT Palaeovalley Map effectively peeled back the widespread cover sequences (e.g. aeolian sands and other younger sediments) to reveal the prior landscape with its intricate distribution of ancient rivers and lakes. The mapping approach has delineated approximately 200 discrete palaeovalleys (major trunk valleys and associated tributary networks) and shown these occurring across most of the major geologic provinces of Australia. Preliminary estimates suggest that the total length of these major buried river systems exceeds 80 000 km, with an area exceeding 600 000 km^2 (more than one-third the surface area of the Great Artesian Basin). Given the capacity of palaeovalleys to store and transmit large volumes of groundwater, albeit of variable water quality, they are a major aquifer class that currently plays a vital role in supplying water to the driest areas of the Australian continent.

The spatial distribution and geographical and geological diversity of palaeovalleys depicted on the WASANT Palaeovalley Map illustrates distinctive regional features that relate to their origin and evolution (Figure 38). Characteristic regional variations include, although are not restricted to, the following factors and influences:

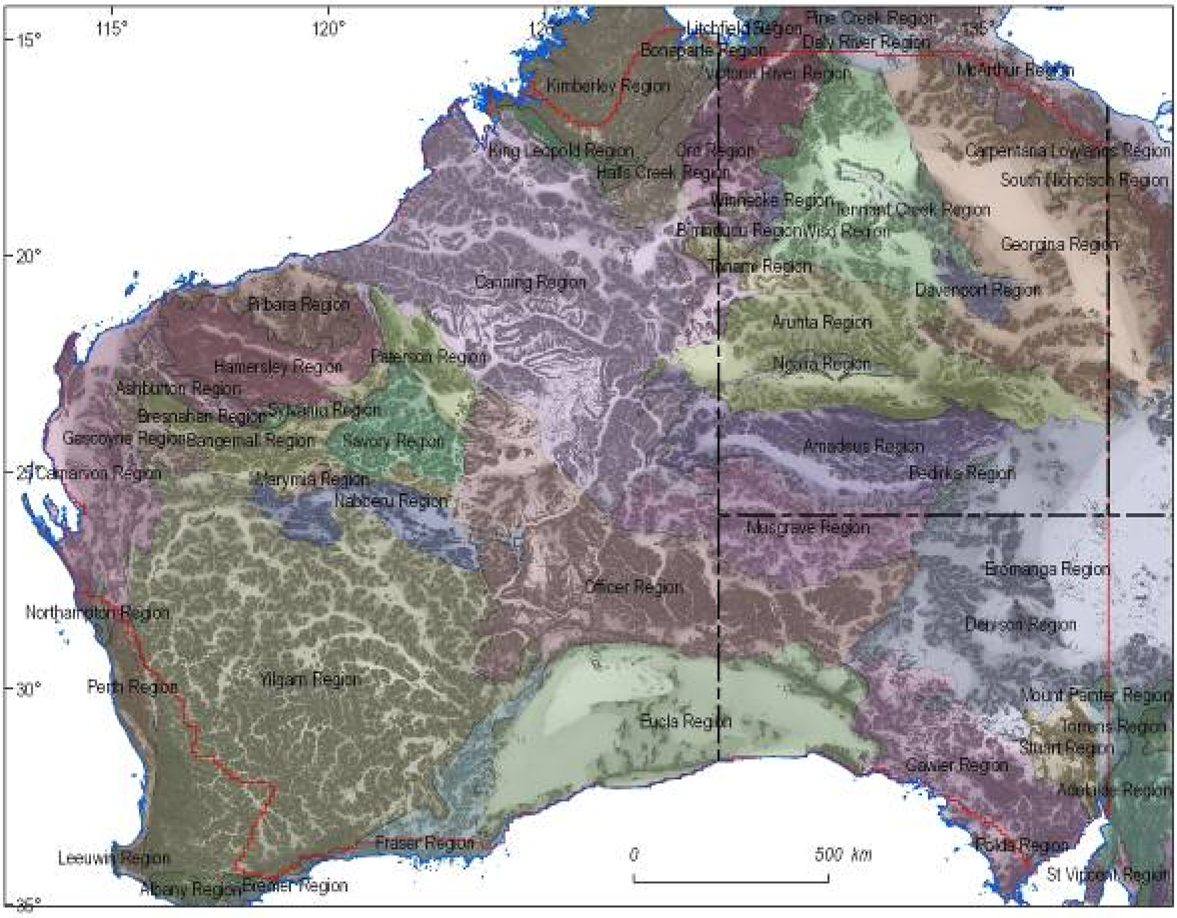


Figure 38: Major geologic provinces of the WASANT area overlain on the MrVBF output. Distinctive patterns are associated with respective provinces. This reflects the influence of basement geology in the evolution of Australia's palaeovalley systems (additional to other factors such as climate and topography). The extents of the arid and semi-arid zones are outlined in red.

1. Palaeovalleys on the Yilgarn Craton in WA (such as those of the Goldfields, Murchison and Wheatbelt) have a typical, intricately branched, dendritic drainage pattern. The main trunk palaeovalleys are predominantly linear features that were carved by rivers that once flowed either north-west across Gondwana and subsequently, after break-up and rifting, south-east towards the ancient Eucla Sea (the boundary of which extended much further inland throughout much of the Cenozoic than it does in modern times), or north-west towards the Indian Ocean. These palaeovalleys have numerous smaller tributaries in the headwater regions that coalesce and form higher order stream segments down-valley. Well-studied examples of the typical style of Yilgarn palaeovalleys include the Roe, Raeside and Carey systems in the Goldfields (which all terminated in the Eucla Sea), whereas the Avon, Moore-Monger, Murchison and Gascoyne palaeovalleys are typical of the western Yilgarn drainage systems. Many of these reached the Indian Ocean despite uplift of the western edge of the craton. The characteristic drainage patterns of the Yilgarn reflect the influence of basement rocks (granite and greenstone terrane), structural features, and a long history of multiple cycles of erosion and deposition, as well as waxing and waning fluvial and lacustrine environments through the Cenozoic. They may also have responded to fluctuating Mesozoic and Cenozoic sea levels and associated base-level changes which, in the west, influenced aggradation and subsidence of adjacent coastal plain basins that would have affected river dynamics on adjacent parts of the Yilgarn plateau.

2. In contrast to the Yilgarn region many palaeovalleys in central Australia form significantly broader depositional systems that lack complex tributary networks. Locally, the palaeodrainage systems are termed ‘basins’, including the Ti Tree, Burt, Lake Lewis and Central Mount Wedge Basins. The basin-style palaeovalleys generally contain thicker Cenozoic infill sediments than other regions, commonly >200–250 m thick. The Central Mount Wedge Basin is infilled with up to 474 m of sediments (Woodgate et al., 2012). The deeper and broader basin style implies that the major processes responsible for their development were considerably different to inferred seaward-flowing river systems that formed extensive palaeovalleys in WA and SA. The basin and range geologic setting invokes intracratonic tectonism playing an important role in the formation of the palaeovalleys (English, 2002). This region is characterised by significant topographic relief with east-trending upland ridges and adjacent broad, flat valleys. Mountains rise up to 900 m above the adjacent plains. Faulting and displacement along major structural zones that separate the ridges and basins has promoted mountain-front erosion with deposition in adjacent subsiding basins. These settings also tend to contain persistent low-energy depositional environments compared with sediments typical of more through-flowing fluvial systems such as across the Yilgarn or the Canning Basin. Thick sequences of fine-grained sediments typical of lacustrine environments are suggestive of long quiescent periods. So, for considerable durations in their evolution, these were probably ‘lake basins’ with centripetal alluvial fans, and centripetal run-off pathways, flowing basin-ward from bedrock ranges. This is represented by the massive clay-rich sequences typical of the Central Mount Wedge Basin, Lake Lewis Basin and Burt Basin, for example.
3. In the Paterson Province of northern WA there are widespread, mostly buried Permian sedimentary rocks that accumulated from glacial activity. They are known as the Paterson Formation and are tens of metres thick (up to 250 m), with some outcropping as residuals on hilltops but commonly buried beneath dune fields with the actual subsurface extent unknown (English et al., 2012b). These are essentially palaeovalley sediments that do not conform to linear ‘fluvial’ patterns more typical of other areas of WA. In elevated bedrock regions, glacially scoured palaeovalleys may have similar forms to valleys incised by high-energy rivers.
4. Deformed trunk palaeovalleys west and south of Lake Mackay in the Officer Basin, particularly major topographic anomalies of the order of tens of metres to 100 m vertical amplitude, may indicate the presence of underlying salt diapirs (topographic highs in the valley floor) or dissolved near-surface diapirs (topographic hollows in the valley floor).
5. In the Hamersley Province of the Pilbara there are complex networks of sub-parallel gorges which are palaeovalleys incised into iron-rich Archean bedrock. At least one palaeovalley system is offset at approximately 90° relative to the modern overlying drainage system. The channel iron deposits (CID) of the Robe Pisolite are in the Hamersley Province and form discrete palaeochannels consisting of iron oxide pisolites. The Robe CID are an unusual palaeovalley scenario, for as well as a valuable local aquifer system they are high-grade iron ore deposits.
6. Several geologic provinces contain very few palaeovalley systems. In particular, the Georgina Basin in eastern NT and the contiguous Wiso Basin in the centre of the NT predominantly comprised Cambrian-Devonian limestone deposits with karstic zones characterised by sinkholes and solution cavities (Figure 38). The modern landscape is dominated by extensive, mostly flat ‘black soil’ plains with gilgai-patterned surfaces. This type of geologic environment is incompatible with the development of palaeovalleys. Incised alluvial systems are difficult to establish and maintain over prolonged cycles of erosion and deposition in this landscape. Sediment yields from eroded limestone terrains are also relatively low, especially compared with those from areas of coarser grained bedrock.

7. The Eucla region of WA and SA is devoid of mapped palaeovalleys, primarily because of the extensive marine limestone deposits that cover most of the area. The Eucla Basin experienced multiple stages of marine transgression and regression during the Cenozoic, with the inundation of southern Australia extending up to several hundred kilometres landward from the modern coastline. The WASANT Palaeovalley Map highlights the extent of major sand ridges and shoreline deposits that formed during Cenozoic marine highstand. The high beach ridges are termed the Eucla Basin Coastal Barrier system. Many palaeovalleys that flowed towards the Southern Ocean disappear at this coastal barrier. Extensive, flat-lying marine platform carbonates are the main depositional feature in the area that was covered by the Eucla Sea. These marine deposits obscure palaeovalley features that may have developed during regressive stages, making it very difficult to map the continuation of palaeovalley systems southward beyond the coastal barrier zone (especially using the methods of the WASANT Palaeovalley Map). Notwithstanding, flooded segments of palaeovalley sequences are predicted to occur broadly across this region below the uppermost limestone deposits of the Eucla Basin, i.e. the Nullarbor Limestone. The recent palaeovalley discovery (using a detailed AEM survey and follow-up drilling) by Iluka Resources close to their Jacinth-Ambrosia mineral sands deposit in the eastern Eucla Basin confirms this theory (Lewis et al., 2012).
8. In WA, the onshore western Eucla Basin is generally known as the Bremer Basin (Hocking, 1995) but is more broadly regarded as part of the Eucla Basin in terms of Australian provinces (Clarke, 2003; Australian Geological Provinces database[13]). On the WASANT Palaeovalley Map it has been labelled the Bremer Basin to be consistent with Geological Survey of Western Australia and WA Department of Water terminology. The basin comprises numerous small sediment-filled depressions rather than a continuous basin, and is apparently associated with numerous faults, some possibly a legacy of the break-up from Antarctica. Drainage systems were already established on the Yilgarn Craton and the Albany-Fraser Orogen by the Late Mesozoic and these filled with fluvial and swamp deposits (Werillup Formation) during the Eocene. Marine transgression drowned the valley system in the Late Eocene and led to deposition of marine sediments (Pallinup Formation). The Werillup Formation is regarded as the target palaeovalley aquifer in the basin, although its distribution can only be inferred beneath blanketing marine sediments (aquiclude). Published 1:250 000 hydrogeology maps and the high-resolution DEM were used as a guide to refine the distribution of Bremer Basin sediments. Interrogation of logs for numerous boreholes in the basin would more accurately reveal the buried distribution of fluvial palaeovalley sediments and, along with 3D model development, is recommended for the next phase of palaeovalley mapping in the region.

4.1.1 GIS analysis using the WASANT Palaeovalley Map

The WASANT Palaeovalley Map, described in Chapter 3, is a composite approach to assist future exploration for and assessment of palaeovalley groundwater resources in arid and semi-arid Australia. The map is intended to be useful to a range of groundwater users (e.g. miners, pastoralists, communities) as well as government departments and other organisations involved in the development and management of groundwater resources. Additional to the hard-copy thematic map, free public access to the key digital datasets depicted on the map will ensure that a wide range of analytical tasks can be performed using GIS. The focus of future GIS analyses will probably be broader than originally envisaged for the *Palaeovalley Groundwater Project*. Suggested map applications include:

13 http://www.ga.gov.au/products-services/data-applications/australian-geological-provinces.html

- Providing an initial overview and first-pass assessment of the distribution and disposition of regional palaeovalleys in respective geologic provinces of the WASANT area, to help potential users better understand the potential for accessing groundwater from relatively shallow palaeovalley aquifers;
- Identifying regions where palaeovalley systems are likely to provide the only viable long-term groundwater resources for future developments, e.g. in cratonic provinces such as the Musgrave, Yilgarn and Pilbara. On the other hand, regions underlain by large sedimentary basins with aquifers that are better groundwater targets than overlying palaeovalley aquifers can be distinguished. Relatively simple GIS-based analysis can readily define such regions, including parts of the Canning Basin in WA, the Officer Basin in WA and SA, and the Amadeus Basin in the NT. Overlying palaeovalleys, nonetheless, may provide useful interim resources for lesser or temporary water supplies for road maintenance, small communities, and exploration camps or infrastructure construction, prior to installation of deeper bores to basinal aquifers for long-term and/or high-volume water supplies;
- Identifying areas where future development of palaeovalley aquifers is likely. Medium to large-scale development in the arid zone is likely to be related to mining. Using GIS analysis, particular palaeovalley segments that occur within a pre-defined buffer zone around individual mine sites or mineral deposits can be identified (Figure 39 and Figure 40). The radius of the buffer zone would depend upon the distance that the consumer is prepared to pump water, or the distance to where required volumes can most readily be accessed. Where palaeovalleys are the most viable or the only groundwater resource targets (e.g. in areas dominated by cratonic rocks), strategic analysis of compiled GIS datasets allows early planning of resource use as well as focusing investment in the highest priority and most prospective regions;
- In geoscientific datasets for future studies of the geology or hydrogeology of specific regions. For example, palaeovalley aquifers may need to be considered as near-surface groundwater sinks in water balance calculations. Palaeovalleys may also be significant in understanding recharge–discharge dynamics and groundwater throughflow processes at a regional scale, whether they are the only aquifers or are part of much larger or more complex groundwater systems;
- In exploration for sandstone-uranium deposits (also known as palaeochannel uranium deposits), for alluvial (placer) gold deposits, and for alluvial (placer) diamonds or pathfinder minerals for diamond exploration.

4.2 Origin and evolution

Most palaeovalleys in arid and semi-arid Australia are remnants of prior river systems and surface alluvial environments, although some, including many in the Paterson Province of Western Australia, are of glacial origin. In fluvial settings, high-energy rivers incised the original valleys into bedrock and transported and deposited alluvium within those valleys. Ancient rivers also influenced the deposition of colluvium on valley flanks. These erosional and depositional processes are no longer active, or at least insufficiently so to scour valleys of the magnitude observed and to transport volumes of sediment comparable to those preserved in the relict valleys. Although it remains uncertain when most palaeovalleys originally formed, the extant sedimentary infill is mostly Cenozoic in age, i.e. the geologic time span which began about 65 million years ago (Ma) and which continues to the present day (Appendix 1). Large areas of the Australian continent have been exposed above sea level since the Mesozoic (261–65 Ma) and, in places, since the Paleozoic (542–261 Ma) or preceding Proterozoic (Brown et al., 1968). Therefore, rivers have no doubt been part of the evolution of exposed continental surfaces throughout most of the geologic timescale. There are even interpreted Cambrian river terraces persisting in the present-day landscape (Stewart et al., 1986). However, most early sedimentary deposits have either been washed to ancient shorelines and oceans or recycled in the landscape. Pollen in sediments indicates that sediments in palaeovalleys are mostly Cenozoic (Figure 41). The wide distribution and significant thicknesses of alluvial sediments infilling palaeovalleys are testimony to significantly higher rainfall, run-off and river flow, and lower evaporation rates throughout much of the Cenozoic, compared to the present day.

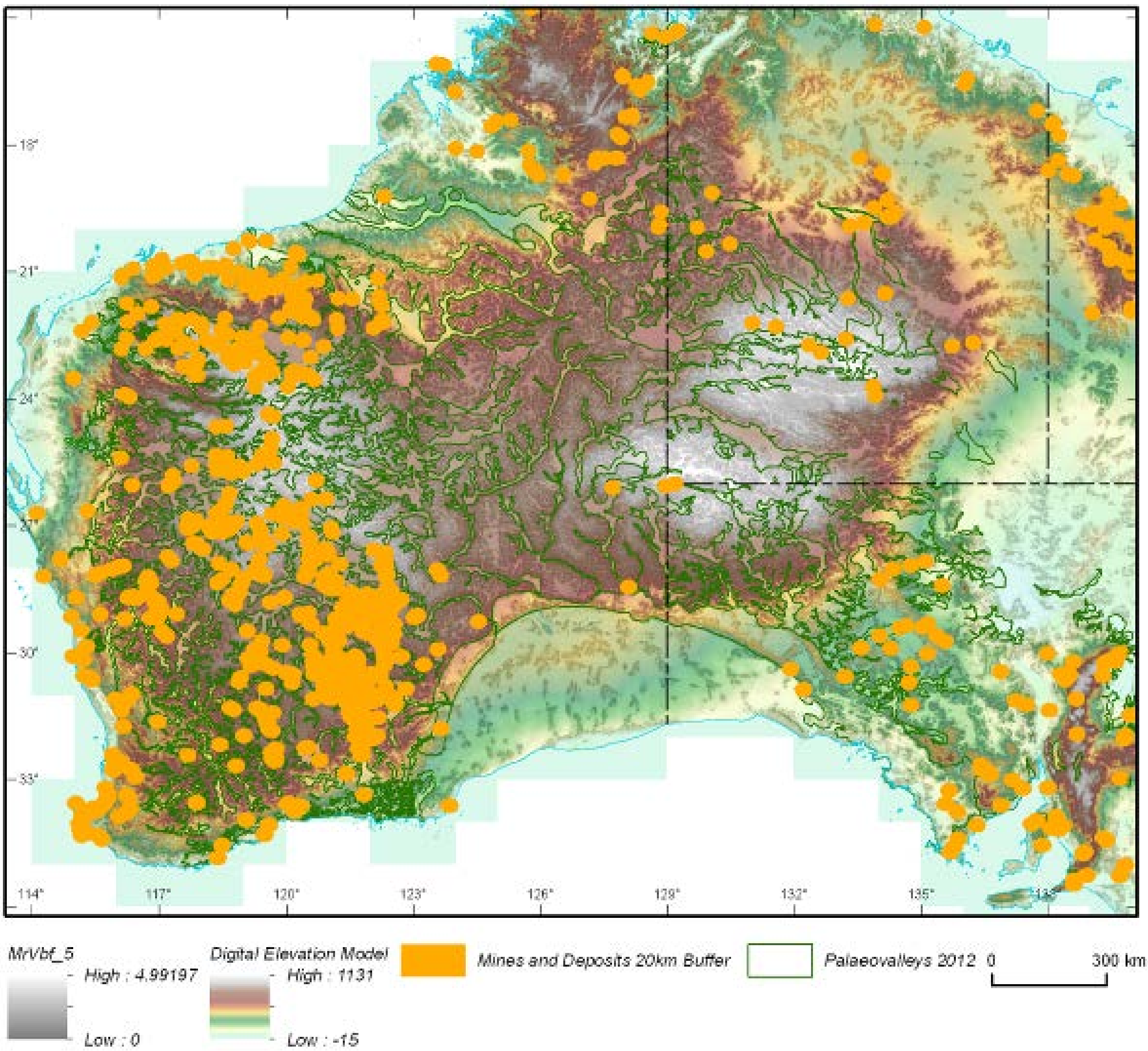


Figure 39: Mines and mineral deposit localities with 20 km-wide buffer zone (orange) and mapped palaeovalleys overlain on the MrVBF output in the WASANT study region.

Palynostratigraphic analyses (Appendix 3) of organic-rich sediments recovered from a number of WASANT palaeovalleys (from both previous work and this study) indicate that their deposition was mainly during two discrete periods in the Cenozoic. Basal Eocene sediments (containing spores and pollen exemplified in Figure 41) and overlying Miocene sediments typify much of the sedimentary infill of widespread palaeovalleys. The near-surface sediments in these systems commonly include chemical precipitates in salt lakes, particularly calcrete and evaporites, testimony to the onset of aridity in later phases of palaeovalley evolution. The latter characterise internally draining (endoreic) palaeovalley systems, where salts accumulate in response to evaporative concentration in closed hydrologic systems. Externally draining systems (exoreic), where rivers reach the sea, tend to be better flushed of both salts and sediments. An example of the latter may be the major palaeovalleys in the Murchison region, where older Cenozoic sediments appear to no longer reside in the valleys, despite the very considerable valley depths.

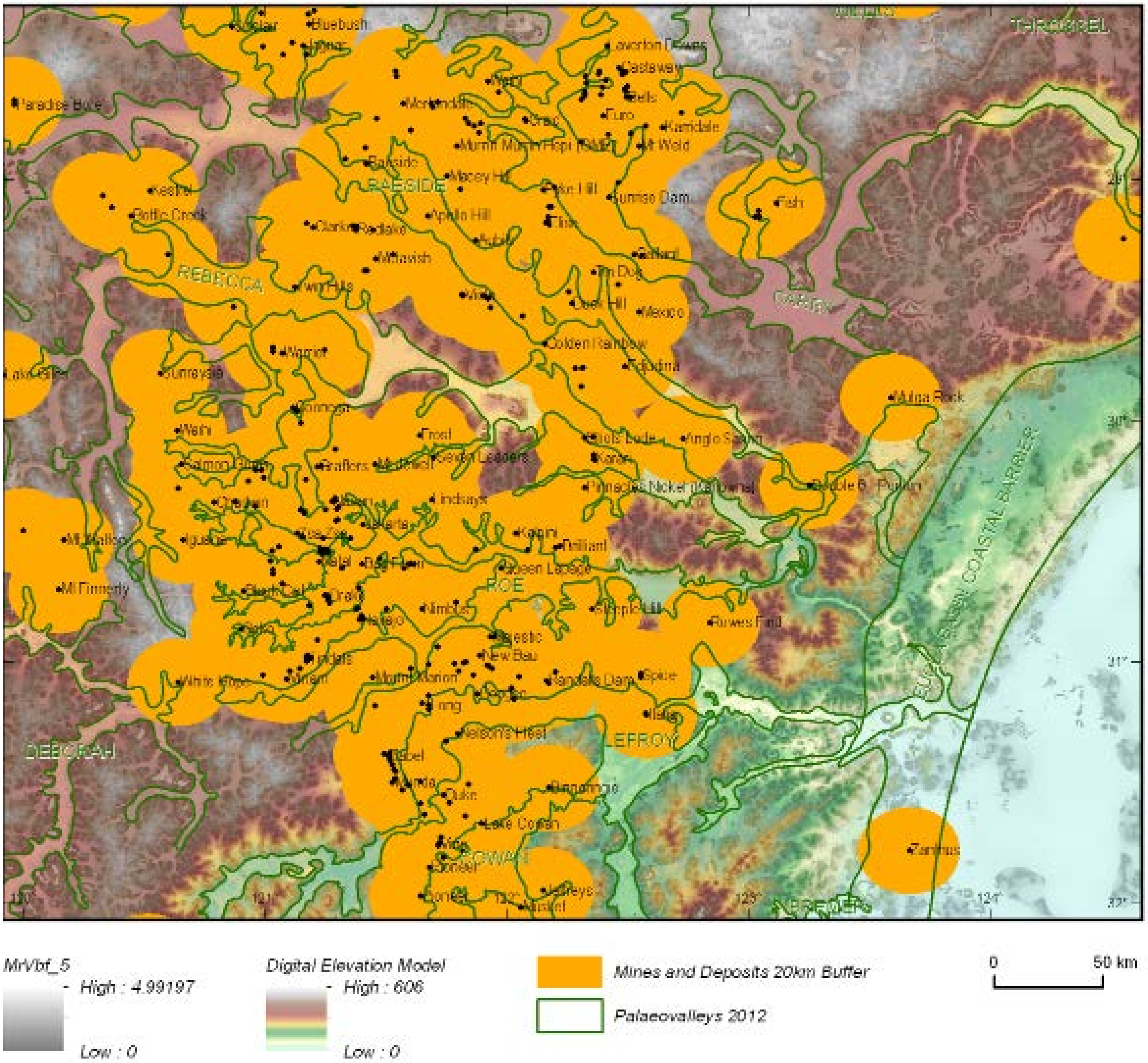


Figure 40: Palaeovalley systems most likely to be exploited for mining activities. This detailed map view over part of the Yilgarn Craton (WA) shows the potential for GIS analysis to assist water planners and managers.

Faults, where present, have doubtlessly played a role in palaeovalley evolution, especially the Cenozoic basins in central Australia. Integration of mapped faults with satellite imagery in the Murchison demonstration study for example (English et al., 2012a), correlated with field observations, particularly gravity and drilling profiles. Faults were found to be spatially and causatively related to where and how palaeovalleys formed. Features of palaeovalleys elsewhere that remain unexplained may also be related to unmapped faults.

Neotectonic activity, broad-scale tilting or continental warping may also have influenced the evolution of palaeovalleys, in addition to climate and ancient faults in the landscape (whether mapped or buried beneath dune fields or other surficial sediments). Sandiford (2007) and Sandiford et al. (2009) discussed continental-scale tilting of Australia in response to rifting from Antarctica with the break-up of the Gondwana supercontinent, with potential consequent influences on the development of Cenozoic basin and drainage systems. Remnant upward tilting of the southern part of the continent has been postulated, for instance along the Great

Australian Bight where seaward cliffs are 200 m high (Sandiford et al., 2009). However, in a large part of the Yilgarn it appears that there was then downward tilting to the south that stopped northward flow of rivers (Commander, WA Department of Water, pers. comm., 2012).

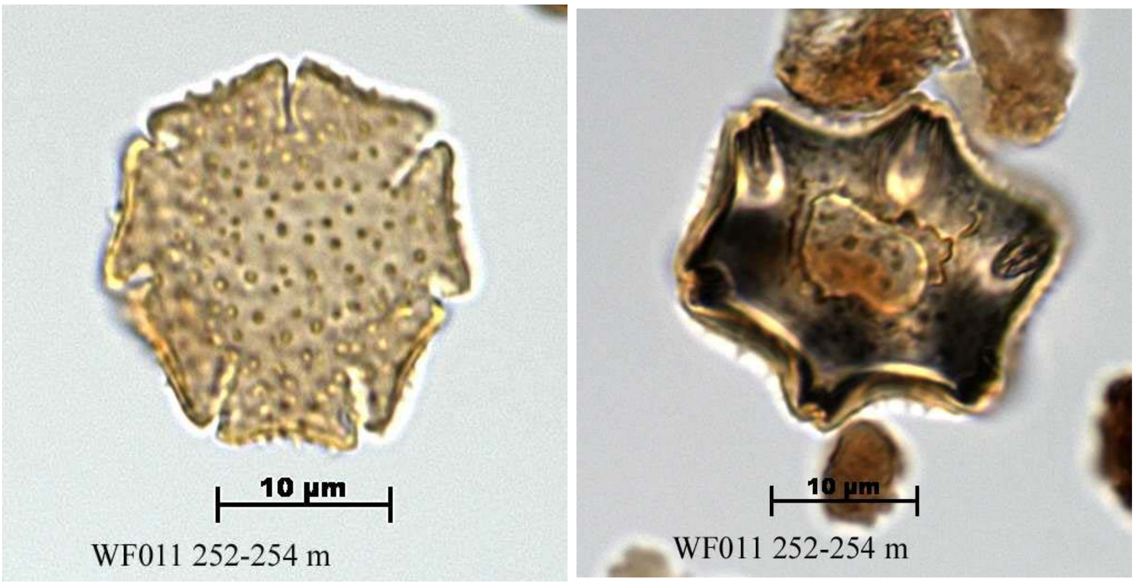


Figure 41: Photomicrographs of *Nothofagus* microflora preserved in sediment layers recovered from 252–254 m interval in drill hole WF011 (NuPower Resources Ltd) from the Ti Tree Basin: (left) *Nothofagidites emarcidus* complex; (right) *Nothofagidites falcatus*. The occurrence of these microfloras indicates that the deep sediments in this part of the Ti Tree Basin were deposited during the Middle to Late Eocene under cool, humid conditions (analogous to the Nothofagus forests in modern Tasmania and New Zealand).

4.3 Stratigraphy and sediment sequences

4.3.1 Stratigraphic complexity and heterogeneity

A key finding from the *Palaeovalley Groundwater Project* is recognition of the complexity and diversity of the stratigraphic sequences of Australian arid-zone palaeovalleys. The detailed reconnaissance-scale investigations carried out across multiple study sites emphasised (with almost every case) that palaeovalley stratigraphy is markedly heterogeneous. At the regional scale this variability reflects major changes in geological provinces, sediment source rocks, climatic regimes, depositional environments, and the origin, timing and duration of palaeovalley life cycles (Figure 42).

Stratigraphic heterogeneity exists at a range of scales and precludes construction of a nationally consistent stratigraphic classification framework (an objective proposed in the original project plan). However, several broad-scale generalisations about the nature of sedimentary sequences in palaeovalleys can be made:

- Deposition of Cenozoic palaeovalley sediments mainly occurred in two temporally distinct stages. The initial infill stage encompasses the Middle to Late Eocene, and generally consists of medium- to coarse-grained sediments typical of relatively high-energy fluvial environments (although local fine-grained variations are known, e.g. in palaeovalleys near Uluru, R. Read, NT NRETAS, pers. comm., 2012). Example formations are the North Royal Formation in the WA Goldfields (formerly known as the Wollubar Sandstone) and the Pidinga Formation (Gawler-Eucla region of SA). Basal sedimentation was followed by a depositional hiatus during the Oligocene (possibly with minor erosion), with subsequent deposition occurring onwards from the Late Oligocene to the Miocene. Typically the sediments deposited during the latter stage were finer grained and typical of lower energy settings, for example lake deposits.
- Intracratonic basin-style palaeovalleys are spatially restricted to parts of central Australia near upland ranges that were subject to tectonic activity. These palaeovalleys tend to have thick infill sequences (300–500 m) and a greater proportion of fine-grained sediments; for example, contrast the Kintore Palaeovalley in Figure 26, a more typical ‘fluvial’ palaeovalley setting with <100 m of sediments, and the Central Mount Wedge Basin in Figure 27, which was evidently a lake basin for much of its history.
- The stratigraphic thickness of more typical fluviatile palaeovalleys generally tends to increase with downstream distance from the uppermost headwaters. Thus, major trunk palaeovalleys tend to contain thicker infill sequences, with greater storage potential for groundwater resources, than smaller (upstream) tributary systems. However, the total groundwater volume contained in intricate palaeovalley tributary systems, such as in the Yilgarn, can be significant. These tributaries may also be hydraulically connected with adjacent weathered bedrock aquifers.
- Delineating and correlating stratigraphy both within and across many inland Australian palaeovalleys is hampered by the effects of deep chemical weathering. This has substantially modified the infill sequence, promoting development of secondary clay minerals and oxidation of spores and pollen (rendering it unsuitable for palynostratigraphic analysis). Weathering has also largely destroyed sedimentary structures in the infill, further inhibiting detailed analysis of sedimentology and depositional environments.

The stratigraphic heterogeneity of arid-zone palaeovalleys is not restricted to the regional scale. Individual palaeovalley systems may possess variable drainage patterns, stratigraphy and aquifer properties that impede local correlations (and thwart regional characterisation). The difficulty in correlating sedimentary sequences between different basin-style palaeovalleys in central Australia has been noted by Senior et al. (1995), English (2002) and Wischusen et al. (2012). Considerable spatial variability, along and across palaeovalleys, has been documented for specific regions or geologic provinces (Figure 43).

4.3.2 Discriminating valley infill sediments from weathered bedrock

Drilling programs carried out for the *Palaeovalley Groundwater Project* at Kintore, Wilkinkarra and Ti Tree provided evidence of the corrosive impact that palaeovalley groundwater systems can have on the mineral composition of incised bedrock. The extensive weathering of bedrock can make it extremely difficult to distinguish from the basal palaeovalley sediments, hampering accurate determination of the contact. Similar extensive *in situ* weathering of basement rocks beneath palaeovalleys was reported for the Yilgarn in Western Australia by Commander et al. (1992) and Anand and Butt (2010), and for the Gawler region of South Australia by Hou (2004).

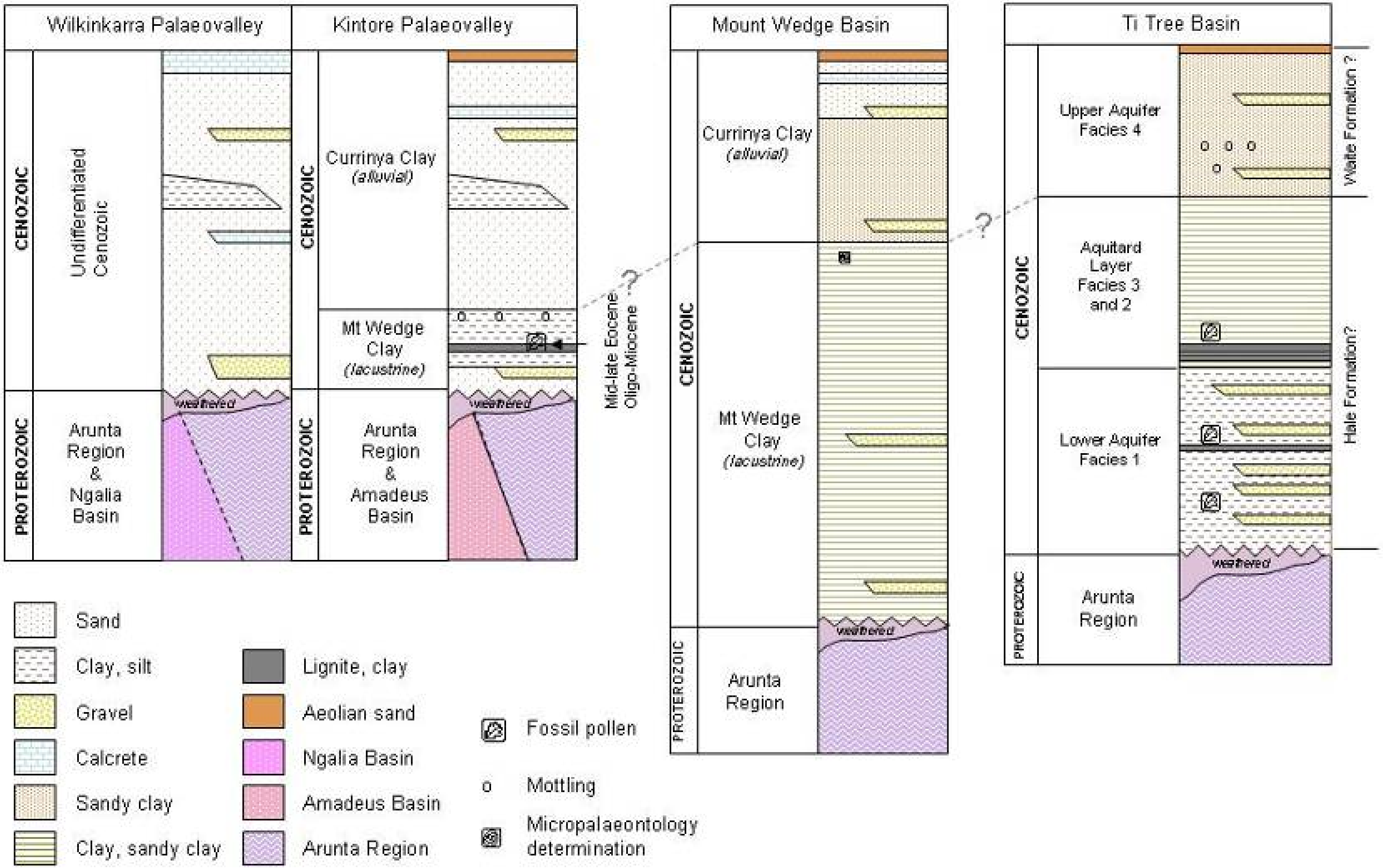


Figure 42: Stratigraphic sections for palaeovalleys in the Wilkinkarra, Kintore, Central Mount Wedge and Ti Tree regions of central Australia.

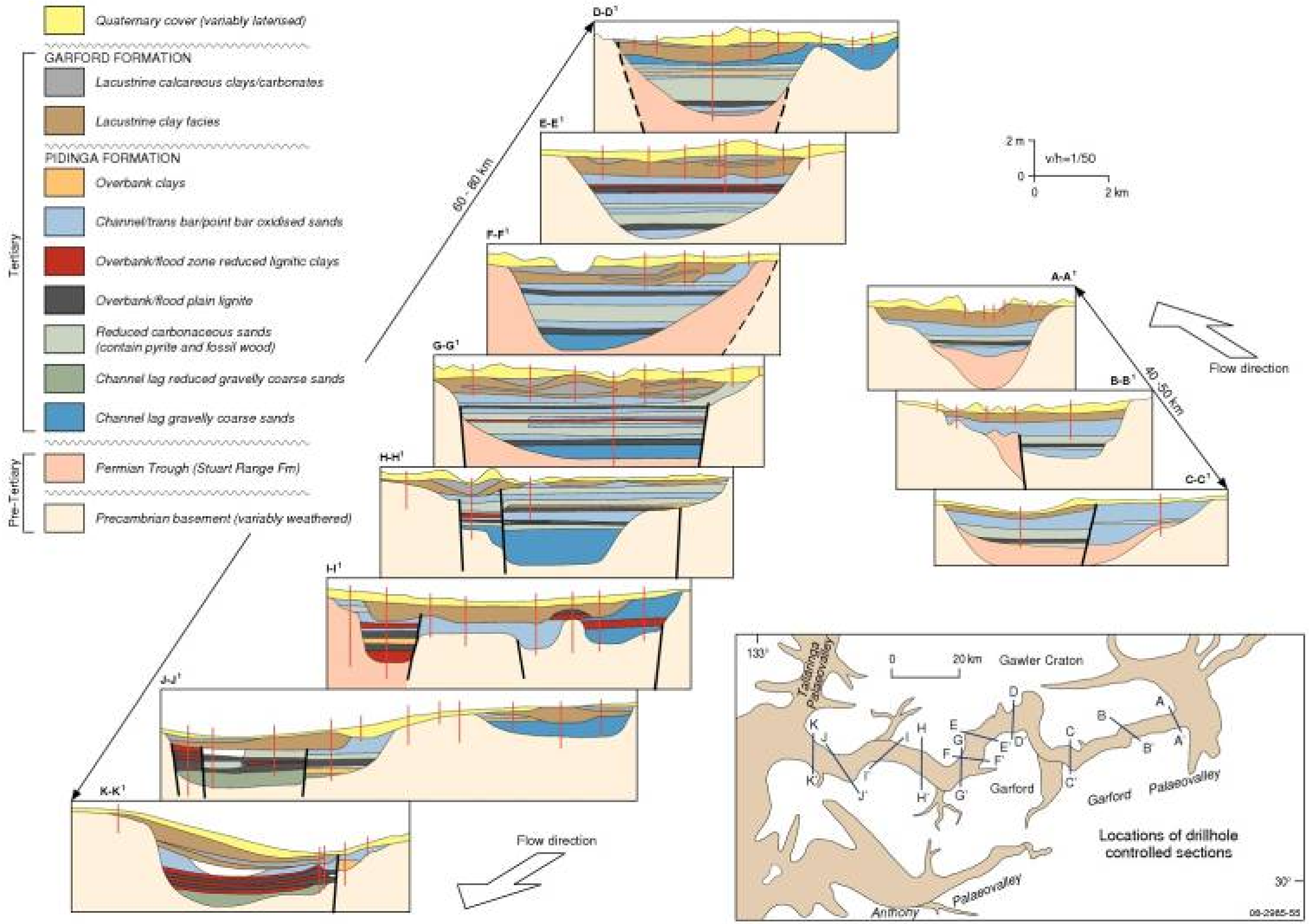


Figure 43: Stratigraphic cross-sections along the Garford Palaeovalley (Gawler Craton, SA) showing variations in channel morphology and sediments. These sections are based on detailed drilling transects by the Geological Survey of South Australia (figure modified after Hou et al., 2001).

Inaccurate determination of the sediment–basement contact in palaeovalley aquifers may lead to overestimation of the sediment volume and hence the stored groundwater volume. Although the weathered bedrock may be hydraulically connected to the thalweg aquifer this zone typically is less permeable. Strongly weathered bedrock and basal palaeovalley sediments may also cave in during drilling, further hampering definition of the contact zone. Consequently, it is critical to log palaeovalley drill holes in considerable detail so that the basal sediment sequence is accurately recognised. The use of downhole geophysical logging tools (e.g. gamma or conductivity logs) can also assist in defining the bedrock contact. Logging is made more difficult when rotary percussion drilling is used (commonly because of lower costs and better availability), as this method complicates logging by providing mostly rock chips and dust (Figure 44).

To improve stratigraphic definition in future investigations consideration should be given to obtaining core, either by diamond drilling or sonic drilling, from palaeovalley sequences. Core recovery is beneficial for detailed aquifer characterisation and groundwater resource assessment, along with valuable stratigraphic and sedimentologic information. Additionally, diamond core could be used to calibrate certain field-based analytical methods which are capable of characterising infill sediments from weathered bedrock, for example use of hand-held X-ray fluorescence (XRF) or portable infra-red mineral analyser (PIMA). Core obtained from sonic drilling enables pore fluid analysis to fully characterise the chemistry of *in situ* groundwater.

Figure 44: Logging sediment chips from rotary percussion drilling of palaeovalley infill in the Murchison region (WA). The palaeovalley bedrock, including Archean granite, Proterozoic quartzite and schist, is highly weathered. Discerning the sediment-weathered bedrock interface is difficult in some palaeovalley settings (photo by Pauline English, July 2010).

4.4 Groundwater resources

Palaeovalley aquifers in arid Australia (like other aquifers) receive very low rates of natural recharge due to low rainfall and high evaporation. The modern climate regime generally leads to saline groundwater systems over time, as the concentration of residual salts in solution increases with age due to multiple evaporative cycles. Recharge events in arid-zone palaeovalley aquifers require significant high-intensity rainfall, such as major storm events that are capable of precipitation of >100 mm over short timeframes. Such weather systems are infrequent and erratic in most arid zones. Areas that are nearer to the coast may be subject to more frequent cyclonic activity, such as the north-west of Western Australia. In these areas remnant weather fronts associated with cyclones are capable of producing very significant rainfall which may lead to more frequent palaeovalley aquifer recharge, for example in the Paterson Province of Western Australia (English et al., 2012b).

4.4.1 Estimating palaeovalley groundwater resource volumes

Many of the arid-zone palaeovalleys are high-quality groundwater targets. Existing extraction across the WASANT area amounts to over 250 GL per year (Chapter 1). This estimate is projected to continue increasing, as new mining and infrastructure developments begin to come on line in the short to medium term. It will be critical, for future large-scale operations that may use palaeovalley aquifers, to undertake sufficiently detailed studies to estimate total groundwater resources with upwards of 80 per cent confidence. This will allow for planning and management of the available resources for the long term.

The WASANT Palaeovalley Map can help derive a very rough estimate of the total combined groundwater resources contained in arid and semi-arid palaeovalley systems. As previously mentioned, there are ~200 major palaeovalleys in the study area with the combined total length upwards of 80 000 km. Assuming a simplistic prism-like aquifer 2500 m wide with a saturated thickness of 50 m and effective specific yield of 5 per cent as average estimates for the key hydraulic dimensions of this region (based on findings from demonstration site investigations), then the volume of extractable palaeovalley groundwater in arid Australia may be of the order of 250 x 10^3 GL. However, much of this will be brackish or saline, and yields may be low such that the resource is not particularly useful for intended purposes.

Developing accurate estimates of groundwater volumes in individual palaeovalley aquifers is difficult due to the complexity and variability of palaeovalley dimensions and sediments and the potential input from other hydraulically connected aquifers. Pumping from palaeovalley ‘thalweg’ aquifers may induce lateral inflow (‘recharge’) from adjacent weathered or fractured bedrock, without drawing substantially on overlying palaeovalley sediments. This may introduce either more saline or fresher groundwater, or water with contrasting chemistry that may include undesirable solutes. Pumping from palaeovalley sediments may also induce downward inflow from overlying calcrete aquifers or water bodies. Detailed investigations are required to constrain the range of potential groundwater inputs to any palaeovalley system so that the total groundwater resource and its dynamics can be gauged more accurately. The extent and degree of connectivity of groundwater stored in the network of tributary systems connected to larger trunk palaeovalleys are also important considerations for determining the potential resource.

Sustainable yields, or ‘environmentally sustainable levels of extraction’ (Australian Water Resources, 2005), are difficult to estimate for palaeovalleys. This is especially so where groundwater resources are ‘fossil’ water (palaeowater) that are only being slightly replenished (if at all) in the present-day climate. A national groundwater sustainable yield definition has not been adopted by all states and territories. The definition agreed upon by the National Groundwater Committee is:

The groundwater extraction regime, measured over a specified planning timeframe, that allows acceptable levels of stress and protects dependent economic, social and environmental values.

The reconnaissance nature and broad scale of the *Palaeovalley Groundwater Project* precluded addressing sustainable yields. Detailed investigations in specific regions and sites are required before guidelines for water extraction levels for given systems can be developed. The present study has shown substantial heterogeneity and complexity of palaeovalley aquifer systems. The near-surface settings and apparent close links with vegetation and other ecosystems potentially makes palaeovalleys more sensitive than aquifers being used in large sedimentary basins or extensive dolomite terrains. There is a high risk that key environmental assets or ecosystem functions may be adversely impacted if sustainable yields are exceeded.

4.4.2 Palaeovalley aquifers as multi-component water-bearing systems

Palaeovalleys have excellent potential as groundwater resources throughout much of arid Australia, both in areas where they are currently used, as well as in more remote, not yet built on ('greenfields') regions. This study has demonstrated that one of the key factors contributing to the resource potential is that many palaeovalleys are effectively multi-component aquifer systems (Figure 45). This means that groundwater may be stored within several different water-bearing 'compartments' of the hydrostratigraphic sequence. These potential water-bearing zones or units include:

- The basal thalweg sediment facies which occupies the main fluvial palaeochannel incised into (and inset within) the bedrock. This zone typically contains the largest volumes of groundwater in storage and has the greatest yield capacity due to the presence of coarse-grained sediments (sands and gravels) and relatively high hydraulic conductivities;
- Overlying sedimentary layers surrounded by finer grained sediment zones of relatively lower hydraulic conductivity. These may be isolated sand-rich layers or lenses which occur above the main thalweg zone within an otherwise clay-dominated sequence;
- Near-surface alluvial deposits. These are younger and generally thinner sediment layers that may have accumulated in the palaeovalley depression during more recent geologic times;
- Near-surface calcrete deposits. These are secondary deposits formed by precipitation of calcium carbonate. Many calcrete deposits in arid Australia have formed in palaeovalleys (as shown in Figure 25). It is not uncommon for these so-called 'valley calcrete' bodies to be silicified;
- Other rocks or sediments hydraulically connected to the palaeovalley aquifer. These may include weathered or fractured bedrock systems, or confining sediment layers above the main palaeovalley aquifer (further discussed below).

The main channel zone is typically the part of the palaeovalley incised deepest into the bedrock, and is the recommended highest priority target for drilling to access the largest volume of groundwater. The thalweg aquifer may not always have the best quality groundwater, especially in areas that are distant from the palaeovalley recharge zones. In such areas, near-surface calcrete deposits may have fresher groundwater, although volumes are usually less than in the thalweg aquifer.

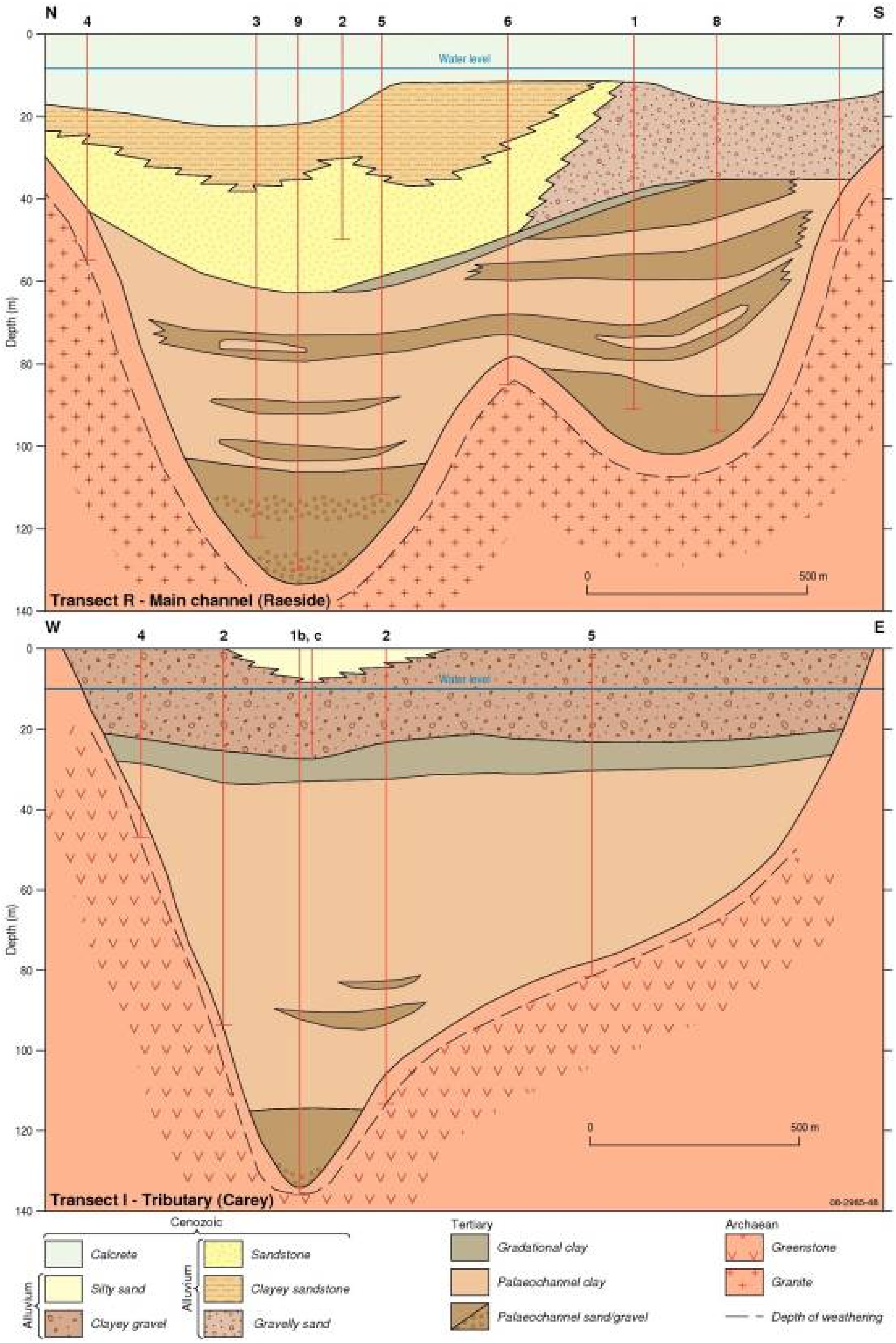


Figure 45: Schematic cross-sections for the Raeside and Carey Palaeovalleys in WA, illustrating multi-component aquifer zones within a palaeovalley infill sequence (after Johnson et al., 1999). The numbered vertical red lines represent drill-hole locations used to construct the cross-section.

In areas where present-day river channels are co-located with the palaeovalley, the location of the contemporary channel may not coincide with the location of the deep palaeo-thalweg, as revealed in the Murchison drilling program (English et al., 2012a). This has important implications for determining the optimal location to site a bore. Ground gravity surveys across a palaeovalley are a relatively simple and effective method of finding the deepest part. Where a discernible density contrast exists between the palaeovalley sediment infill and the bedrocks, the gravity survey can accurately pinpoint the deepest part of the palaeovalley.

4.4.3 Capacity for enhanced lateral and vertical inflow

An important factor that may increase the groundwater resource within any given palaeovalley aquifer is the potential for inflow from adjacent aquifers. This may occur during or after groundwater extraction from the basal palaeochannel where there is hydraulic connection with weathered or fractured bedrock aquifers (e.g. Figure 8 and Figure 46). Alternatively, saturated confining units such as fine-grained silt or clay layers may be in direct hydraulic contact with a palaeovalley thalweg aquifer. Pumping from the thalweg zone over time can draw groundwater from the confining layer and into the main aquifer zone, thereby contributing to the total groundwater volume. This can significantly upgrade the groundwater resource available for extraction, and probably means that the total groundwater resource estimated above represents a conservative value. However, inflow from connected aquifers may also adversely affect groundwater quality, for example if the other aquifers contain more saline groundwater.

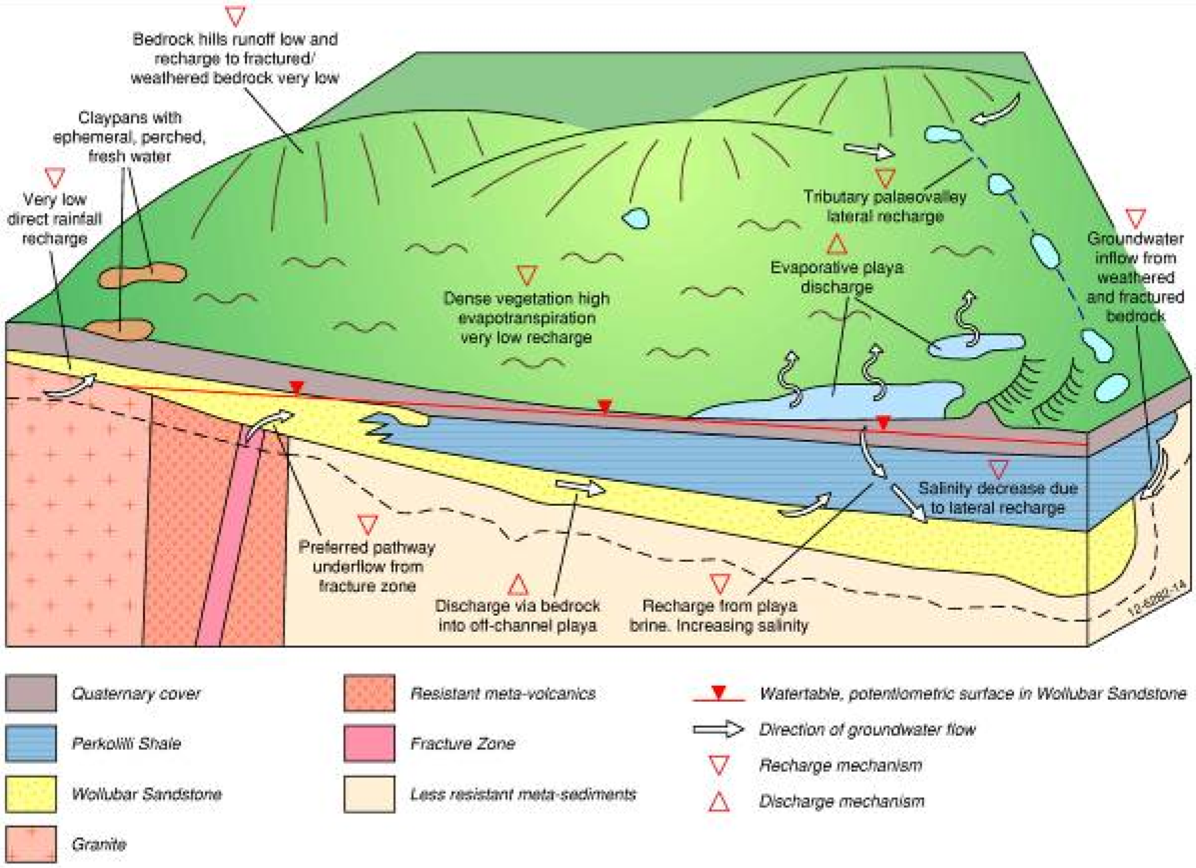


Figure 46: Conceptual model of hydrodynamic processes in the Roe Palaeovalley in the WA Goldfields (after Commander et al., 1992).

Inflow (or delayed yield) can potentially contribute to the available groundwater resource for most palaeovalleys. However, the rate and magnitude of this process needs to be investigated prior to production to assess impacts on the overall hydrogeological system, especially if significant extraction is planned. Such assessment may require the design of suitable aquifer characterisation and pumping tests to properly evaluate the effects of prolonged groundwater extraction on the watertable and on other confined aquifers. Previous work on groundwater resources of palaeovalleys in the Western Australia Goldfields (Figure 46) provides a conceptual understanding of the hydrodynamic processes of aquifer inflow, as well as a case study on the management implications (Commander et al., 1992; Johnson, 2007).

4.5 Hydrogeochemistry

This section summarises observations on groundwater chemistry throughout the *Palaeovalley Groundwater Project*, emphasising the common features and processes of hydrogeochemical evolution. Site-specific information is provided in Chapter 2 and in the respective demonstration study reports (Table 1).

4.5.1 Groundwater quality and salinity

Groundwater quality ranges from fresh to hypersaline (TDS of hundreds, to hundreds of thousands mg/L) in Australian arid-zone palaeovalley aquifers (Figure 47 and Figure 48). This variability is evident at various scales, from regional systems (e.g. contrast between geologic provinces and climatic zones) to discrete palaeovalleys. Fresher groundwater resources are most commonly in higher order segments of palaeovalley systems, such as tributaries in shallower systems overlying bedrock, and are associated recharge zones (see below).

Calcrete or silicified calcrete aquifers in trunk palaeovalleys also commonly contain fresh groundwater, recharged directly from rainfall or from sporadic river flow.

4.5.2 Major ion compositions

Chemical compositions of analysed groundwater for this project plot along relatively consistent trends on the Piper classification diagram (Figure 49). The groundwater is dominantly sodium chloride in composition (Na-Cl facies). Other facies are mostly slight derivations from Na-Cl, such as Na-Ca-Cl, Na-Mg-Cl, Na-HCO_3-Cl, Na-Ca-HCO_3-Cl, and Na-HCO_3. The facies enriched in HCO_3 correspond to the freshest (less mineralised) groundwater. The ratio of bicarbonate to chloride (HCO_3 to Cl anions in milli-equivalents per litre) was interpreted by McDonald (1990) as an indicator of groundwater recharge, with values >1 closely correlated with low levels of TDS and low chloride concentrations.

Historically, the richest dataset from the project demonstration sites is that for the Ti Tree Basin (see Wischusen et al., 2012 and references therein). McDonald (1990) and Harrington (1999) gave regional overviews of the chemical characteristics of the groundwater in the Ti Tree shallow aquifer. Very detailed work found in Harrington and Herczeg (2000, 2003) and Harrington et al. (1999, 2002) provides a benchmark for groundwater chemistry studies and future interpretation in other palaeovalleys.

According to Harrington et al. (1999, 2002), two dominant groups of processes account for the chemical composition of the shallow Ti Tree Basin groundwater system:

- Dissolution of calcite ($CaCO_3$) and gypsum ($CaSO_4.2H_2O$), with silicate weathering (acquisition of HCO_3 and HSO_4 at initially low Cl concentrations)
- Evapotranspiration, precipitation of carbonate minerals, cation exchange of calcium for sodium on clay minerals, and in some instances weathering of silicates.

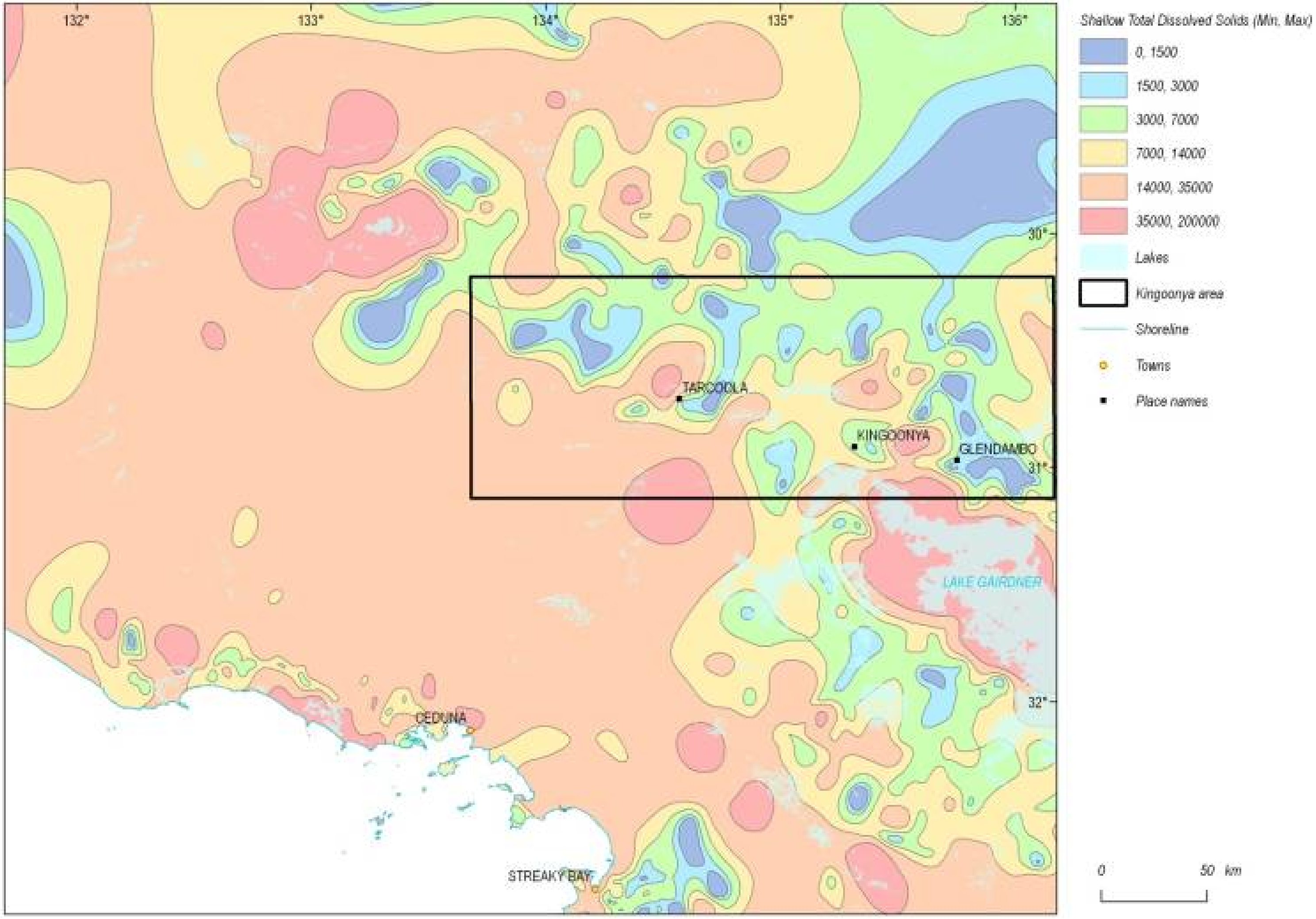


Figure 47: Groundwater salinity varies widely across the Gawler-Eucla demonstration site, including in the many regional palaeovalleys. This variability indicates that predictions of groundwater quality are difficult without sufficient data and a reliable understanding of the hydrogeology.

The second set of processes is responsible for the data trend observed on the Piper diagram (Figure 49) and for the decreasing (HCO_3+HSO_4) to (HCO_3+HSO_4+Cl) ratio when plotted against total chloride or TDS (Figure 50). Visual examination of the Piper diagram suggests the HSO_4 to Cl ratio does not change much for a particular palaeovalley system. In other words, removal of bicarbonate and accumulation of chloride are the main features of the chemical evolution of arid-zone palaeovalley aquifers. This observation justifies the simplified approach of McDonald (1990) who suggested plotting HCO_3 to Cl ratios to indicate groundwater recharge areas for the Ti Tree Basin.

This approach was also used by English (2002) for the Lake Lewis Basin in central Australia. In this groundwater system, located between Ti Tree Basin and Central Mount Wedge Basin, the spatial distribution of HCO_3/Cl >1 corresponds with aquifers beneath mountain-front areas and along creek lines and their mid-basin floodout areas. These are all interpreted as groundwater recharge zones. English (2002) further correlated these zones with groundwater ^{14}C data and showed that relatively elevated percent modern carbon (pMC) corresponds with HCO_3-rich recharge areas. Conversely, more mature water (palaeowater with low pMC), occur in other parts of the basin away from mountain fronts and creek lines, i.e. aquifers in distal reaches and interfluvial areas of the basin (English, 2002). McDonald (1990) and English (2002) also found excellent correlation between HCO_3 to Cl ratio and TDS. In general, using the (HCO_3+HSO_4) to (HCO_3+HSO_4+Cl) ratio is more widely applicable as it accounts not only for bicarbonate removal, but also for sulfate removal, i.e. precipitation of gypsum. Both ratios are well correlated and can be used interchangeably for arid-zone palaeovalley aquifers.

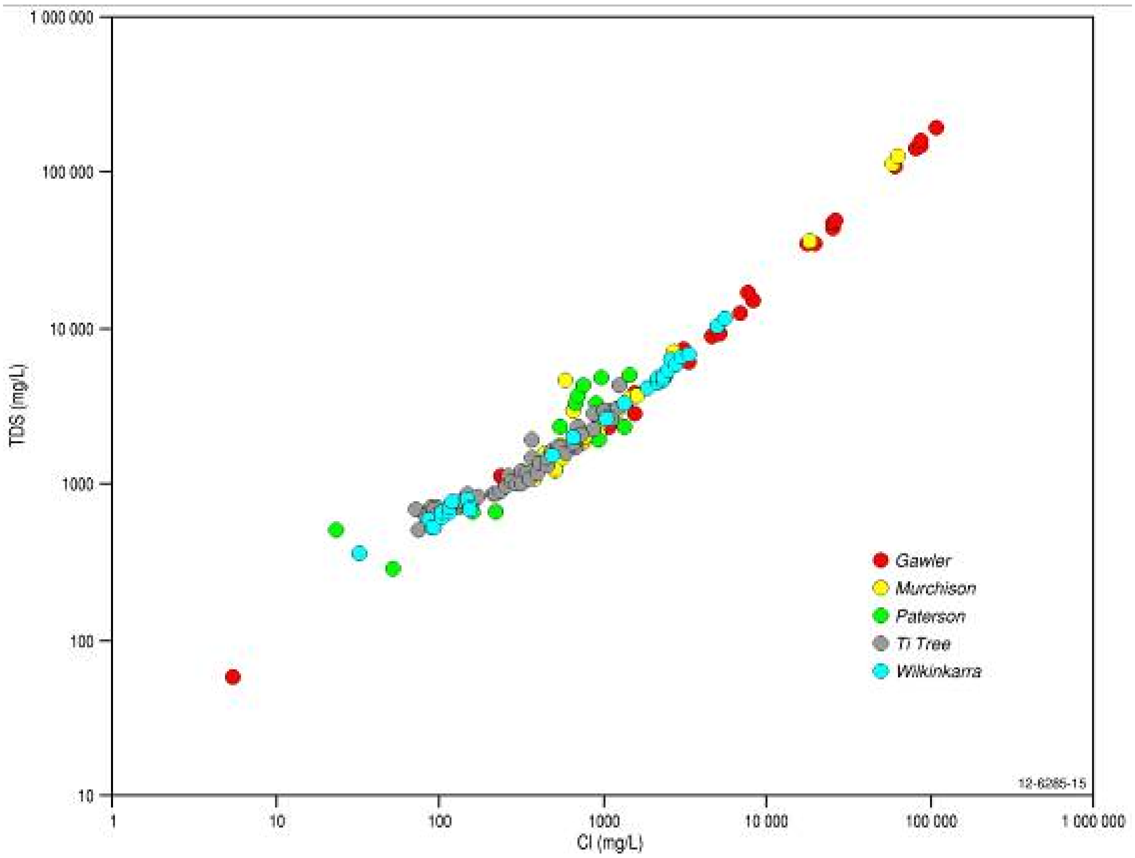


Figure 48: Correlation of TDS and chloride abundance (logarithmic scale) in groundwater analyses from the *Palaeovalley Groundwater Project*.

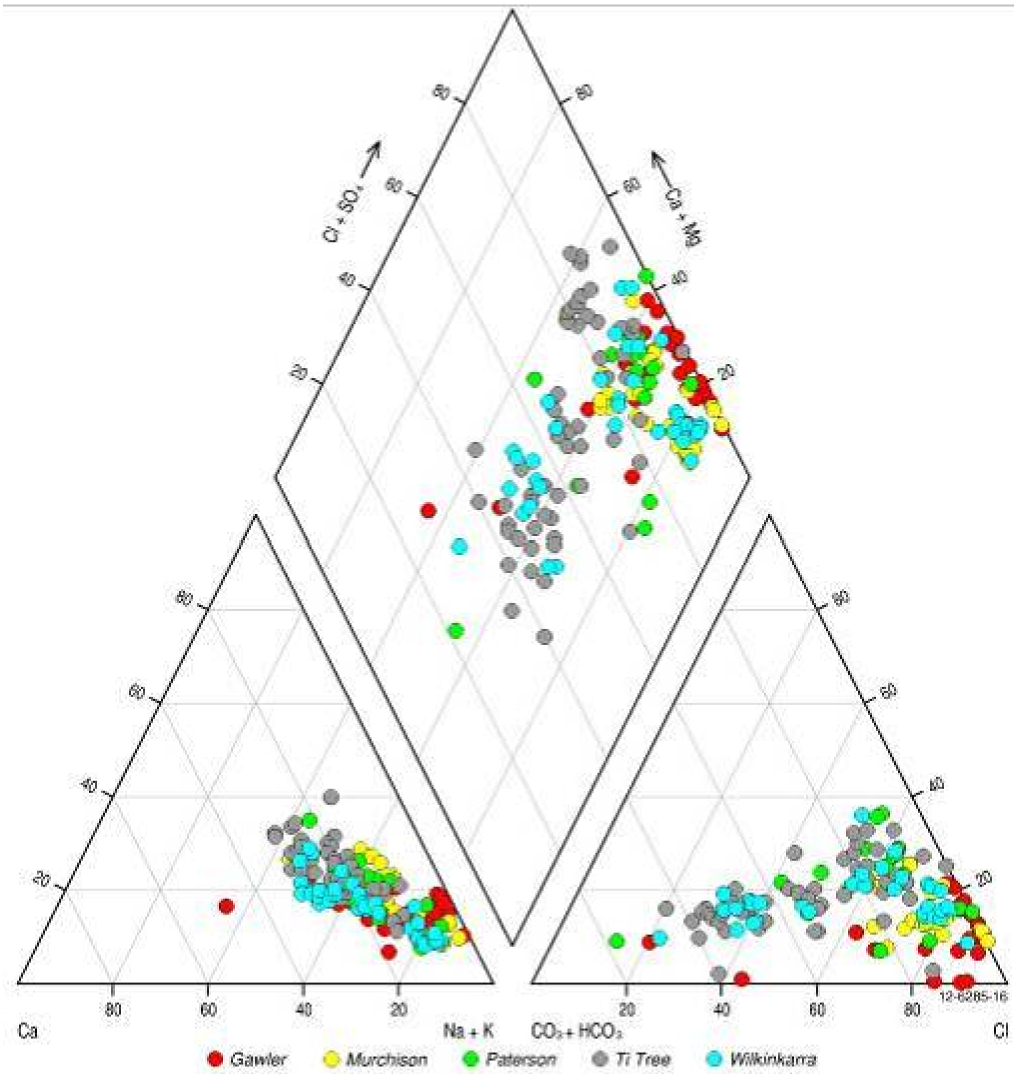


Figure 49: Major ions in groundwater from the palaeovalley demonstration sites.

Harrington et al. (1999, 2002) suggested that the composition of the NaCl-type groundwater reflected greater levels of evaporative concentration in the soil zone resulting in precipitation of carbonate minerals, cation exchange of calcium for sodium on clay minerals, and, in some instances, weathering of silicates. Saturation indices of calcite and gypsum calculated with the PHREEQC geochemical code (Wischusen et al., 2012) suggest that Ti Tree Basin groundwater evolves in the direction of calcite (and, ultimately, gypsum) saturation as the evaporative concentration of chloride progresses. This latter effect explains why the evolutionary trend of the groundwater is expressed mainly in terms of HCO_3 to Cl ratio. Locally, this simple evolutionary trend on the Piper diagram can be 'reversed' in the case of mixing between the brackish groundwater and lower salinity water (Wischusen et al., 2012). Despite such local variations, the major conclusion is that the more 'evolved' and 'mature' groundwater systems develop in the direction of concentrated NaCl-rich water.

4.5.3 Oxygen and deuterium isotopes

Oxygen and deuterium isotopes are commonly used in hydrogeologic studies to evaluate the relative importance of physical processes that may affect groundwater, such as evaporation, mixing and recharge mechanisms (Mazor, 1997). There is a worldwide correlation (known as the global meteoric water line, or GMWL) between the oxygen and deuterium isotope composition of groundwater, given by the equation $\delta D=8*\delta^{18}O+10$. This correlation can be refined for particular geographic areas with the introduction of local meteoric water lines (LMWL). The direction of shift in an oxygen-deuterium isotope dataset away from the meteoric lines indicates the dominant processes that have affected the groundwater system during its evolution from the initial isotopic precipitation signature.

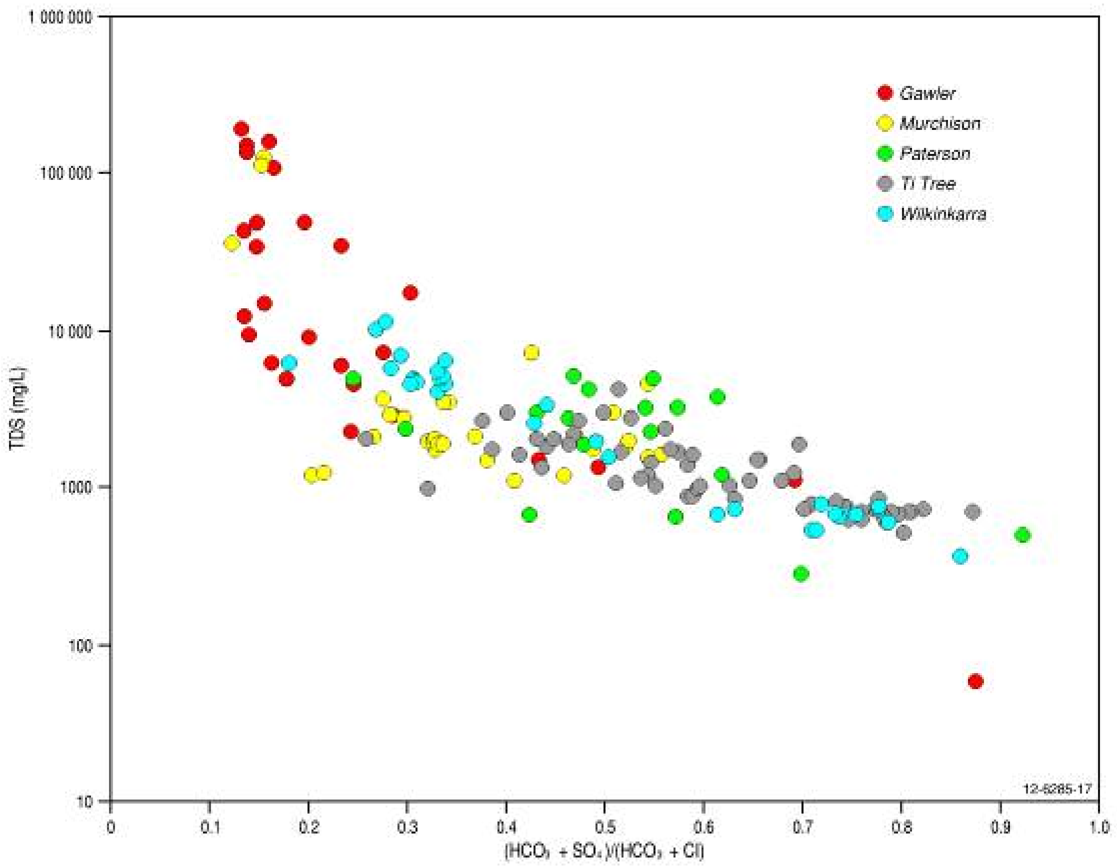


Figure 50: The chemical composition of palaeovalley groundwater expressed as a function of TDS and the relative contributions of HCO_3, Cl and SO_4 (mg/L).

Oxygen and deuterium isotope data derived in the present study are plotted in Figure 51. For all the analysed groundwater, oxygen-18 ($\delta^{18}O$) and deuterium (δD) isotopes show systematic enrichment in the heavier isotopes away from the meteoric water lines. For particular palaeovalley systems, the plotted datasets define relatively linear trends away from the GMWL. These trends are consistent with evapotranspiration as the dominant physical process affecting the chemistry of palaeovalley groundwater systems. There is a general correlation with stable isotope data and median salinity for each site, such that the site with the most depleted isotopic compositions (Paterson) correlates with the freshest palaeovalley groundwater (median TDS). Conversely, groundwater from the Gawler palaeovalleys is the most saline group, and these have the most enriched stable isotope signatures.

4.5.4 Trace elements

Elevated levels of trace elements which potentially adversely affect human health, such as fluorine (F), boron (B), manganese (Mn), lead (Pb), arsenic (As), and uranium (U), may occur in groundwater within palaeovalley aquifers (Figure 52). Some of these values exceed thresholds for the Australian Drinking Water Guidelines.

Concentration of trace elements is a complex function of the initial composition, water–rock reactions, and the dynamics of the groundwater system and concentration processes like evaporation. Generally, inorganic groundwater contaminants that may exceed Australian Drinking Water Guidelines correlate with chloride ions, suggesting that their elevated levels result from concentration by evaporation (Figure 52). Some elements (such as uranium) do not exhibit this correlation, and elevated levels most likely relate to water–rock interaction. Elevated uranium concentrations commonly occur in groundwater hosted in fractured rock aquifers from Australian Precambrian (older than 542 Ma) granite terranes (Champion and Sheraton, 1997).

Nitrates are commonly elevated in arid regions of Australia (e.g. Barnes et al., 1992). Nitrate concentrations in palaeovalley groundwater are not correlated with chloride, indicating that evaporative concentration does not cause elevated nitrate levels. High nitrate levels are caused by near-surface biological fixation, commonly by bacteria in soils and termite mounds (Barnes et al., 1992).

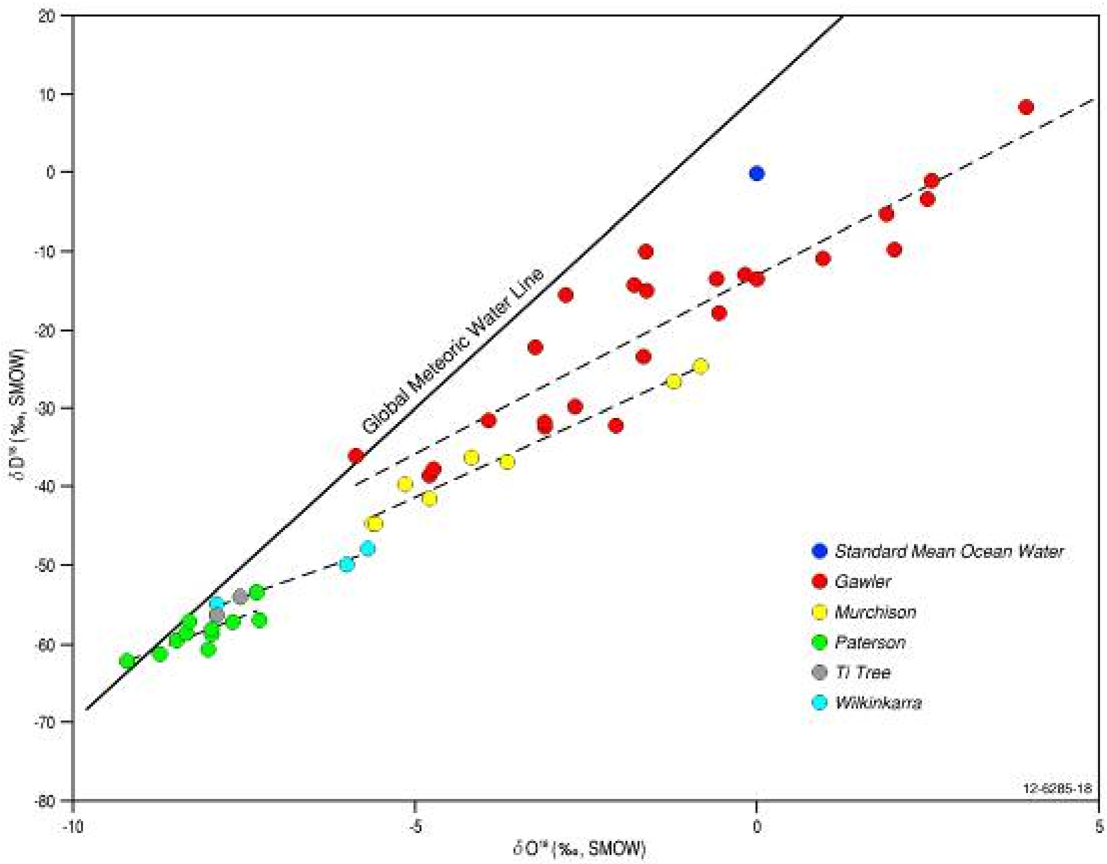


Figure 51: Stable isotope data ($\delta^{18}O$ vs δD) for groundwater from palaeovalley demonstration sites (SMOW, standard mean ocean water).

4.5.5 Groundwater residence times

Groundwater from the demonstration sites hasradiocarbon ages of approximately 1300 to 29 250 years BP (Figure 53). These ages are mostly uncorrected and assume no water–rock interaction, indicating the maximum possible groundwater residence time. The only exception is the work of Harrington (1999; 2002) for the Ti Tree Basin (modern age to ~24 000 years). These data suggested broad correlation between groundwater chemistry and the groundwater age based on corrected ^{14}C data, with Cl-enriched and HCO_3-depleted water being older. This is consistent with their more evolved nature.

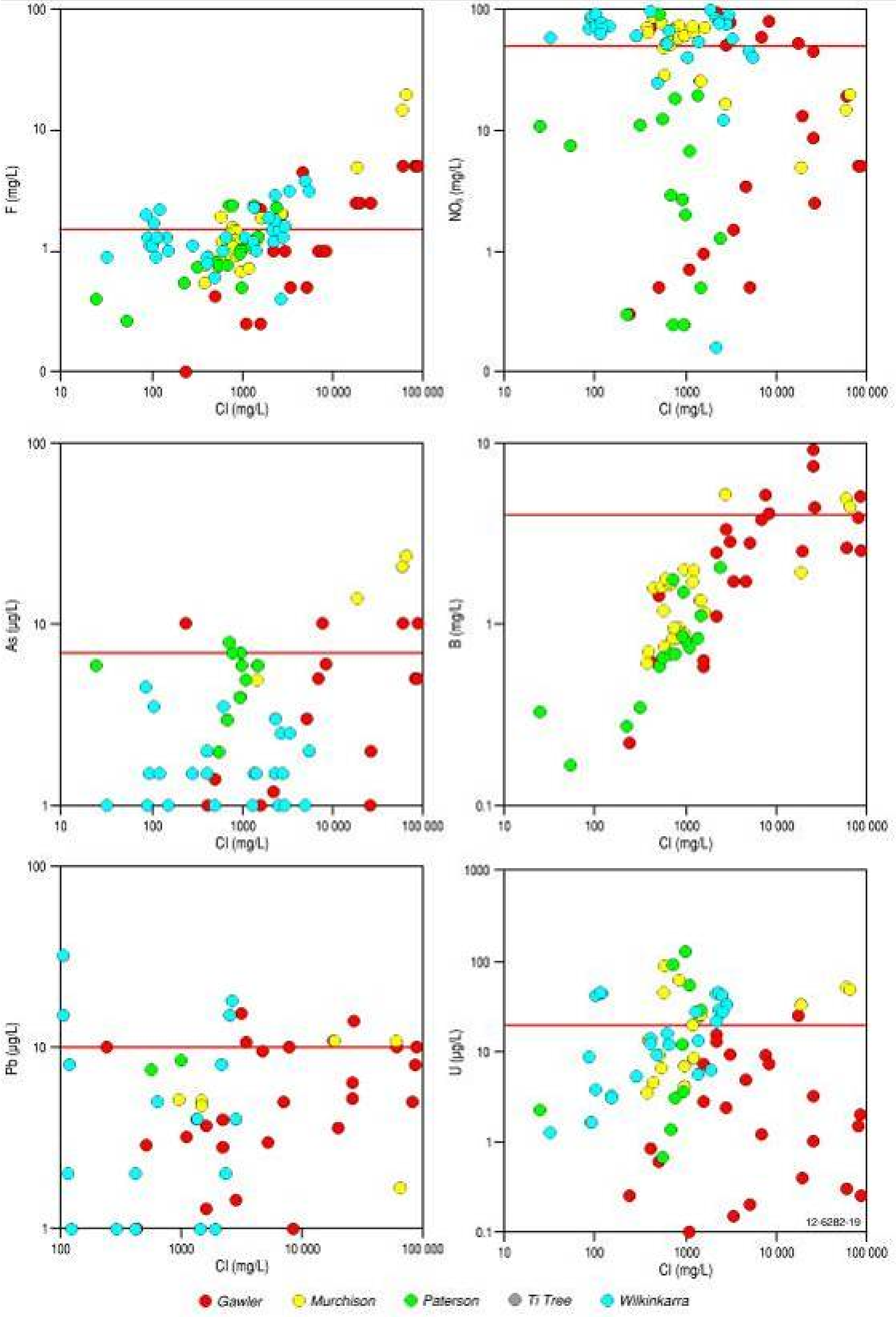


Figure 52: Compilation of concentrations of trace elements that occasionally exceed Australian Drinking Water Guidelines thresholds (red line) plotted against chloride (abbreviations: As, arsenic; B, boron; Cl, chloride; F, fluorine; NO_3, nitrate; Pb, lead; U, uranium).

Older groundwater (>20 000 years old) typically occurs in deeper parts of the aquifers, and 'modern' groundwater is likely to occur in shallower near-surface parts, for example the Kingoonya Palaeovalley (Chapter 2) (Lewis et al., 2012). Palaeovalley groundwater systems that are developed for water supplies are at risk of being over-exploited (irreplaceably depleted) due to low modern recharge rates. These resources may be non-renewable if extracted at medium- to large-scale volumes.

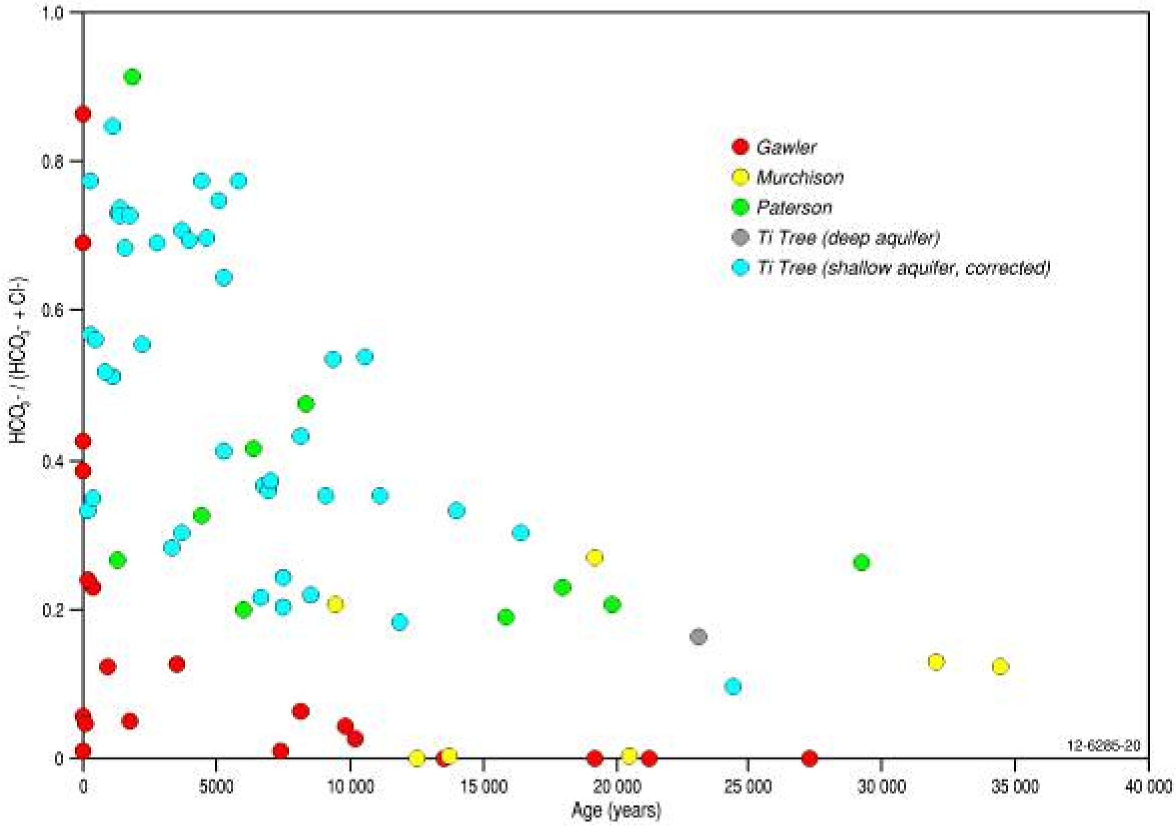


Figure 53: Uncorrected ^{14}C ages of groundwater from the palaeovalley demonstration sites.

5. Key project outcomes, major recommendations and lessons learnt

The four-year work program carried out for the *Palaeovalley Groundwater Project* has substantially improved knowledge of palaeovalleys and their groundwater resources in arid Australia. The reconnaissance-scale studies completed at five regional demonstration sites have answered many specific research questions that were generated during the initial phase of the project (see Chapter 2). Additionally, the key outputs from these individual demonstration studies have assisted in recognising broader aspects of Australian palaeovalleys, and enhanced conceptual understanding of aquifer dynamics and groundwater processes. This chapter reviews key project outcomes, and provides recommendations for:

- improved management of palaeovalley groundwater resources
- exploration and assessment approaches
- future research opportunities in arid zone hydrogeology.

Lessons learnt are then identified.

5.1 Key project outcomes

Important outcomes from the *Palaeovalley Groundwater Project*:

1. Palaeovalley aquifers present many challenges for their use, appraisal and management. Based on the findings of this project, it is inappropriate to attempt to accurately predict and quantify key characteristics of palaeovalley groundwater systems for all of arid Australia. Palaeovalley variability applies to all major geologic and climatic zones within the WASANT area, and has major implications for planning and implementing future assessments of their groundwater resources. For example, water quality (salinity) in palaeovalley aquifers may change considerably over relatively small distances, e.g. fresh to brackish in a tributary aquifer connecting to a hypersaline groundwater system in a trunk palaeovalley aquifer over a few kilometres, or even less. Groundwater quality may deteriorate over time with extraction scenarios, such as if poorer quality water is drawn into the aquifer to replace fresher water. Other variable characteristics are the hydrostratigraphy, geometry, and the degree of hydraulic connection with adjacent aquifers (e.g. fractured rocks or regolith-hosted systems). These are all important characteristics that play a major role in determining appropriate management strategies for palaeovalley groundwater resources. Detailed site-specific hydrogeologic investigations are needed for all new major developments to adequately characterise the palaeovalley groundwater system and form the foundation for a suitable management strategy.
2. Significant potable groundwater resources were found at several of the study site locations. These resources potentially benefit nearby remote groundwater users, such as the Aboriginal community of Kintore, future mining operations in the Murchison region, and existing mine sites in the Paterson region. The broader implications of these specific findings are that:
    a. significantly greater volumes of palaeovalley groundwater are now believed to exist within the arid and semi-arid zones of Australia
    b. considerable potable to brackish groundwater resources exist in buried palaeovalleys about which little was previously known, and almost definitely exist in additional areas that this project has not investigated
    c. methods adopted and proven in the *Palaeovalley Groundwater Project* provide guidelines for discovering and assessing as yet undisclosed palaeovalleys.

These resources are likely to be more widespread and abundant than has previously been recognised or considered, and occur in areas where groundwater resources have not been investigated. Groundwater quality is variable and usually not potable, requiring treatment such as desalination or denitrification.

3. Significant broad-scale structural and hydrostratigraphic differences exist between palaeovalley systems in central Australia and elsewhere. Many central Australian palaeovalleys are broader and deeper basin-like depositional environments, compared to the narrower fluvial-derived systems of western and southern Australia. Subtle neotectonic activity focused along major long-lived geologic structures has likely driven the development of the central Australian basin-type palaeovalleys (English, 2002; Woodgate et al., 2012), whereas fluvial incision and ongoing cycles of erosion and deposition are the main processes leading to the formation and evolution of palaeovalley systems that may be regarded as more typical in style.
4. The degree of connection that palaeovalleys have with adjacent aquifers (be they fractured rocks, regolith hosted, or larger sedimentary basins) is not always apparent, and hence the store of water that could be drawn upon is difficult to estimate without detailed aquifer characterisation studies.
5. High resolution digital elevation model (DEM) datasets and their derived outputs, such as the Multi-resolution Valley Bottom Flatness index (MrVBF), are very useful tools for preliminary assessment of palaeovalleys. At the national scale the 1-arc second DEM derived from the Shuttle Radar Topography Mission (SRTM) is an excellent initial dataset to analyse by GIS. These data and derived products have helped generate the WASANT Palaeovalley Map (Chapter 3), enabling consistent analysis and interpretation of palaeovalley features at the regional and continental scale.
6. The discovery of significant deep groundwater resources in the Ti Tree and Central Mount Wedge Basins of central Australia has broader implications for the future management and use of other basin-style palaeovalleys in this region, such as the Outer Farm Basin near Alice Springs. Total groundwater resource estimates could be upgraded for both Ti Tree and Central Mount Wedge Basins because of the recognition and preliminary assessment of the previously unknown Cenozoic basal sand aquifers as part of the *Palaeovalley Groundwater Project* (Chapter 2). The reconnaissance-scale work of the present project in these basins provides indicative groundwater storage volumes at least double the current resource. Further work is now required to gain a better understanding of groundwater compositions, residence times and spatial variations of the deeper aquifers, and the degree of hydraulic connection between them and the shallower resources that are currently being extracted. New research endeavours are needed to address questions such as: are the deeper aquifers hydraulically isolated (confined) from the shallow aquifer system or do they interact to some degree and, if so, where is this interaction focused? Basin-wide understanding is critical to better inform future management plans and ensure that any groundwater management actions address the entire resource.
7. The most appropriate methods for reconnaissance investigation of palaeovalleys depend on the geology of the study region. There is no prescriptive assessment approach that can be broadly applied to all arid-zone situations. One of the key factors to consider is that a detectable physical or chemical contrast is required to differentiate the palaeovalley sequence (or at least part of the infill sediments or groundwater resource) within the geologic terrane. These contrasts may be relatively minor and difficult to detect *in situ.*

8. Significant advances have been made with the application of integrated GIS and field-based investigation programs to evaluate palaeovalley groundwater systems in arid Australian environments. Datasets at many scales have been successfully employed to delineate, map and appraise groundwater resources, at least at a preliminary level. In some cases the techniques applied, and the integrated datasets used, represent an innovative approach not traditionally employed as part of hydrogeologic investigations. Diverse exploration and assessment methods have been tested in respective palaeovalley groundwater systems in different regions, using both broad- and local-scale approaches. This work has shown that a wide variety of techniques are available to explore, map and characterise palaeovalley aquifers, arguably a greater arsenal of tools and approaches than used in the past. The methods vary in costs, timeframes and technical specifications. However, work carried out for the *Palaeovalley Groundwater Project* has shown that even relatively simple and cost-effective techniques can provide useful data to enable interpretation of the location and important characteristics of palaeovalley aquifers. For example, the initial work program in the Murchison region used inexpensive remotely sensed data, starting with DEM and their derived products, to plan effective geophysical and drilling traverses. Ground-based gravity measurements were then used to define the main thalweg zone within each palaeovalley (English et al., 2012a). This simple approach accurately defined profiles of Murchison palaeovalleys, including buried inset valleys, attesting to multi-phase evolution and considerable offset of the modern river channels relative to the palaeo-thalwegs. Relatively inexpensive drilling disclosed very deep palaeovalleys, the deepest documented to date from the Yilgarn, with thick sandy units containing large volumes of brackish groundwater suitable for pastoral use and mining, as well as both fresh and hypersaline water (English et al., 2012a). The investigation approach used in the Paterson region, in contrast, centred on application of recently acquired airborne electromagnetics (AEM) survey data that had been flown for mineral exploration. The AEM dataset provided high-quality regional-scale data that, although not designed for hydrogeologic work or groundwater resource investigation *per se*, still enabled mapping of complex palaeovalleys incised into contrasting bedrock types as well as definition of major structures. The interpretation intimated that large volumes of fresh to brackish groundwater occur in diverse aquifers within the Paterson region, including widespread palaeowater, although with evidence for recharge from cyclonic systems encroaching from the north-west coast (English et al., 2012b).
9. The *Palaeovalley Groundwater Project* has demonstrated that data acquired by mineral exploration and mining companies is commonly very useful for hydrogeological studies, but it is commonly not interpreted for such assessments. At several investigation sites mining and exploration companies provided access to significant datasets, including drilling and airborne geophysical survey data that were useful in mapping and assessing palaeovalley groundwater resources. This wide variety of data has also helped compile extensive, well-planned and coordinated GIS geodatabases for each demonstration site, as well as at the national scale.
10. This project has highlighted the value of archival data in state or territory government libraries or data repositories, particularly for the Ti Tree Basin. This led to the development of the new research program that identified the potential for significant groundwater resources in the deeper Ti Tree Basin.
11. At a local level, the installation of the emergency hand-pump known as Winner’s Bore along the Kintore to Nyirripi back road (Wilkinkarra demonstration site) was a unique project outcome (Wischusen and Lewis, 2010). This followed successful reconnaissance-scale drilling of the Nyirripi Palaeovalley. The work highlighted the value of follow-up liaison and interaction with local groundwater users, and provided a tangible outcome for local communities with the potential to be a life-saving water supply.

5.2 Recommendations

5.2.1 Improved management of palaeovalley groundwater resources

The broad-scale management recommendations outlined here are designed to assist government water planners and managers to improve the sustainable use of palaeovalley groundwater resources. The scope of the *Palaeovalley Groundwater Project* did not extend to the definition of actual extraction limits (i.e. volumes or sustainable yields) for any of the demonstration sites. This reflects the reconnaissance style of the project, and that individual jurisdictions are ultimately responsible for management. Subject to appropriate water planning and management arrangements being put in place, there is scope for further development of palaeovalley aquifers and extraction of substantial volumes of groundwater resources across many parts of arid Australia; however, future developments should be aligned with the National Water Initiative and be based on a detailed understanding and appreciation of the groundwater systems.

Important recommendations for effective management of palaeovalley groundwater resources:

- Detailed aquifer characterisation studies are required prior to resource development to fully understand the geometry and hydrostratigraphy of the aquifer. This includes information on groundwater quantity and quality, as well as aquifer confinement or connectivity.
- Pumping tests are required to determine aquifer parameters and groundwater yields, since the spatial and compositional complexity of palaeovalleys, and the potential for interconnection with adjacent and subjacent aquifers, means that groundwater responses may be unpredictable. This will especially be the case for smaller palaeovalley reaches, such as headwater tributaries.
- Adequate groundwater system monitoring is a key requirement, especially as this will provide the mechanism to determine potential adverse system impacts of large-scale groundwater use. As a minimum standard there will always be a strong need to monitor water levels and quality concurrently and on a regular basis, with an adequate monitoring-bore network designed with the best possible understanding of the aquifer system geometry, groundwater flow paths, and major processes in mind. As part of any initial monitoring strategy there is also the need to understand (and quantify if possible) a standard set of pre-development water-quality parameters. Groundwater residence times are important to understand in this context, as they provide critical information on recharge rates.

Principles for improved management of palaeovalley groundwater resources

Principles that should be considered for future palaeovalley groundwater developments:

- The starting assumption for management should be that the groundwater system will be mined as a consequence of extraction. This position should be re-assessed as further data becomes available, e.g. through a monitoring program.
- Extraction of potable-quality groundwater from arid-zone palaeovalley aquifers with TDS levels <1500 mg/L should be via licensed allocation (unless for domestic purposes).

- Presume that all palaeovalley groundwater extraction will adversely affect associated groundwater-dependent ecosystems (GDEs). These GDEs should be clearly identified as part of the initial groundwater resource characterisation study, so that analysis of the likely impacts of groundwater extraction can be assessed. Consideration of these will aid groundwater managers to ensure that significant natural values associated with GDEs are not diminished by extractions of palaeovalley groundwater resources.
- Licensed extraction proposals above a significant quantity (initially suggested as >300 ML/year) should only be approved following rigorous assessment and appraisal of potential environmental impacts, and would also require the implementation of a long-term monitoring strategy to assess ongoing water quality and levels.
- Aquifer storage parameters and connectivity between aquifers (as defined by the initial characterisation study) should be taken into account when deciding on licence requirements for palaeovalley groundwater systems.

5.2.2 Exploration and assessment approaches

Many investigative techniques are available to aid exploration and assessment of arid-zone palaeovalley systems and their groundwater resources. An overview of methods used for the *Palaeovalley Groundwater Project*, as well as other approaches described in the scientific literature, has been compiled (to be published in September, 2012): *'The Palaeovalley Investigative Toolbox – Exploring and Assessing Palaeovalley Groundwater Resources in Arid Australia'* (Gow et al., 2012). The toolbox provides an outline of these investigative approaches, along with details of the properties that each technique measures, how the techniques should be employed, and how the data can be used to help explore palaeovalleys and their settings and groundwater resources.

As a starting point for future investigations, the toolbox should be used to guide selection and application of the most appropriate methods for identifying and assessing palaeovalley aquifer systems. The general approach recommended for regional-scale investigations should include the following actions.

1. Assess the available data and plan further investigations based on initial understanding of the geology and hydrology of the study area.
2. Identify potential avenues for access to 'non-traditional' hydrogeologic data, e.g. drilling and geophysics results held by mining and exploration companies.
3. Analyse DEM and derived interpretive products, such as the MrVBF that partitions the landscape into low and flat versus high and steep areas. The national 1-arc second DEM should be the initial basis for terrain and landscape studies. Higher resolution elevation data (e.g. LIDAR) may need to be acquired if landscape features of interest are below the resolution of the national DEM.
4. Evaluate the potential use of satellite-borne data to depict palaeovalleys and their related landforms. Night-time thermal infra-red data, acquired by the NOAA-AVHRR and ASTER satellites, may be particularly useful as palaeovalley aquifers can be detected due to thermal contrasts with surrounding bedrock. Other satellites such as Landsat and MODIS are also recommended.
5. Acquire and assess regional geophysical survey data for the study area. This includes national magnetics, gravity and radiometrics data held by Geoscience Australia. These geophysical data provide useful information to understand regional geology and structures that may have influenced palaeovalley development.

6. Acquire any AEM data available for the area.This data provides a very useful regional-scale tool for mapping and delineating palaeovalley systems in three dimensions. AEM can provide information on *in situ* water quality as well as geology, because the bulk conductivity response is substantially affected by groundwater salinity. Access to existing AEM data may have to be negotiated with mining or exploration companies. If budget and work priorities allow, acquisition of new AEM survey data specifically for palaeovalley groundwater investigations is highly recommended.
7. Undertake ground geophysical surveys to guide siting of drill holes, following the interpretation of airborne geophysics and remotely sensed data. Ground-based micro-gravity surveys are particularly useful in detecting subtle density variations that can be used to pinpoint the deepest part of the palaeovalley system. These deeper zones typically depict the buried palaeovalley thalweg (or palaeo-thalweg) containing coarse-grained saturated sediments and the highest yielding palaeovalley aquifers. Ground electromagnetic (EM) surveys (e.g. SIROTEM) can also be useful for palaeovalley detection and assessment.
8. Use reflection seismic methods. They can provide unparalleled subsurface depiction of palaeovalley shape, stratigraphy and nature of sediment infill. Seismic data are useful for developing a reliable conceptual understanding of palaeovalley structure, although the information is spatially restricted to the traverse lines, and data acquisition and processing remain cost-prohibitive for many palaeovalley groundwater resource assessments.
9. Drill the aquifer. This is vital for the investigation program. Drilling is crucial for obtaining samples of sediments and groundwater from palaeovalleys. Although several different drilling methods can be employed to evaluate palaeovalleys, the deciding factor is usually based on budget considerations and the availability of drilling contractors. The best sites for drilling should be based on prior analysis of existing information and interpretation of geophysics and remotely sensed data.
10. Undertake 3D-modelling using AEM and drill-hole data. This provides a particularly useful investigative technique to improve the delineation of palaeovalleys. 3D-conceptual hydrostratigraphic models are also a highly effective means of communicating groundwater systems and processes to non-technical audiences. These need to be kept relatively simple and focused on illustrating the most important features of the palaeovalley, without excessive detail.
11. Undertake more detailed aquifer characterisation studies involving pump tests and installation of monitoring bores. These are needed for thorough groundwater resource evaluation, and for ongoing monitoring programs to assess impacts on groundwater levels and quality. These were beyond the scope of the present reconnaissance project, but remain important parts of further assessment and management.

Importantly, the relative success of these various methods at different localities will vary depending on the local geologic setting, the nature of the groundwater systems and the water resource requirements sought. Adequate background understanding and analysis of the geology and hydrogeology of regional and local palaeovalley systems is crucial prior to any substantial groundwater extraction.

5.2.3 Potential future research opportunities in arid-zone hydrogeology

At the final Technical Advisory Group workshop for the *Palaeovalley Groundwater Project*, held at Yulara in the Northern Territory in March 2012, project partners, advisers and key stakeholders were canvassed for ideas for and opinions about potential hydrogeologic research opportunities in arid Australia. Although cognisant of the need to receive adequate funding and support for priority research programs to be developed over coming years, the summary list below provides an overview of suggestions for possible follow-on investigative work.

1. A coordinated, national-scale groundwater investigation program to characterise water quality of remote towns and communities in the arid and semi-arid zones of Australia. Anecdotal evidence, supported in places by monitoring data, indicates that many small population centres across this region have access to only relatively poor-quality drinking water. Although not solely specific to palaeovalleys, a coordinated research program is required to provide an improved dataset and understanding that could identify the most vulnerable localities and outline recommended approaches to improve water supply quality at these communities.
2. A baseline hydrogeologic investigation into the main aquifer systems and groundwater resources of the Officer Basin. This major sedimentary basin spans a vast arid region in WA and SA, yet very little hydrogeologic information is available due to its remote geographic location, low population, and lack of existing development. Mining activities and associated infrastructure projected over the medium to long term will require access to safe, secure and sustainable groundwater resources that may be provided from the aquifers of the Officer Basin. Indigenous Ngannyatjarra residents have also expressed an interest in potentially using groundwater resources for horticulture. Future research in the Officer Basin would benefit from a well-planned and multi-disciplinary approach similar to that used for the demonstration sites for the *Palaeovalley Groundwater Project*. This would include use of regional-scale geophysical data, coupled with targeted drilling and hydrochemical groundwater analyses.
3. Further developing and enhancing the WASANT Palaeovalley Map (2012). There is great potential for this; regular updating and re-evaluation of key datasets could be undertaken approximately every 5 years, so that new information (e.g. using newer remotely sensed datasets and drilling data) can be incorporated. The 2012 Palaeovalley Map represents the present level of conceptual understanding based on available data. Future technological developments may improve the spatial resolution, accuracy or definition of diagnostic properties of some datasets.
4. Building on the multi-component GIS methodology developed for production of the WASANT Palaeovalley Map and extending this approach to generate a new and improved national hydrogeology map of Australia. The most recent continent-scale hydrogeology map dates to the late-1980s (Jacobson and Lau, 1987) and significant advances in understanding and conceptualisation of many aquifers means that an updated GIS-based exercise is now required to improve map accuracy and quality. A revised hydrogeology map of Australia could extend the WASANT palaeovalley mapping into other jurisdictions, adapting the design approach in targeting the other aquifer systems. In the 25 years since the first hydrogeology map was produced, Geoscience Australia has acquired large, national-scale geophysical datasets (gravity, magnetics, radiometrics and numerous regional seismic profiles) that in combination with structural information and national-scale satellite and DEM datasets, could contribute to a new hydrogeological map of Australia. Bore data and groundwater data could be integrated with the hydrogeological map and regularly updated. Revised national-scale hydrogeological mapping would also take into account the requirement for data to be developed and widely available in digital formats.

5.3 Lessons learnt

This section outlines some important lessons learnt by the Geoscience Australia team involved over the course of the *Palaeovalley Groundwater Project*. These are largely non-technical aspects of the work program, focusing on important themes such as project management, collaboration and stakeholder engagement:

1. Developing and maintaining strong, productive working relationships within the project's leadership (or management) team was crucial to the success of the project. This led to a high level of commitment and participation from government delegates from WA, SA and NT, including at the five important workshop meetings of the project's Technical Advisory Group. Recognising the vital contribution made by these project partners (credited in the Acknowledgments section of this report) also strengthened the project and its outcomes. An inclusive and congenial approach to project development and implementation would be beneficial/essential to future Commonwealth and state/territory collaborative projects.
2. Improving and maintaining strong links between relevant Commonwealth and state/territory agencies will be crucial to enhance future mapping and investigation of aquifer systems that extend beyond jurisdictional borders and to contribute to improved national collection, analysis, interpretation and custodianship of water resource and geoscientific data. Nationally scoped hydrogeological projects bring together hydrogeologists and water resource managers from respective states/territories and also improve the use of data and information. This project demonstrated that commonly there are areas of overlap between hydrogeological work conducted in water resource departments and geologic mapping and research being carried out by geological surveys, but not necessarily high levels of awareness of or communication about the complementary work. Likewise, with better levels of collaboration and communication, hydrogeologists would benefit from awareness of mineral exploration work carried-out by private mining companies, and may capitalise on synergies between exploration programs and hydrogeological assessments. For example mining companies or hydrogeological consultant firms may be willing to share data and knowledge with government agencies working on broad-scale investigative projects.
3. To gain the most benefit from (and for) local stakeholders involved in this type of research project, it is prudent to look at opportunities for developing goodwill and fostering a collaborative approach with communities. Examples from this project include the installation of Winner's Bore within the Wilkinkarra demonstration site (Wischusen and Lewis, 2010), and the selection of drilling sites in the Murchison region where new bores may benefit local landholders as well as achieve project objectives (English et al., 2012a). This approach provided a means to engage positively with local communities and rural residents while providing an immediate tangible asset.

Glossary

Australian Drinking Water Guidelines (ADWG): 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 sand and finer sediments such as dust transported (blown) and laid down by the wind.

Airborne electromagnetic (AEM) survey: A geophysical survey method that maps the subsurface conductivity structure of the survey area using a loop mounted on a fixed-wing aircraft or carried beneath a helicopter. Many such systems exist with different performances, allowing the survey to be tailored to the needs of the end users. Sometimes also referred to as ‘airborne EM’.

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

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 an aquifer, and may form confining strata.

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

Aquitard: A relatively impermeable geological layer that caps a confined aquifer. Its low hydraulic conductivity allows some movement of water through it, but at a slower rate than that of the adjacent aquifer.

Archean: Rocks older than 2.5 billion years (2500 million years).

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

Artificial recharge: The deliberate recharge of aquifers through pumping water into them via bores or increasing surface-water infiltration through pits. Also known as managed aquifer recharge. Artificial recharge in coastal aquifers may be used to slow, contain or reverse seawater intrusion.

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 size, 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.

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 palaeovalley or palaeolacustrine 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.

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 tend 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 watersheds.

Cenozoic: Geological era for the last 65.5 million years that encompasses three periods: Paleogene, Neogene and Quaternary. It is also subdivided 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); sometimes occurs in silicified calcrete that may be a significant near-surface aquifer.

Clay: Refers to either grain size 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.

Craton: Part of the earth's crust which is no longer affected by tectonic activity and has been stable for about a billion years (1000 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.

DEM: See Digital elevation models*.*

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 surveys, airborne radar and laser surveys, and satellite radar.

Discharge: The flow of groundwater to surface water, to bores, from one aquifer to the other, or to 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.

Dolerite: A dark, medium-grained rock, similar in mineral and chemical composition to basalt but coarser grained. Commonly intruded as molten rock into older rock bodies or into fracture lines.

Dolines: A depression formed by the dissolution and collapse of the underlying rocks through the percolation of groundwater. It is a karst landform. Dolines can form directly in the soluble rocks or in insoluble rocks when the underlying soluble rocks are dissolved, forming cavities into which the insoluble rocks collapse. This is known as sub-adjacent karst.

Dolomite: Calcium-magnesium carbonate, $CaMg(CO_3)_2$, a common rock type in the Paterson region, for example, and other Proterozoic and Paleozoic regions that were once marine settings.

Dolostone: A sedimentary rock consisting largely of the calcium-magnesium carbonate mineral dolomite; in some literature these rocks are referred to as dolomite.

Downhole logging: A method of measuring the geophysical properties of the rocks, soils or sediments penetrated by a drill hole. 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. Downhole 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.

Electrical conductivity (EC): A measure of conductivity and a proxy for salinity, typically measured in micro-siemens per cm (µS/cm). Fresh drinking water is, ideally, less than 100 µS/cm and sea water has conductivity of 54 000 µS/cm.

Erosion: Part of the process of denudation that includes the physical breaking down, chemical solution, and transportation of material. Movement of soil or rock material is caused by running water, wind and/or 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 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.

Freshwater lens: A lens-shaped body of less dense fresh water floating on top of denser saline water in an unconfined coastal aquifer.

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

Geographical information systems (GIS): Computer-based systems for creating, storing, analysing and managing multiple layers of spatial data. These datasets 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.

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).

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.

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 and 4 mm in diameter.

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

Gypsum: Calcium sulfate ($CaSO_4.2H_2O$). '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 lake bed and redeposited by aeolian action.

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 sea water, which has TDS 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 crystallised 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 that which occurs when sediments are turned into rock by various cementing agents, or hardening of some exposed rock surfaces that can occur during weathering.

Karst: A landscape formed by the dissolution of soluble rocks, such as limestone or dolostone. Karst features include caves and dolines. Karst-like features formed in normally non-soluble rocks, such as sandstones and siltstones, through the action of exceptionally aggressive groundwater, is termed pseudokarst.

Kilolitre (kL): 1000 litres (equivalent to one cubic metre: 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's surface. Seven satellites have been launched in the series.

LIDAR: Light detection and ranging. A means of highly accurate topographic surveying using an aircraft-mounted laser scanner to measure the variation in altitude.

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.

Lithology: Rock type identified in terms of its mineral composition and texture.

Mafic: Describes dark-coloured igneous rocks that are rich in iron and magnesium.

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 (aeromagnetic surveys).

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

Megalitre (ML): One million (1 000 000) litres.

Opaline: Variety of amorphous silica ($SiO_2.H_2O$); sometimes occurs in silicified calcrete that may be a significant near-surface aquifer.

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 subsurface (typically in AEM surveys or drilling).

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

Palaeovalleys: 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: Geological era spanning approximately 542 Ma (million years ago) to 251 Ma. Australia was part of the Gondwana supercontinent during this time.

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

Permeability: See *Hydraulic conductivity*.

Permian: Geological period that extends from approximately 299 Ma (million years ago) to 251 Ma. Glaciers covered much of the Gondwana supercontinent during the early part of the Permian and left a legacy of glacially carved valleys and glaciogenic sediments infilling these valleys.

PIMA: Portable infra-red mineral analyser. A short-wavelength infra-red spectrometer that allows semi-quantitative assessment of the abundance of minerals containing CO_3, OH, H_2O, etc. and thus useful to detect clays, carbonates and other minerals formed during aqueous alternation.

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.

Proterozoic: A geological era that encompasses the time between 2500 and 545 million years ago (Ma). The Proterozoic is formally divided into the Paleoproterozoic (2500 and 1600 Ma), Mesoproterozoic (1600–1000 Ma), and Neoproterozoic (1000–545 Ma).

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 million years. The Quaternary is subdivided into two epochs, the Pleistocene (2.5 Ma to approximately 11 000 years ago) and the Holocene (11 000 years ago to the present). The Quaternary is characterised by extreme climate fluctuations and alternating glacial and interglacial periods, with aridification of the Australian inland being a legacy of the last glacial.

Radiometric: 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. The volume of water that is added to the total amount of groundwater in storage in 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.

Rotary mud drilling: A relatively cheap drilling method that uses a rotating cutting bit to drill a hole. Samples are brought to the surface as cuttings supported by a circulated drilling fluid containing mud, and this also keeps the hole 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, salination 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: <1000 mg/L TDS = fresh water, 1001 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.

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.

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.

Sonic drilling: A relatively high-cost drilling method that relies on acoustic-frequency vibrations and slow rotation to recover core of relatively undisturbed material uncontaminated by drilling fluids and shallower intervals.

SRTM data: Digital elevation model data collected during the 2000 STS-99 Shuttle Radar Topography Mission 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.

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

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

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 1000 ppm (mg/L); sea water 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 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 borehole target.

Tillite: Unsorted and unstratified rock material, including boulders and gravel, deposited by glacial ice in a clayey 'rock flour' matrix.

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 became inundated by sea water and accumulated marine sediments, as in the Eucla Basin/Nullarbor Plain.

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 aquifer: See *aquifer.*

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.

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

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Appendix 1 – International stratigraphic chart

This appendix contains a reproduction of the International Stratigraphic Chart published by the International Commission on Stratigraphy (2006): http://stratigraphy.org/

Eon	Era	Period	Epoch	Stage	Age (Ma)
Phanerozoic	Cenozoic	Quaternary	Holocene		0.0117
			Pleistocene	Tarrantian	0.126
				Ionian	0.781
				Calabrian	1.806
				Gelasian	2.588
		Neogene	Pliocene	Piacenzian	36.00
				Zanclean	5.332
			Miocene	Messinian	7.246
				Tortonian	11.608
				Serravallian	13.82
				Langhian	15.97
				Burdigalian	20.43
				Aquitanian	23.03
		Paleogene	Oligocene	Chattian	28.4 ± 0.1
				Rupelian	33.9 ± 0.1
			Eocene	Priabonian	37.2 ± 0.1
				Bartonian	40.4 ± 0.2
				Lutetian	48.6 ± 0.2
				Ypresian	55.8 ± 0.2
			Paleocene	Thanetian	58.7 ± 0.2
				Selandian	ca 61.1
				Danian	65.5 ± 0.3
	Mesozoic	Cretaceous	Upper	Maastrichtian	70.6 ± 0.6
				Campanian	83.5 ± 0.7
				Santonian	85.8 ± 0.7
				Coniacian	ca 88.6
				Turonian	93.6 ± 0.8
				Cenomanian	99.6 ± 0.9
			Lower	Albian	112.0 ± 1.0
				Aptian	125.0 ± 1.0
				Barremian	130.0 ± 1.5
				Hauterivian	ca 133.9
				Valanginian	140.2 ± 3.0
				Berriasian	145.5 ± 4.0

Eon	Era	Period	Epoch	Stage	Age (Ma)
					145.5 ± 4.0
Phanerozoic	Mesozoic	Jurassic	Late	Tithonian	150.8 ± 4.0
				Kimmeridgian	ca 155.6
				Oxfordian	161.2 ± 4.0
			Middle	Callovian	164.7 ± 4.0
				Bathonian	167.7 ± 3.5
				Bajocian	171.6 ± 3.0
				Aalenian	175.6 ± 2.0
			Early	Toarcian	183.0 ± 1.5
				Pliensbachian	189.6 ± 1.5
				Sinemurian	196.5 ± 1.0
				Hettangian	199.6 ± 0.6
		Triassic	Late	Rhaetian	203.6 ± 1.5
				Norian	216.5 ± 2.0
				Carnian	ca 228.7
			Middle	Ladinian	237.0 ± 2.0
				Anisian	ca 245.9
			Early	Olenekian	ca 249.5
				Induan	251.0 ± 0.4
	Paleozoic	Permian	Lopingian	Changhsingian	253.8 ± 0.7
				Wuchiapingian	260.4 ± 0.7
			Guadalupian	Capitanian	265.8 ± 0.7
				Wordian	268.0 ± 0.7
				Roadian	270.6 ± 0.7
			Cisuralian	Kungurian	275.6 ± 0.7
				Artinskian	284.4 ± 0.7
				Sakmarian	294.6 ± 0.8
				Asselian	299.0 ± 0.8
		Carboniferous	Pennsylvanian	Gzhelian	303.4 ± 0.9
				Kasimovian	307.2 ± 1.0
				Moscovian	311.7 ± 1.1
				Bashkirian	318.1 ± 1.3
			Mississippian	Serpukhovian	328.3 ± 1.6
				Visean	345.3 ± 2.1
				Tournaisian	359.2 ± 2.5

Eon	Era	Period	Epoch	Stage	Age (Ma)
					359.2 ± 2.5
Phanerozoic	Paleozoic	Devonian	Late	Famennian	374.5 ± 2.6
				Frasnian	385.3 ± 2.6
			Middle	Givetian	391.8 ± 2.7
				Eifelian	397.5 ± 2.7
			Early	Emsian	407.0 ± 2.8
				Pragian	411.2 ± 2.8
				Lochkovian	416.0 ± 2.8
		Silurian	Pridoli		418.7 ± 2.7
			Ludlow	Ludfordian	421.3 ± 2.6
				Gorstian	422.9 ± 2.5
			Wenlock	Homerian	426.2 ± 2.4
				Sheinwoodian	428.2 ± 2.3
			Llandovery	Telychian	436.0 ± 1.9
				Aeronian	439.0 ± 1.8
				Rhuddanian	443.7 ± 1.5
		Ordovician	Late	Hirnantian	445.6 ± 1.5
				Katian	455.8 ± 1.6
				Sandbian	460.9 ± 1.6
			Middle	Darriwilian	468.1 ± 1.6
				Dapingian	471.8 ± 1.6
			Early	Floian	478.6 ± 1.7
				Tremadocian	488.3 ± 1.7
		Cambrian	Furongian	Stage 10	ca 492
				Stage 9	ca 496
				Paibian	ca 499
			Series 3	Guzhangian	ca 503
				Drumian	ca 506.5
				Stage 5	ca 510
			Series 2	Stage 4	ca 515
				Stage 3	ca 521
			Terreneuvian	Stage 2	ca 528
				Fortunian	542.0 ± 1.0

	Eon	Era	Period	Age (Ma)
				542.0 ± 1.0
Precambrian	Proterozoic	Neo-proterozoic	Ediacaran	ca 635
			Cryogenian	850
			Tonian	1000
		Meso-proterozoic	Stenian	1200
			Ectasian	1400
			Calymmian	1600
		Paleo-proterozoic	Statherian	1800
			Orosirian	2050
			Rhyacian	2300
			Siderian	2500
	Archean	Neoarchean		2800
		Mesoarchean		3200
		Paleoarchean		3600
		Eoarchean		4000
	Hadean (informal)			ca 4600

Appendix 2 – Northern Territory palaeovalley systems

This appendix contains summary information on the major palaeovalleys in the Northern Territory.

Name	*Length*	*Width*	*Depth*	*Width/depth ratio*	*Geologic setting*	*Landscape setting*	*Stratigraphy*	*Groundwater quality*	*Water depth*	*Comments*	*Reference data*
16 Mile Basin	33 km	18 km	200 m		Arunta region	Intermontane	Clay, sand, silt, calcrete	Brackish	36 m	Low yield	Bore data
Amputjuta	7 km	4 km	35 m (RN12465)		Musgrave Complex	Intermontane	Claystone, gravels, sandstone	Brackish to saline	24 m	Low yield	Bore data
Aremra	71 km	16 km	84 m	Low	Arunta region	Edge of broad flat basin (GAB)	Sand, claystone, interbedded sandstone, siliceous calcrete	Fresh along Illogwa and Aremra creeks, saline in north-east	27–30 m, 66 m	Low to moderate yield, modern recharge (RN15152 ^{14}C pMC 88.4)	Senior et al. (1994), NTGS seismic data
Armstrong Creek	41 km		50 m (RN10696)		Amadeus Basin	Basin	Sands, gravels and clay	Fresh	Unknown	Unknown	Bore data
Atula	122 km	22 km	125 m	Low (176)	Great Artesian Basin	Edge of broad flat basin (GAB)	Calcrete, mudstone, gravel, sandstone, siltstone	Fresh to saline	21 m	Unknown	Bore data, gravity low
Ayers Rock–Katiti Basin	206 km	41 km	100 m (RN10455, RN11755)	Very high (410)	Amadeus Basin	Basin	Sand, clay, sandstone, calcrete, basal gravel	Fresh close to outcrop, saline in the central part of palaeovalley (PV) close to salt playas	15–20 m	Various aquifers	Jacobson et al. (1989), Van de Graaf et al. (1977), English (1998)
Birrindudu	300 km+	14 km	43 m		Victoria-Birrindudu Basin	Dissected ferricrete plateaus	Clay, calcrete, silcrete/chalcedony	Fresh-brackish, saline in the aquifer beneath the downstream section of the Sturt Creek flood plain	3–12 m	Silcrete aquifer 10–40 m, yields up to 5 L/s	Tickell & Rajaratnam (1996)
Bloods Range	10 km	10 km	20 m		Musgrave Block	Intermontane	Sand, calcrete	Unknown	57 m	Underlying fractured basalt aquifer, bore on edge of basin – may be water further into basin	Bore RN11777
Bonney	220 km	6 km	36 m up to 200 km at Ali Curung	High	Wiso Basin	Partly mountain front	Sand, clay, gravel, siltstone, sandstone, calcrete	Fresh in Ali Curung area, saline otherwise	8 m	Unknown	Bore data
Buck	200 km	4 km	Unknown	Unknown	Wiso Basin	Subdued valley plains	Unknown, salt playas in places	Unknown	Unknown	Unknown	Mapping
Bundey Basin			40 m		Arunta region	Intermontane	Siltstone, claystone, interbedded sandstone and conglomerate beds	Fresh to saline	Variable	Variable	Senior et al. (1994)
Docker River	23 km	1.6 km	91 m (RN10391)	16	Musgrave Province	Intermontane	Clay, sand and gravel	Fresh	16 m	Unknown	Wischusen (2005)
Ethel Creek	76 km	20 km	Unknown		Arunta region	Plains	Unknown	Unknown	Unknown	Unknown	Mapping
Fiddlers	70 km	5 km	Unknown		Arunta region	Plains	Extensive chain of salt playas at surface	Unknown, but likely saline due to salt playas	Unknown	Unknown	Mapping
Hale Basin	126 km	43 km	60 m		Arunta region		Interbedded clay and sand, fluvial and lacustrine clastics, silcrete and carbonaceous clay	Fresh to brackish	Unknown	Unknown	Senior et al. (1994)
Hanson	278 km	10 km	19–60 m, deepest at Numagalong		Wiso Basin	Subdued valley plains	Sandy clay	Fresh to brackish	45 m		Mapping, bore data
Karlantjipa	Roughly 700 km	4 km	Unknown		Wiso Basin	Flat, extensive chains of saline playas	Unknown, salt playas in places	Unknown	Unknown	Unknown	Tickell (2008), mapping

Name	*Length*	*Width*	*Depth*	*Width/depth ratio*	*Geologic setting*	*Landscape setting*	*Stratigraphy*	*Groundwater quality*	*Water depth*	*Comments*	*Reference data*
Hale Basin	126 km	43 km	60 m		Arunta region		Interbedded clay and sand, fluvial and lacustrine clastics, silcrete and carbonaceous clay	Fresh to brackish	Unknown	Unknown	Senior et al. (1994)
Hanson	278 km	10 km	19–60 m, deepest at Numagalong		Wiso Basin	Subdued valley plains	Sandy clay	Fresh to brackish	45 m		Mapping, bore data
Karlantjipa	Roughly 700 km	4 km	Unknown		Wiso Basin	Flat, extensive chains of saline playas	Unknown, salt playas in places	Unknown	Unknown	Unknown	Tickell (2008), mapping
Killi Killi	75 km (on NT side)	2 km	14 m		Tanami region	Broad valley	Clays, weathered siltstone, calcrete	Unknown	Unknown	No significant water in the two holes in this PV	Bore data
Kintore	120 km	12 km	105 m (RN018580)	High (114)	West Arunta Complex	Mountain front	Calcrete on one flank of PV, more at depth, sandy clays, clayey sands	Fresh to saline, salinity increases down-gradient and in main channels overlying Ngalia Basin, fresh at southern fringe – tributary High nitrates	4–5 m	Major aquifer in PV, moderately productive, basement water likely to be low	Woodgate et al. (2012)
Lake Lewis	124 km	51 km	160 m		Arunta	Intermontane basin	Lacustrine and alluvium	Fresh to saline, more saline to the north towards Lake Lewis	30–40 m	Variable yields, calcrete and alluvium aquifers	English (2002)
Lake White	45 km	2 km	Unknown		Tanami region	Broad valley	Unknown	Unknown	Unknown	Unknown	Mapping
Lucas	10 km on NT side										
Mc Dills Basin	71 km	36 km	60 m		Great Artesian Basin	Dune-covered plains	Unknown	Unknown	Unknown	Unknown	Gravity low, exploration drill-hole data
Mina Mina	103 km	3.5 km	Unknown		Tanami region	Broad valley	Unknown	Unknown	Unknown	Unknown	Mapping
Mongrel	68 km	2.5 km	30 m		Tanami region	Broad plains, minor hills	Calcrete, claystone	Fresh to brackish	16 m	Low yield in calcrete	Bore data
Mount Wedge Basin	150 km	100 km	475 m (RN18599)	High (95)	Arunta Complex	Basin and range	Highly weathered sandy clay, olive-green clay and bands of sand	Fresh in the southern upper aquifer of basin. Saline at depth and increasing northwards	35 m	Thick sandy clay between upper and lower aquifer	Western Water Study, Woodgate et al., 2012
Mt Theo	100 m	4 km	Up to 58 m (RN700)		Arunta region	Subdued valley plains					
Mungkarta	37 km	3 km	48 m	Low	Wiso Basin	Intermontane basin	Sandy clay, gravel, silcrete	Fresh to brackish	25 m	Moderate yield, fresh along creek line	Bore data
Ngalabaldjiri	350 km	8 km	Mainly 30 m but ~200 m at the south-east end	Very high (267)	Tanami region, Arunta region	Subdued valley plains	Calcrete, sands, clays	Fresh at the south-east end, brackish to saline otherwise	7 m at Tanami gold borefields, 20–30 m at south-east end	Range of aquifers, calcrete at north end, deep basin at south end unknown between	Bore data
Nora	38 km	2 km	25 m		Tanami region		Silcrete, alluvium	Fresh	20 m	Low yield	Bore data
Palparti	150 km	2 km widening to 11 km at Tennant Creek borefield	Up to 30 m at Tennant Creek borefield	High	Wiso Basin	Basin and range at Tennant Creek, subdued valley plain for western end	Grey silcrete, white silcrete, sands, clays, siltstone, sandstone	Fresh to brackish at Kelly Well borefield end	17–21 m	Recharge from floodout of Kelly Creek, best aquifers silcrete due to vughs = higher transmissivity	Verhoevan & Knott (1980), Lau (1993), Childs (1989)

Name	*Length*	*Width*	*Depth*	*Width/depth ratio*	*Geologic setting*	*Landscape setting*	*Stratigraphy*	*Groundwater quality*	*Water depth*	*Comments*	*Reference data*
Pingidijarra	54 km on NT side	3.5 km	Unknown		Tanami region	Broad valley between hills	Unknown	Unknown	Unknown	Unknown	Mapping
Ngalabaldjiri	350 km	8 km	mostly 30 m but ~200 m at the south-east end	Very high (267)	Tanami region, Arunta region	Subdued valley plains	Calcrete, sands, clays	Fresh at the south-east end, brackish to saline otherwise	7 m at Tanami gold borefields, 20–30 m at south-east end	Range of aquifers – good calcrete aquifers at north end, and good, deep basin at south end – in between unknown	Bore data
Question Mark	66 km	2 km	Unknown		Tanami region	Broad valley between hills	Unknown	Unknown	Unknown	Unknown	Mapping
Raapi	107 km	5 km	Unknown		Tanami region	Broad valley between hills	Unknown	Unknown	Unknown	Unknown	Mapping
Rabbit Flat	140 km	5 km	30 m		Tanami region	Broad valley between hills	Silcrete, calcrete, ferricrete, clay, gravel	Fresh to saline	16 m	Calcrete aquifer, water supply Rabbit Flat roadhouse and granite mines	Bore data
Sandy Blight	64 km	5 km	75 m		Arunta region	Plains, minor hills	Sandy clay, sand, sandstone, claystone, basal gravel	Brackish to saline	30 m	Groundwater in basal sandstone and gravel	Western Water Study, bore data
Santa Theresa Basin	N/A	4 km	163 m near the airstrip		Arunta region	Rocky	Interbedded clayey coarse sand, sand, silt and clay	Fresh, deteriorating with depth	18 m	7 L/s	Northern Territory bore data
Surprise	230 km	5 km	30 m	High	Wiso Basin	Subdued valley plains	Clayey sand, quartz gravel	Fresh to saline adjacent to Lander River, unknown elsewhere	23 m		Bore data
Tanami region		6 km	Up to 90 m near Tanami Downs Homestead & Tanami gold borefield	Low (67)	The Granites–Tanami Block, Birrindudu Basin, Wiso Basin	Plains, low relief, minor low ranges	Calcrete middle of PV (unlike in WA). Clay and silt mainly – dominated by fines. (Suspended load channels, dominated by bank accretion.) Chalcedony common. Moderate sinuosity	Fresh to saline, PVs are high salinity where groundwater is shallow in low-areas, fresher water in some tributaries and fringe zones to main channels, fresh water at Rabbit Flat, Tanami Downs Homestead and Tanami borefield		Major aquifer in PV. Calcrete most productive, shallow. Small supplies from fractured bedrock, lower Proterozoic basement rocks	Domahidy (1990)

Name	*Length*	*Width*	*Depth*	*Width/depth ratio*	*Geologic setting*	*Landscape setting*	*Stratigraphy*	*Groundwater quality*	*Water depth*	*Comments*	*Reference data*
Tarawera Basin	51 km	17 km	500 m+	High (102)	Amadeus Basin	Intermontane	Clay, sand, sandstone-lacustrine & alluvium	Fresh to brackish	15 m	Good yields	Lau (1993), Seismic
Ti Tree Basin			320 m								
Waite Basin			180 m								
Wallamunga	53 km on NT side	1 km	Unknown		Tanami region	Valley	Unknown	Unknown	Unknown	Unknown	Mapping
Walu			59 m (RN14656)				Gravel, clay, calcrete	Fresh to brackish	45 m	Unknown	Bore data
Whitcherry Basin			250 m (RN16587)		Ngalia Basin						
Wildcat	95 km	3 km	Unknown		Tanami region	Broad valley between hills	Unknown	Unknown	Unknown	Unknown	Mapping
Wilkinkarra	120 km	20 km	130 m (RN18359)	Very high (153)	West Arunta Complex, Ngalia Basin	Flat plains	Calcrete at surface across entire PV. Sandy clays, clayey sands	Fresh to saline, salinity increases down-gradient and in the main channels overlying Ngalia Basin, fresh at southern tributary, high nitrate	4–5 m	Major aquifer in PV, moderately productive, Ngalia Basin basement likely to contain good water (friable sandstone), basement minimal groundwater	Woodgate et al. (2012)
Willowra Basin	128 km	20 km	Up to 40 m	Very high (500)	Arunta region	Subdued valley plains	Sandy clay, gravel, fluvial channel sand – two channel sands with main aquifer in lower unit, weathered basement	Fresh to moderately saline, groundwater in weathered basement is saline	15–20 m	Main aquifer is basal channel sand, separated from upper sands by aquiclude, lenticular aquifer thickens down-gradient, maximum width of 1.7 km, flow to north. 1000 ML/yr sustained yield with water flows into PV from adjacent weathered bedrock	Bore data, Morton (1965)
Wilson	160 km	1.4 km	Unknown		Tanami region	Broad valley between hills	Unknown	Unknown	Unknown	Unknown	Mapping
Winnecke	240 km	2 km	Unknown		Wiso Basin	Subdued valley plains	Unknown	Unknown	Unknown	Unknown	Mapping
Yaloogarrie Basin			100 m		Arunta region		Dominated by silt and clay, calcrete at the north end the basin	Brackish to saline, fresher in calcrete at northern part of basin	32 m	Low yield	Mt Theo explanatory notes, Stewart (1976)
Yaparta	200 km	3 km	Unknown					Unknown	Unknown	Unknown	Mapping
Yingurddu	187 km	7 km	Unknown		Amadeus Basin	Subdued valley plains	Sandy clay, gypsum	Fresh to brackish	12 m	Low yield	Bore data

Appendix 3 – Palynostratigraphy for hydrogeological investigations

Fine-grained sedimentary rocks deposited since the Devonian (415 Ma), which have not been subjected to excessive heat, pressure or weathering, may preserve evidence of their age in the form of organic plant microfossils such as algal cysts (acritarchs, dinoflagellates), spores and pollen (Pillans, 1998). The Cenozoic (and older) sediments infilling palaeovalleys in arid Australia are potential repositories of preserved microflora. This has been confirmed from work in the central Australian and Murchison regions for the *Palaeovalley Groundwater Project*.

Organic plant microfossils can assist in understanding the hydrogeology of an aquifer by:

- dating and correlating the impervious (aquitard) and finer grained facies of aquifers at the local (palaeochannel) and extra-local (palaeovalley) scales
- determining depositional rates
- differentiating between lithologically similar formations of different age
- detecting subtle environmental factors that may influence groundwater chemistry, e.g. marine influences several hundreds of kilometres away from the palaeoshoreline in the Eucla Basin
- helping define appropriate sites for drilling in 'greenfield' regions
- contributing to our understanding of the geological, landscape and palaeo-environmental evolution at the regional to basin scale.

Examples of the above include:

- establishing the geological framework to help manage salinity in the Murray-Darling Basin, eastern Australia (Brown and Stevenson, 1991, Macphail, 1999)
- investigating the economic potential of groundwater resources in the Alice Springs district, Central Australia (Macphail, 1997)
- using existing aquifers as an alternative to storing water in the Menindee Lakes system, western New South Wales for the Broken Hill Managed Aquifer Recharge Project (Macphail, 2010, Clarke et al., in prep.)
- improving knowledge of palaeovalley groundwater systems in arid regions of Western Australia and the Northern Territory in the Australian arid zone via demonstration sites such as the Ti Tree Basin (NT) and Murchison Palaeovalley, western Yilgarn Plateau (WA).

A3.1 Principles for palynostratigraphic investigation for hydrogeology

The application of palynostratigraphy to hydrogeological investigations may be guided by the following principles:

A3.1.1 Sampling sites

Terrestrial depositional environments known to preserve organic plant microfossils include lakes, low-energy rivers, cut-off channels and back swamps, flood plains, fens, mires and peat-bogs of all sizes, and the 'O' and 'A' horizons of buried soils (palaeosols). In the case of palaeovalley groundwater systems, the preservation, quality varies for the main facies zones:

- coarse-grained sediments in the thalweg are less suited to the long-term preservation of plant microfossils than are the finer grained sediments outside the main channel
- lateral migration of the main channel over time means that the stratigraphy at any point within the palaeovalley is usually a stacked sequence of fine- and coarse-grained sediments.

A3.1.2 Sediment types

Almost all fine-grained sediments preserve plant microfossils (in lesser or greater numbers) unless subjected to metamorphism, located above the weathering front (up to 50 m depth in arid regions) or where oxygenated groundwater is flowing through the sediment. Within these constraints:

- sediments most likely to preserve plant microfossils are lignites, clays, muds and dirty (carbonaceous) sands and their lithified equivalents (coals, claystones, shales, mudstones, sandstones with carbonaceous stringers)
- sediments that almost never preserve plant microfossils are well-sorted sands deposited in high-energy fluvial environments, carbonaceous sands, buried by ferric or organic matter (humates), reduced (gypsiferous, calcareous) clays and mottled red-yellow clays.

A3.1.3 Sample selection

The quality of samples submitted for palynostratigraphic analysis depends on the type of drilling method:

- the highest quality samples are conventional cores from diamond drill holes, or from sonic cores
- the lowest quality samples are cuttings from unflushed drill holes, i.e. rock chips from the drill-bit which are circulated to the surface in drilling mud. The exception is where the overlying rocks are devoid of plant microfossils, which may occur in semi-arid and arid regions
- caving of younger plant microfossils into older sediments (downhole caving) is common in weakly or non-lithified deposits
- reworking of older plant microfossils into younger sediments is widespread in fluvio-lacustrine deposits
- geological samples can be contaminated with modern plant microfossils, especially pollen, when cuttings are laid out on the ground before bagging or cores are left exposed in trays for any length of time.

Other sample types, for example side-wall cores and dust from the cyclone in percussive rotary air blast (RAB) drilling, are of intermediate quality, so yields and reliability of the age determinations will depend on the geological context and care taken when sampling and storing the sediment.

A3.1.4 Processing methods

The organic fraction of the rock and sediment samples (which includes plant microfossils) is recovered using standard techniques involving physical disaggregation, removal of the clay fraction via hydrofluoric acid, concentration of the organic fraction (kerogen) using heavy liquid separation, removal of acid-soluble organic material by chemical oxidation and removal of acid-insoluble fines by sieving through 5- and 10-micron micro-pore filters (see Traverse 1988). Caveats are:

- poorly preserved or fragile microfossils (including many dinoflagellate species) can be destroyed by chemical oxidation. In these instances, reliable age determinations can be made from the filtered kerogen extracts
- very small microfossils will be lost by 10-micron sieving
- the relative abundance of common microfossils will vary with changes in the combination of chemical and physical techniques used for sample processing.

The laboratories that process samples for plant microfossils are in government institutions such as Geoscience Australia or commercial equivalents serving the exploration industry, for example Core Laboratories (Australia) Pty Ltd in Perth (WA).

A3.1.5 Microscope equipment

Biostratigraphically useful plant microfossils range in size from less than 10-microns to over 90-microns. For this reason:

- the presence and relative abundance of microfossil species needs to be verified using binocular research-grade microscopes capable of up to 1000–2000 times magnification
- appropriate microscope objectives are 10x (for quick scanning) and 25, 40, 63 and 100x (oil) for more detailed analysis.

A3.1.6 Palynostratigraphic schema

Organic plant microfossils have been used in Australia to subdivide geologic time into biostratigraphic zones encompassing the Devonian (416 Ma) to the Quaternary (2.5 Ma to present). Most of these were developed by (or for) the hydrocarbon exploration industry. Examples of the more recent and widely used zonation schema are:

- Devonian-Carboniferous (416–299 Ma): Grey (1992), Jones and Truswell (1992)
- Permian (299–251 Ma): Price (1983), Foster and Waterhouse (1988), Backhouse (1998)
- Triassic (251–199.6 Ma): Dolby and Balme (1976), Helby et al. (1987)
- Jurassic (199.6–145.5 Ma): Helby et al. (1987, 2004), Backhouse (1988), Partridge (2006a, 2006b), McKellar (2010)
- Early Cretaceous (145.5–99.6 Ma): Burger (1986), Morgan (1980), Backhouse (1988), Helby et al. (1987, 2004), Sajjadi and Playford (2002a, 2002b), Partridge (2006a, 2006b)
- Late Cretaceous-Cenozoic (99.6 Ma–recent): Stover and Partridge (1973, 1982), Harris (1985), Helby et al. (1987), Macphail (1997, 1999), Partridge (1999, 2006c, 2006d).

These schema depend on the fact that most plant microfossils have appeared (evolved/migrated) then disappeared (become extirpated or extinct) in the fossil record at varying stages. Similarly, changes in global to regional climate (often forced by geologic or palaeogeographic events) have favoured the distribution of some of the parent plants relative to other plants. Accordingly:

- different plant microfossils have different distributions in geologic time
- the first (FAD) and last (LAD) appearance datums of widely occurring species with short age ranges can be used as evidence of geologic age (presence/absence criteria). Similarly, relative abundance can also be a useful indicator of geologic age (quantitative criteria)
- zones and zone boundaries can be defined by the presence/absence or changes in relative abundance of particular plant microfossils, in particular in sedimentary basins
- past depositional environments can be reconstructed using the ecology of the nearest living relatives (NLRs) of the fossil plants.

Important caveats:

- Spore-pollen based zonation schema covering Paleozoic to Mesozoic time usually can be applied (or adapted to apply) to date and to correlate rocks and sediments across the Australian continent (pan-continental zonations) (Helby et al., 1987).
- Spore-pollen based zonation schema covering Cenozoic time tend to become less reliable away from the sedimentary basins along the southern margin of the continent because (1) the key (age diagnostic) microfossil species are absent, or (2) because the times of first and last appearance differ between sedimentary basins due to strong climatic gradients south to north and east to west across the continent (Macphail, 2007). This applies with particular force to 'greenfield' palaeovalley systems in northern Australia and Western Australia.
- Although the zones can be assigned to particular geological periods, epochs and stages with a high degree of confidence, it is more difficult to date the zone boundaries in terms of millions of years due to (1) the lack of independent age control in the form of isotopes, palaeomagnetism and/or marine microfossil (Pillans, 1998), and (2) the evolving nature of the International Time Scale *per se* (Ogg et al., 2008).

A3.2 Summary

Groundwater-focused projects undertaken over the past three decades confirm the need for a multi-disciplinary approach if groundwater is to be used sustainably by agriculture and the minerals industry, particularly in semi-arid and arid regions of the continent. Palynostratigraphy is one of the disciplines that has provided, and can continue to provide, valuable, if not essential, information on the age, stratigraphic and palaeo-environmental relationships of Australian aquifer and aquitard systems, ranging from the palaeochannel to the palaeodrainage system scale. As with other sciences, palynostratigraphy is both evolving from, and living on, past intellectual capital. The chronostratigraphic resolution, and confidence of the individual age determinations, for sediments hosting groundwater will improve, but only if prerequisites such as detailed drilling/sampling of suitable sediments are met.