AUSTRALIAN GOVERNMENT INITIATIVE ON COAL SEAM GAS AND LARGE COAL MINING

ARCKARINGA BASIN AND PEDIRKA BASIN GROUNDWATER ASSESSMENT PROJECTS

Government of South Australia
Department of Environment, Water and Natural Resources

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Department of Environment, Water and Natural Resources

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FOREWORD

The Department of Environment, Water and Natural Resources (DEWNR) is responsible for the management of the State's natural resources, ranging from policy leadership to on-ground delivery in consultation with government, industry and communities.

High-quality science and effective monitoring provides the foundation for the successful management of our environment and natural resources. This is achieved through undertaking appropriate research, investigations, assessments, monitoring and evaluation.

DEWNR's strong partnerships with educational and research institutions, industries, government agencies, Natural Resources Management Boards and the community ensures that there is continual capacity building across the sector and that the best skills and expertise are used to inform decision making.

Allan Holmes
CHIEF EXECUTIVE
DEPARTMENT OF ENVIRONMENT, WATER AND NATURAL RESOURCES

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SUMMARY

The South Australian Government has been engaged by the Department of Sustainability, Environment, Water, Population and Communities' Office of Water Science to undertake groundwater assessment projects in the Arckaringa Basin and the Pedirka Basin. These basins have been targeted because they contain significant coal resources and there is potential for large-scale coal mining or coal seam gas development. This report collates existing groundwater resource information, develops hydrogeological mapping products for key formations and progresses the conceptual groundwater framework for the Arckaringa Basin and the Pedirka Basin.

This project addressed the following tasks: a desktop assessment to collate available data, the development and compilation of basin architecture, an initial bore audit, production of hydrogeological maps and the development of a conceptual model for the Arckaringa Basin and the Pedirka Basin. Key outcomes for each basin are provided in the following summary.

ARCKARINGA BASIN

The Arckaringa Basin, located in the central to far north region of South Australia, is a large sedimentary basin composed of Late Carboniferous to Early Permian-aged rocks (approximately 299-290 Ma). These Permian sequences are largely overlain by younger geological formations including the Great Artesian Basin and Lake Eyre Basin. There are three formations within the Arckaringa Basin: the Mount Toondina Formation, the Stuart Range Formation and the Boorthanna Formation. Aquifers are known to occur within the Mount Toondina Formation and the Boorthanna Formation, while the Stuart Range Formation is generally considered a confining unit.

The western Arckaringa Basin is thin, geologically simple and only moderately faulted while the eastern Arckaringa Basin is deep and geologically complex. The initial basin formation and development were controlled by faulting and then further modified by glacial scouring. This has resulted in the formation of sub-basins, the most well-known being the Billa Kalina sub-basin.

Areas of potential aquifer recharge and inter-aquifer connectivity are influenced by the extent and characteristics of the Stuart Range Formation, and palaeochannels that have been filled with Eromanga sediments.

The direction of groundwater flow within the basin is broadly to the south-east toward the Stuart Shelf and southern Great Artesian Basin springs. Groundwater from Arckaringa Basin aquifers has generally been described as brackish to ultra-saline, although better quality groundwater occurs in the Boorthanna Formation near the south-eastern margin.

PEDIRKA BASIN

The Pedirka Basin, located centrally over the South Australia–Northern Territory border, is a large sedimentary basin comprising mainly Early to Late Permian sediments and coal sequences. Much of the Pedirka Basin occurs at depth, although outcrop occurs along the north-west margin of the basin.

There are two recognised formations within the Pedirka Basin: the Purni Formation and the underlying Crown Point Formation. The Crown Point Formation is a recognised aquifer along the western margin of the basin, however little is known in deeper parts of the basin. There is no information on the hydrogeological status of the Purni Formation.

The basin may be divided into two sub-basins by a large structural feature, the Dalhousie-McDills Ridge, which transects the basin roughly north to south. Connection between Permian sediments either side of

this ridge is provided by a thin continuation of sedimentation across the ridge. The direction of regional groundwater flow is from outcropping recharge areas located along the north-western margin to the south-east. Artesian groundwater conditions are expected to occur in the centre and eastern regions of the basin. Groundwater quality is generally suitable for stock (cattle) and improves around the Finke River to form a potable water resource.

Indirect recharge is believed to occur along the north-west margin of the basin from the Finke River and potentially Goyder Creek. Diffuse recharge is estimated at between 0.02–0.16 mm/y and is considered negligible. Previous studies suggest that Dalhousie Springs may form a regional discharge point for the Crown Point Formation. While waterholes identified in the Finke River adjacent to outcropping Crown Point Formation may reflect local discharge from either the Permian aquifers or the Finke River alluvial system. Cross-formational flow potentially represents a significant groundwater inflow/outflow process for the Pedirka Basin.

KNOWLEDGE GAPS

Existing groundwater data and hydrogeology knowledge concerning the Arckaringa Basin and Pedirka Basin are very limited. Most information regarding the Arckaringa Basin comes from discrete areas associated with mining or energy exploration, while information for the Pedirka Basin is largely limited to outcrop and sub crop areas in the vicinity of the north-west margin. The concentration of previous work in a few spatially constrained areas limits their use to describe the groundwater system on a regional scale.

The conceptualisation of the basin hydrogeology is speculative due to our limited knowledge of structure, recharge mechanisms, discharge mechanisms, water quality and hydrodynamics within the Permian successions. To address these knowledge gaps, a number of future work recommendations are proposed, all specifically designed to increase our understanding through a series of drilling, groundwater sampling, geophysical data acquisition and modelling activities.

1. INTRODUCTION

1.1. PROJECT BACKGROUND

The Australian Government, through the Department for Sustainability, Environment, Water, Population and Communities' (SEWPaC) Office for Water Science (OWS) has funded the South Australian Government to undertake groundwater assessment projects in the Arckaringa Basin and the Pedirka Basin. Significant coal resources have been identified in the Arckaringa Basin and Pedirka Basin and there is potential that large-scale coal mining and coal seam gas (CSG) developments will commence in the future. Both basins are located in the remote north of South Australia with the Pedirka Basin extending into the Northern Territory (Figure 1.1).

Due to the limited number of water wells and constrained nature of previous hydrogeological studies, knowledge of the hydrogeology of these basins is extremely limited, yet they are located in an arid environment where groundwater is the only reliable water resource. In recognition of the coal mining development potential, data scarcity and water resource significance, the South Australian Government, in partnership with the Northern Territory Government, has targeted groundwater assessment projects for both the Arckaringa Basin and Pedirka Basin.

The projects adopt a two staged approach. The first stage involves a comprehensive review of data, the development of basin architecture, first edition hydrogeological maps and the identification of critical knowledge gaps in our understanding of the Arckaringa Basin and Pedirka Basin groundwater systems. A proposed second stage seeks to involve more detailed desktop and field studies to address these selected key knowledge gaps. This report documents the findings and recommendations from Stage 1 of the investigation.

In addition, it is recognised that links between groundwater, surface water and groundwater dependent ecosystems (GDEs) are well known, however the intent of this report is to focus only on hydrogeological considerations; an in-depth discussion of surface water and GDEs will be proved in reports.

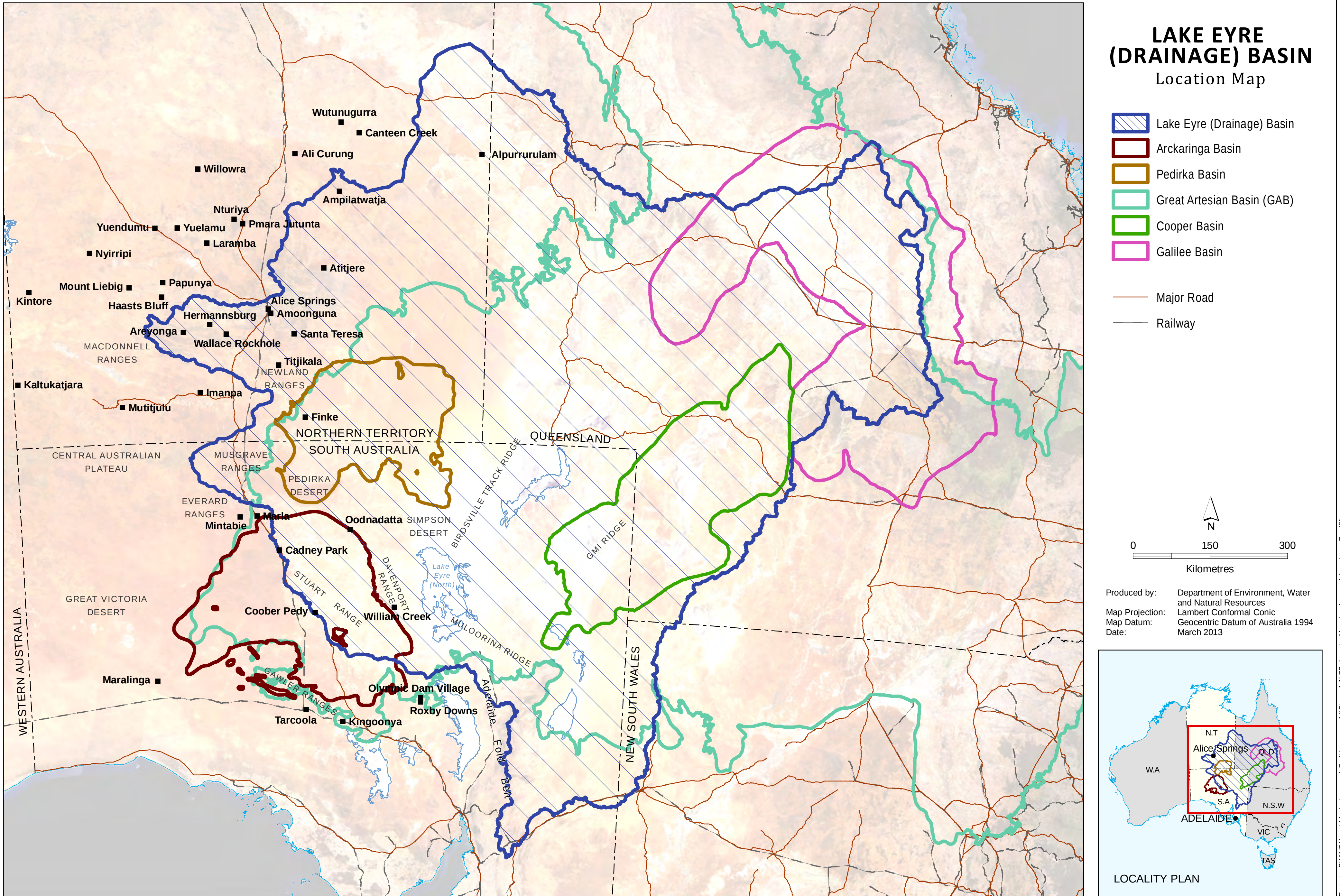

Figure 1.1: Location Map, Arckaringa Basin and Pedirka Basin

1.2. STAGE 1 OBJECTIVES

The objective of the Stage 1 investigation is to summarise known information concerning the groundwater resource within both the Arckaringa Basin and the Pedirka Basin. In doing so, key knowledge gaps will be identified via the review of existing data sets and the generation of new information. This review will provide a basis for the identification of risks to groundwater resources resulting from large scale coal mining and CSG developments. Specific objectives include:

- Developing basin architecture, including improved mapping of the extent and geometry of hydrostratigraphic units within the Arckaringa Basin and Pedirka Basin, plus outlining known and identified structural controls and barriers to groundwater flow.
- Collating existing information and gathering new baseline hydrogeological data including but not limited to: water quality, water level, water chemistry and environmental isotopes.
- Improving the understanding and conceptualisation of hydrogeological processes within the basins, including recharge and discharge processes and mechanisms, and aquifer connectivity between the basin aquifers and aquifers in adjacent basins - in particular connectivity with the main GAB aquifer.
- Highlighting the areas of greatest coal development potential by the collation and representation of existing knowledge from State and Territory mineral and petroleum resource divisions and the private sector.

1.3. STAGE 1 SCOPE

Stage 1 of the Arckaringa Basin and Pedirka Basin Groundwater Assessment Project involved five main tasks, in addition to a reporting component. A summary of the scope of each task is provided in the following section. The five tasks are:

1. Undertaking a desktop assessment to consider the availability of data and identify knowledge gaps
2. Developing basin architecture through the compilation of groundwater, geology and geophysical data
3. Undertaking an initial Bore Audit program
4. Compiling draft first edition hydrogeological maps for both the Arckaringa Basin and Pedirka Basin
5. Developing an initial conceptual hydrogeological model to describe whole–of–basin groundwater processes for each basin

A summary of each task is provided below.

1.3.1. DESKTOP ASSESSMENT

A desktop review was undertaken to compile existing geological and hydrogeological literature and data for both the Arckaringa Basin and Pedirka Basin study areas. This assessment included:

- A literature review to identify published hydrogeological studies, company reports and government groundwater investigations undertaken in the respective basins
- Compilation and validation of baseline hydrogeological, geological and geophysical data including well and seismic data for stratigraphic interpretation
- Compilation of a spatial coverage documenting known and prospective coal reserves.

1.3.2. BASIN ARCHITECTURE

Basin architecture refers to the spatial extent, structural controls, formation surfaces, formation thicknesses, and physical relationship between hydrostratigraphic formations that comprise each basin. The spatial extent encompasses both the visible surface expression and the subsurface extension of these formations. Prior to this study, no attempt has been made to compile basin wide extents of key hydrogeological formations; consequently, the development of the basin architecture forms a fundamental component of the Stage 1 investigation.

A key element of the basin architecture involved the collation, processing and interpretation of seismic data; in addition to the synthesis of outcrop geology and seismic, mineral, petroleum and water well data into a seamless stratigraphic model for each basin. Geophysical contractors were selected to assist with the delivery of this work with professional oversight provided by Sandy Menpes, Principal Geoscientist, Energy Resources Division, Department for Manufacturing, Innovation, Trade, Resources and Energy (DMITRE); FROGTECH was contracted to deliver the Arckaringa Basin architecture and Mr Brent Jensen-Schmidt was contracted to deliver the Pedirka Basin architecture. Key tasks and objectives for the basin architecture include:

- Define the basin architecture, including improved mapping of the extent and geometry of hydrogeological units, plus outlining known and identified structural controls and barriers to groundwater flow.
- Improve the understanding and conceptualisation of aquifer connectivity between the Arckaringa Basin and Pedirka Basin aquifers, and overlying, underlying and adjoining aquifers.
- Identify and document knowledge gaps.

1.3.2.1. Historical Basin Extents

Historical extents for the Arckaringa Basin and the Pedirka Basin were developed by various South Australian agencies such as the DMITRE and DEWNR (and their predecessors) and were primarily based on the occurrence of Permo-Carboniferous sediments. These extents were preliminary at best since understanding of the Arckaringa Basin and the Pedirka Basin was largely unknown due to limited data, limited data integration and limited data interpretation. Extents for the same basin also vary slightly as they were built upon different principles (whether petroleum, mineral or groundwater based) which may include or preclude certain geological sequences.

Since one of the objectives for Stage 1 of this investigation was to accurately define the basin architecture and therefore the Arckaringa Basin and Pedirka Basin extent proper, historical basin extents were used initially to define these basins. For each basin two extents were available, one through the Petroleum Group at DMITRE and accessed through an online portal called the South Australian Resources Information Geoserver (SARIG) and the other available through DEWNR's internal spatial data system. These slightly different extents were combined for each basin (Arckaringa Basin and Pedirka Basin) to produce a single polygon or extent for each basin. A 10 km buffer was also then applied to each basin extent to capture any relevant data or information that would help aid in defining the final Arckaringa Basin and Pedirka Basin extent (Figure 1.2). It is understood that the resultant basin extents are not necessarily more accurate than the precursors upon which they are based, however it is thought that the likelihood of capturing all relevant information pertaining to the hydrostratigraphy and hydrogeology of each basin is improved by using the combined extents as a means of discriminating data spatially.

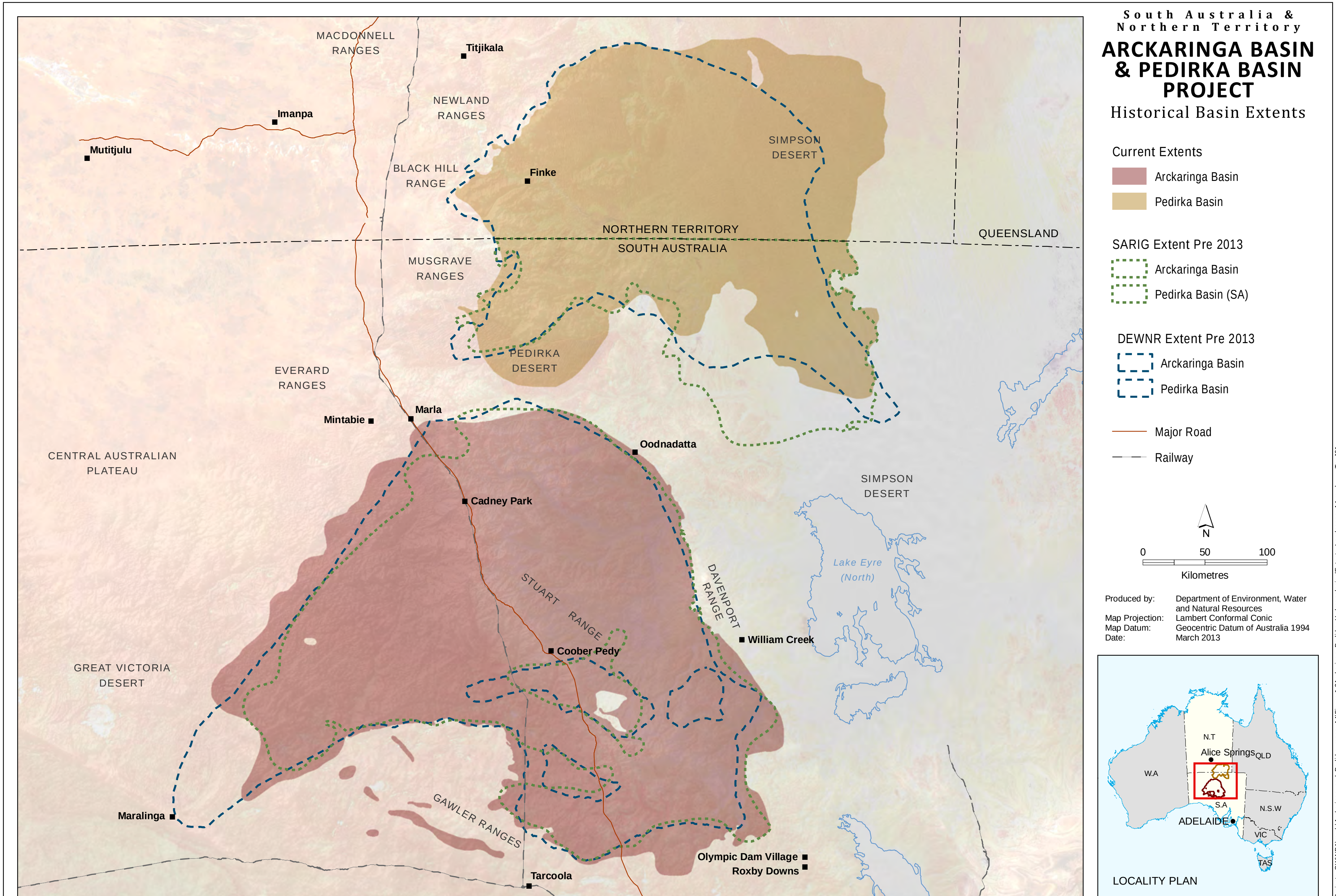

Figure 1.2: Historical Basin Extents, Arckaringa Basin and Pedirka Basin

1.3.3. INITIAL BORE AUDIT PROGRAM

An initial Bore Audit program (or field audit) was instigated to validate the existence, location and status of all practically accessible water wells in the Arckaringa Basin and Pedirka Basin. In South Australia, water well data are stored in a State managed drill hole database (SA Geodata). There are known location errors associated with older water wells and some of those wells registered by third party drilling contractors outside of the artesian part of the Great Artesian Basin. There is limited recent information on water well condition and there are also believed to be a number of unregistered wells or wells that are non-permitted and are not captured in SA Geodata. An accurate and comprehensive record of water well location and status is a prerequisite to any future impact or risk assessment assessing the vulnerability of groundwater resources in the basins.

The field audit consisted of an initial SA Geodata query to identify all water wells (excluding those marked as backfilled) contained within each basin extent (defined in Section 1.3.2.1) followed by site inspections to determine:

- Location of wells – there are known location errors in SA Geodata associated with spatial coordinates of some water wells (particularly older wells)
- Status – existence (i.e. located/not located), condition and purpose of the well
- Head works – whether the well is open or equipped (i.e. windmill, submersible pump, etc.)
- Depth of well, water level and salinity – where possible other information such as total depth, water level depth and salinity measurements were recorded and groundwater samples collected.

1.3.4. FIRST EDITION HYDROGEOLOGICAL MAP

Using the data gathered and interpreted in Tasks 1, 2 and 3, first edition hydrogeological maps and data compilation maps were constructed for both the Arckaringa Basin and Pedirka Basin. Information contained in the mapping products include:

- Basin extent
- Outcropping geology
- Extent of formation(s)
- Formation(s) tops – structure contours and surface
- Thickness of formation(s) – isopach contours and surface
- Contact boundaries and extent of Eromanga Basin sediments, Triassic Simpson Basin formations and Tertiary formations
- Potentiometric surface of formation(s) – if sufficient data are available. This will be corrected for temperature and salinity pending data availability.
- Distribution of groundwater salinity (electrical conductivity) within formation(s).

These maps aim to assist with the determination of:

- Regional extent of impact resulting from large-scale coal mining/CSG extraction
- Region(s) where the potential for inter-aquifer and inter-basin flow exist
- Regions where groundwater, surface water and groundwater dependent ecosystem (GDE) linkages may occur.

1.3.5. INITIAL CONCEPTUAL HYDROGEOLOGICAL MODEL

The final component for Stage 1 involved the formulation of a conceptual hydrogeological model to describe critical processes and knowledge developed during Tasks 1–4. Key components of the conceptual model include:

1. Identifying known and potential recharge mechanisms and recharge zones
2. Identifying known and potential discharge mechanisms and zones
3. Developing an understanding of hydrogeological characteristics of the key formations
4. Assessing groundwater flow mechanisms, nature of flow and scale of flow systems
5. Identifying zones of potential inter-aquifer flow and inter-basinal groundwater flow.

2. CHARACTERISTICS AND OVERVIEW OF THE STUDY AREA

2.1. GEOGRAPHIC EXTENT

2.1.1. ARCKARINGA BASIN

The Arckaringa Basin is located near the centre of South Australia (Figure 2.1), approximately 600 km north-northwest of Adelaide and approximately 400 km south of Alice Springs. The township of Coober Pedy is located near the centre of the basin. Based on newly processed geophysics and drilling data presented as part of this report, the Arckaringa Basin covers an area of approximately 100,000 km^2. The Stuart Highway and the Adelaide–Darwin Railway transect the basin, while the Oodnadatta Track is located along the eastern margin of the basin. Elevations across the basin range between 20 and 380 m AHD, with a mean of approximately 180 m AHD.

The basin is roughly horseshoe in shape with a number of depocentres located around a basement high (Coober Pedy Ridge, Mabel Creek Ridge and Central Basin High) associated with the Mount Woods Inlier located at the centre of the basin (Figure 2.2). These depocentres include the Boorthanna Trough located on the eastern margin of the basin; the Wallira, West, Penrhyn and Phillipson troughs located near the southern margin and the Karkaro and Mt Furner troughs that occupy the northern half of the basin. The Arckaringa Basin is bound to the east by the Peake and Denison Inlier (Davenport Range), to the south by the Gawler Ranges and Stuart Shelf and to the north and west by the Officer Basin. It should be noted that the current basin extent is approximate as scattered outcrop and sub-cropping Permian and Carboniferous sediments equivalent to the Arckaringa Basin sediments have been found beyond the currently defined extent. Hibburt (1995) reports occurrences up to approximately 100 km west of the current north-western boundary.

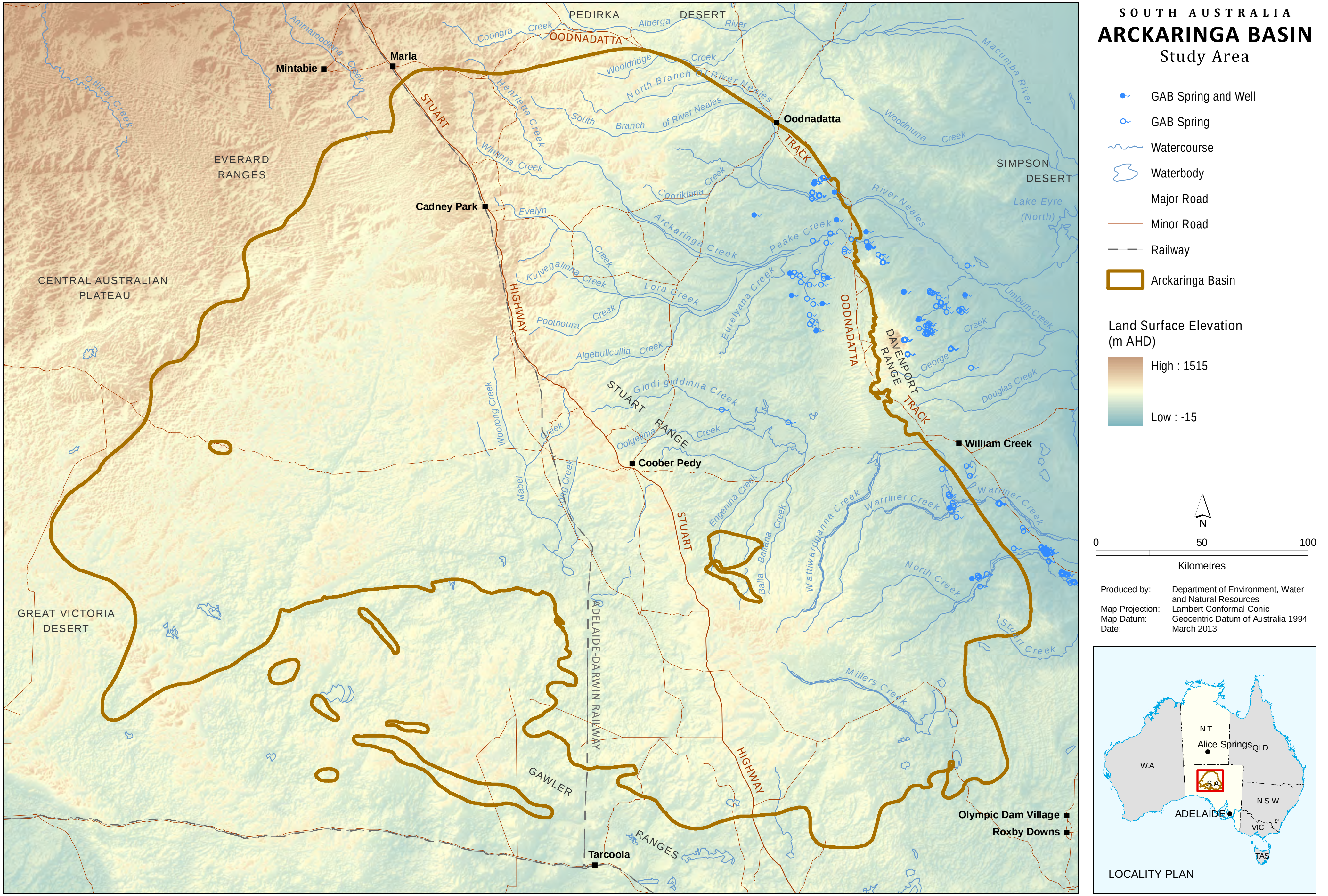

Figure 2.1: Study Area, Arckaringa Basin

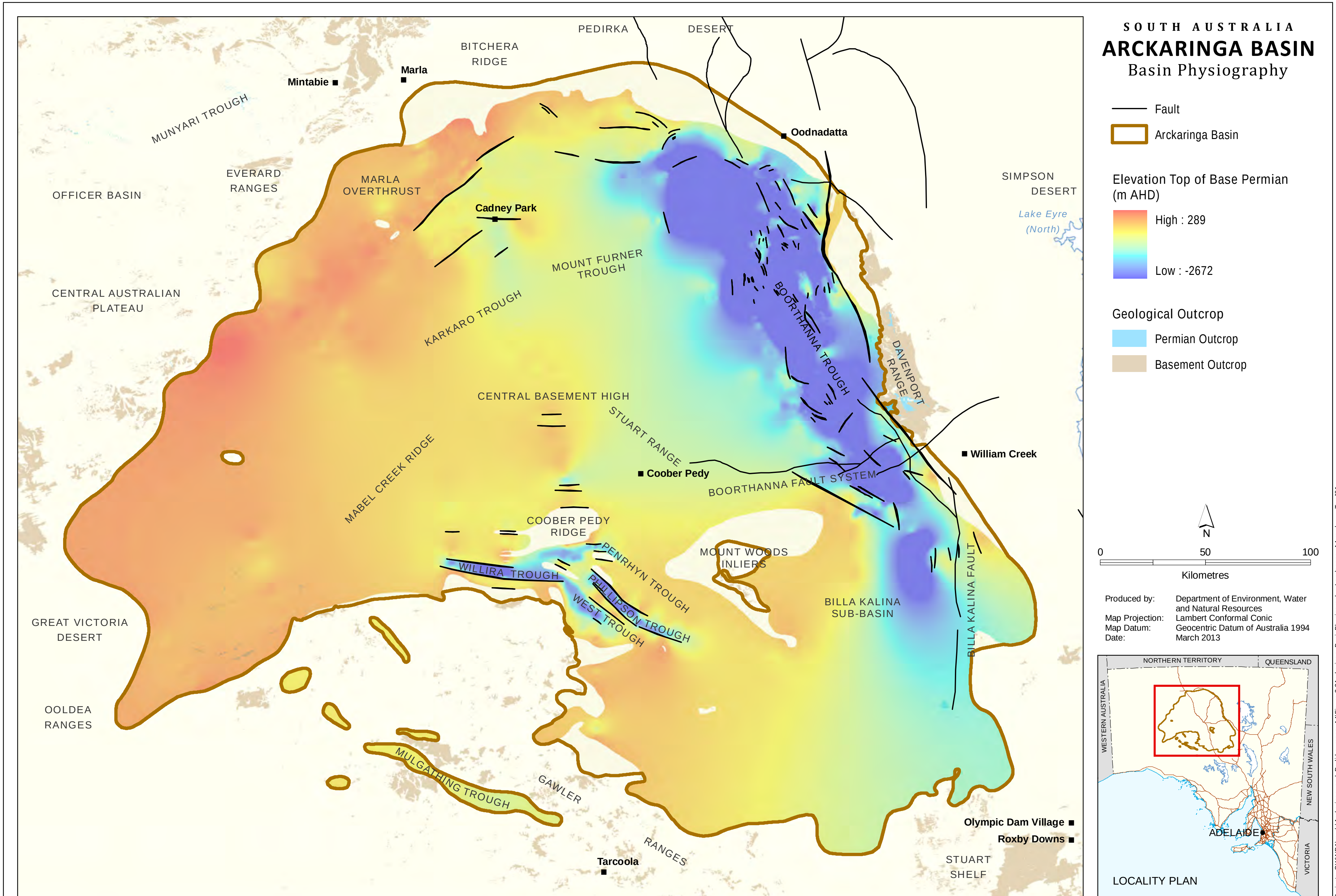

Figure 2.2: Basin Physiography, Arckaringa Basin

2.1.2. PEDIRKA BASIN

The Pedirka Basin is centred on the South Australia–Northern Territory border (Figure 2.3), approximately 860 km north – north-west of Adelaide and approximately 160 km south of Alice Springs. Elevation ranges between 0 and 450 m AHD, with a mean elevation of approximately 144 m AHD. Based on newly processed geophysics and drilling data presented as part of this report, the spatial extent of the Pedirka Basin covers an area of approximately 60,000 km^2. No major highways or railway lines traverse the Pedirka Basin.

The basin is bound to the south-west by the Musgrave Ranges (Figure 2.4). The northern boundary is defined by the Arunta Block and a complex fault block consisting of Mesoproterozoic to Cambrian metasedimentary and volcanic rocks called the Hale River High, the location of which is controlled by the Pellinor Fault Zone (Munson and Ahmad, 2012). A major north-west structural feature called the Dalhousie-McDills Ridge dissects the basin into eastern (Madigan and Poolowanna Troughs) and western (Eringa Trough) portions. A thin deposit of Permian sediment over the ridge connects the two halves. The basin reaches a thickness of up to 1525 m within the Eringa Trough, located west of the Dalhousie-McDills Ridge (Giuliano, 1988). The Poolowanna Trough occupies the far eastern portion of the basin and is separated from the Madigan Trough by the Colson Shelf, upon which approximately only 135 m of Permian sediments have been deposited (Munson and Ahmad, 2012 after Central Petroleum, 2011). Sediments within the Poolowanna Trough are largely of Triassic age (Simpson Basin), with Permian sediments only occurring along the western flank of the trough.

The Pedirka Basin is separated from the Arckaringa Basin to the south and the similarly-aged Cooper Basin to the east by the basement highs of the Bitchera, Muloorina and Birdsville Track Ridges (Hibburt and Gravestock, 1995). Hibburt and Gravestock (1995) postulated that the Pedirka Basin was once connected to the other Permo-Carboniferous basins across these basement highs but was subsequently isolated by the erosion of Permian sediments.

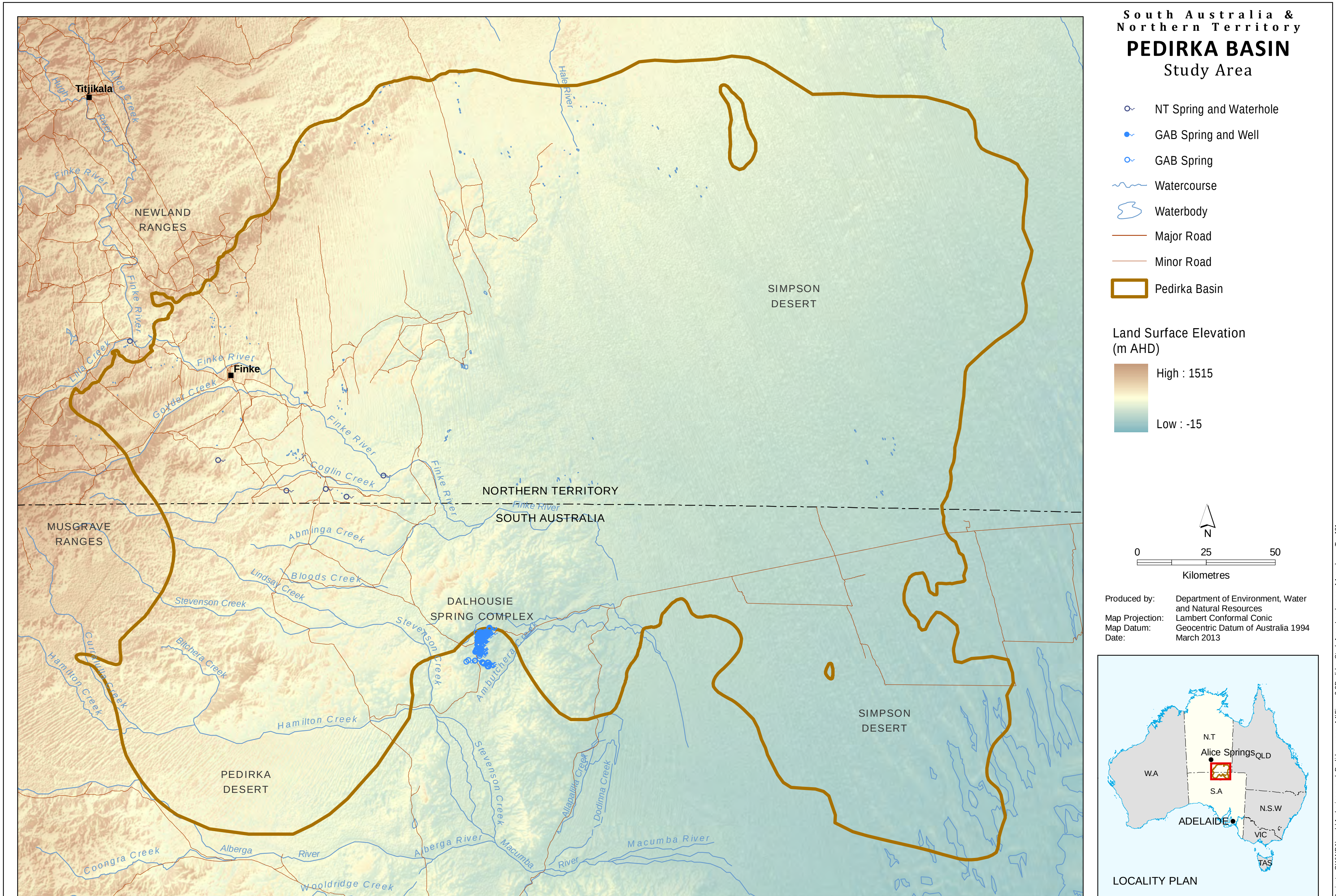

Figure 2.3: Study Area, Pedirka Basin

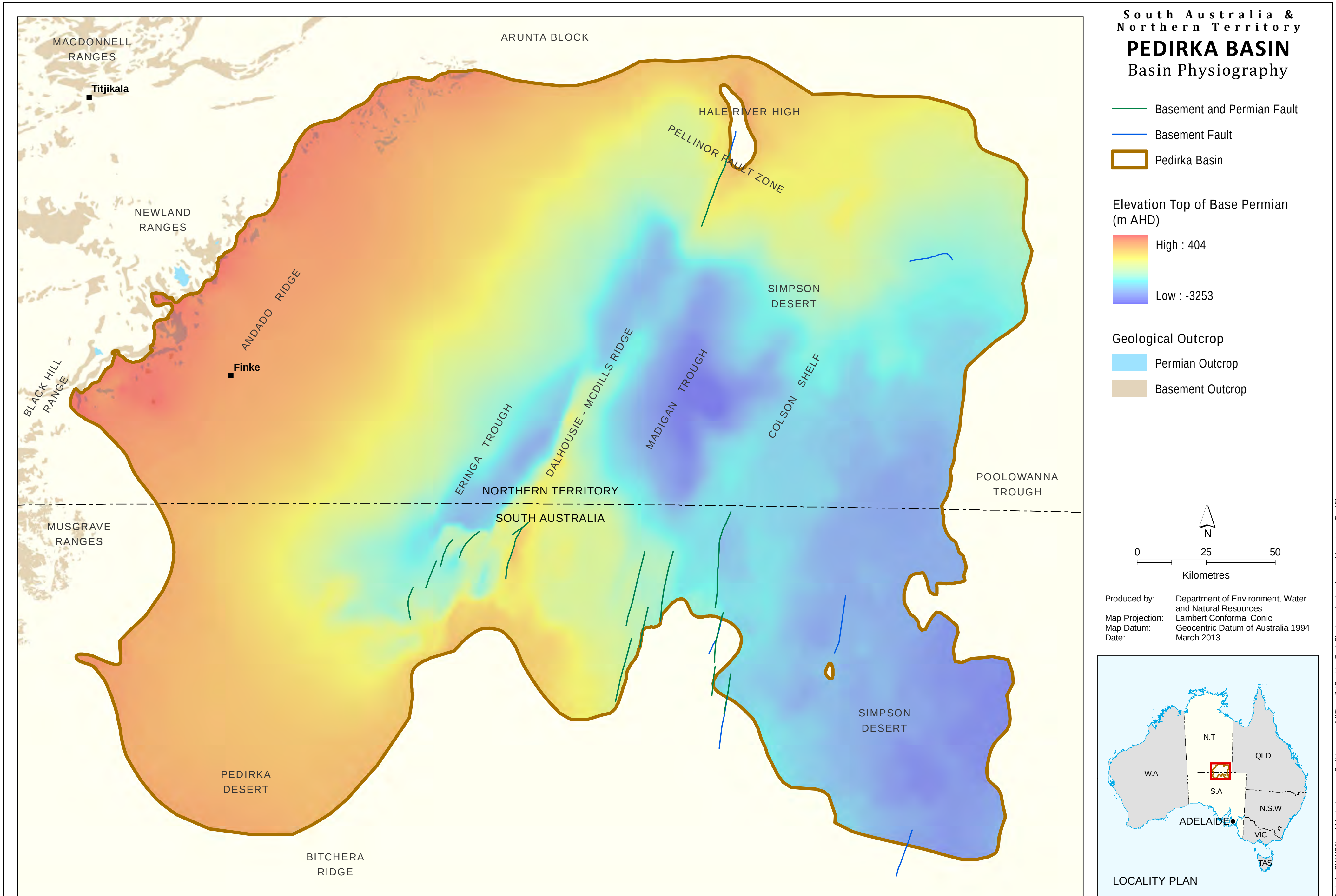

Figure 2.4: Basin Physiography, Pedirka Basin

2.2. PHYSIOGRAPHY AND BIOREGIONS

The topography of the study regions is largely flat-lying or controlled by dune field development. The dominant landscape features of the Arckaringa Basin are gravelly ("gibber") plains and tablelands that support perennial grass and sparse chenopod, samphire or saltbush shrubland vegetation (Marla-Oodnadatta Soil Conservation Board, 2002). In the Pedirka Basin, longitudinal dunes of the Simpson Desert can extend for several hundred kilometres and attain heights of up to 40 m (Ambrose, 2006). Anatomising rivers and creeks that form wide, gently sloped valleys, swales and floodplains provide much of the observed topographic variability. These environments also support stands of Coolabah, Gidgee and River Red Gum vegetation. Sandier terrains support native grasses and areas of hillslope support tall open shrubland (Marla-Oodnadatta Soil Conservation Board, 2002).

The margins of the Arckaringa Basin and Pedirka Basin are commonly defined by highlands and plateaus. Highland areas include the Gawler Ranges to the south and south-west, the Everard and Ooldea Ranges to the west and the Newland, Musgrave and MacDonnell Ranges to the north-west. The tallest peaks in the MacDonnell Ranges are Mount Zeil (1531 m AHD), Mount Liebig (1524 m AHD) and Mount Sonder (1380 m AHD), while the tallest peak in the Musgrave Ranges is Mount Woodroffe (1435 m AHD). To the south of the Arckaringa Basin, the Gawler Ranges occurs on the eastern margin of the Gawler Craton and is comprised of volcanolithics; the highest point is Nukey Bluff at 465 m AHD. The eastern margin of the Arckaringa Basin is adjacent to the Peake and Denison Inlier, located approximately 60 km west of Lake Eyre North. The Peake and Denison Inlier is comprised of up-faulted, outcropping crystalline Proterozoic and Achaean basement units; the area is also known as the Denison and Davenport Ranges (Wopfner & Twidale, 1967). The central parts of the ranges consist of a north-sloping plateau with an elevation between 400–420 m AHD. Of particular importance to the Arckaringa Basin is the Stuart Range, a low-rising escarpment of silcrete-capped Cretaceous sediments that transects the Arckaringa Basin from south to north.

Aeolian-driven deflation is described by Mabbutt (1977) as an important process shaping the physiology of the region. Longitudinal sand dunes in the plains and lunette dunes around playas provide important topographic variation.

2.3. LAND USE AND POPULATION

Pastoral enterprise represents the predominant land use in the region (Figures 2.5, 2.6). Other land uses prevalent in the region include mining, conservation, tourism and defence.

The pastoral industry was established soon after European exploration of the region and has a primary focus of beef-cattle production, while some sheep production occurs in the vicinity of Coober Pedy in the vicinity of the southern and central regions of the Arckaringa Basin.

In more recent times, mining has become an important industry in the region, although activity remains restricted in geographic extent. Most mining operations occur in the vicinity of Coober Pedy (various private opal mines) and towards the south-eastern corner of the Arckaringa Basin at the Prominent Hill mining operation, which produces copper and gold. There are no active mining operations in the Pedirka Basin.

Tourism is another important land use in the region, although like mining, important tourism areas cover only a small proportion of the study areas. Tourism is largely concentrated along the main transport routes, towns and conservation parks. A number of conservation parks are located in the vicinity of the Arckaringa and Pedirka Basins. These include the Wabma Kadarbu, Lake Eyre and Witjira National Parks (NP), the Simpson Desert and Tallaringa Conservation Parks (CP) and the Mount

Willoughby Indigenous Protection Area (IPA). Specific tourist attractions within the region include Coober Pedy and its opal mining industry, the Breakaways, the Painted Desert, GAB springs and historical infrastructure associated with the Old Ghan Railway and the Overland Telegraph Line. In addition, nature tourism, bush walking, wildlife, four wheel drive experiences, camping and indigenous tourism all occur throughout the region (Sapex, 2007). Although limited defence activity occurs throughout the region, of particular focus is the Woomera Prohibited Area (WPA), which overlaps the southern portion of the Arckaringa Basin. Entry to the WPA (except on main road corridors) requires permission from the Commonwealth Department of Defence, in accordance with Regulation 35 of the Defence Force Regulations 1952.

The Arckaringa Basin region includes the Local Government Area (LGA) of Coober Pedy and parts of the basin fall within the Aboriginal freehold lands of the Maralinga Tjarutja and the Pitjantjatjara, Yankunytjatjara and Ngaanyatjarra (or Anangu) peoples. Coober Pedy is the largest town in the region, with a population of approximately 2000 people. Other towns of significance include Marla (population of approximately 100) and Oodnadatta (population of approximately 300). Apatula Community (also known as Finke) is the largest settlement in the Pedirka Basin with an estimated population of 210 people.

The region contains numerous sites of indigenous significance, reflective of a long history of occupation. Such sites may include middens, quarries, worksites, campsites and burial sites. Geographically significant sites include The Breakaways north of Coober Pedy and the Lake Phillipson area south-west of Coober Pedy (Sapex, 2007).

A number of significant spring wetland environments occur near the eastern margin of the Arckaringa Basin and the southern margin of the Pedirka Basin. These spring environments, known popularly as “mound springs” due to many being associated with a distinct mound-like land feature surrounding the spring vent, have cultural and spiritual significance for the indigenous people of the region. These environments have historically provided an important supply of food and water in an otherwise arid region. The traditional owners and custodians of the region’s spring country include the Arrabuna, Dieri, Lower Southern Arrente, Wokangurru and Kuyani peoples.

In addition to their cultural significance, the springs also support a number of rare and endemic wetland ecosystems. These GDEs support unique populations of flora and fauna. The ecological significance of these wetlands is recognised under the Commonwealth’s Environment Protection and Biodiversity Conservation Act 1999 (EPBC). The current scientific understanding of these springs suggests that the majority of water is supplied from groundwater resources in the GAB, which overlies the Arckaringa Basin and Pedirka Basin. Interconnectivity between the GAB and underlying aquifer systems is currently poorly understood.

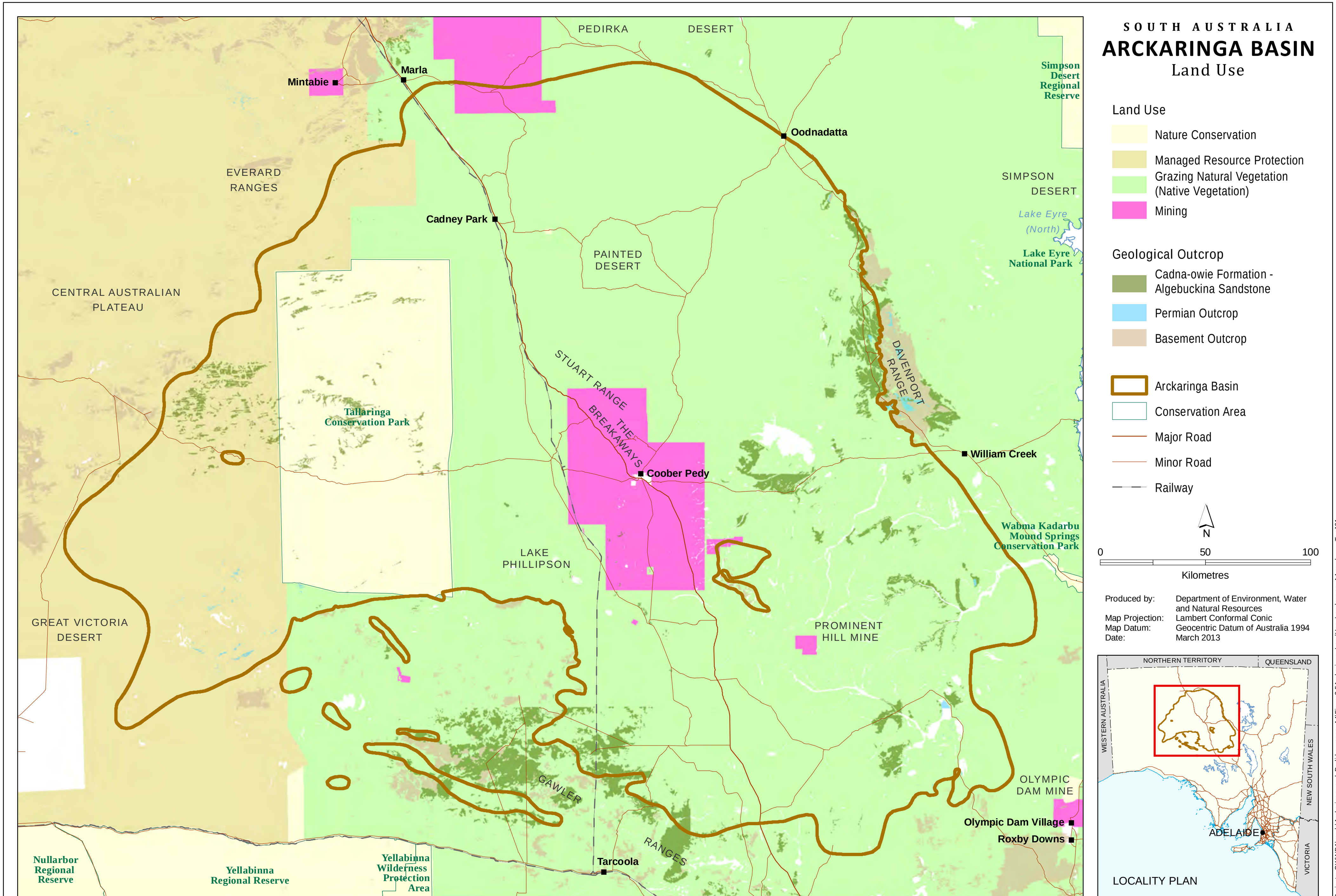

Figure 2.5: Land Use, Arckaringa Basin

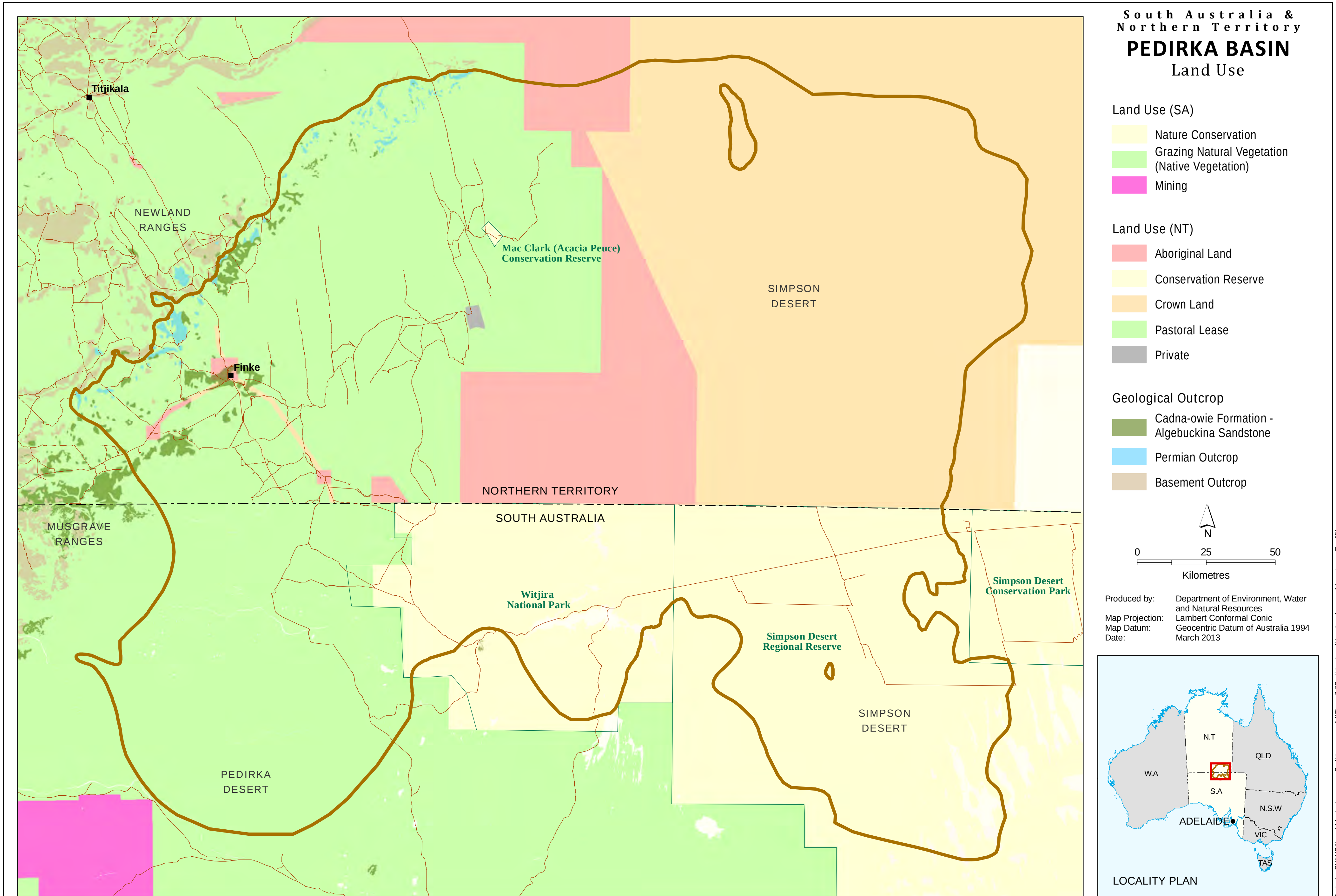

Figure 2.6: Land Use, Pedirka Basin

2.4. CLIMATE

The climate of central Australia has been described by Allan (1990) and McMahon et al. (2005) as arid; while Stern et al. (2000), using a modified version of the Koppen climate scheme, describes the region as 'desert'. Central Australian weather is dominated by persistent high pressure systems; the location of the dominant high pressure system is an important influence on temperature in the region. Average maximum peak-summer monthly temperatures range between 36.1°C and 39.5°C, although daily maximums are regularly above 40°C. In contrast, the minimum peak-winter monthly temperatures range from 4.9°C and 6.4°C, although daily minimums may reach below 0°C. Published rates of evaporation range between 2.5 m/y (Hamilton et al., 2005) and 3 m/y (Tetzlaff and Bye, 1978). Precipitation is primarily sourced from weak winter cold fronts related to ocean temperatures in the Southern Indian Ocean and intermittent summer monsoon rainfall that originates in north-west Australia. Generally, southern-derived winter rainfall is the dominant source of precipitation in the Arckaringa Basin, while rainfall in the Pedirka Basin is more reliant on northern-derived monsoonal precipitation. Average annual precipitation for the related Lake Eyre Basin region varies from greater than 200 mm/y to less than 150 mm/y (Figures 2.7 and 2.8), however rainfall totals vary significantly both temporally and spatially. A distinctive rainfall gradient occurs across both the Arckaringa Basin and Pedirka Basin with average annual rainfall generally decreasing from the west – north-west to the east – south-east.

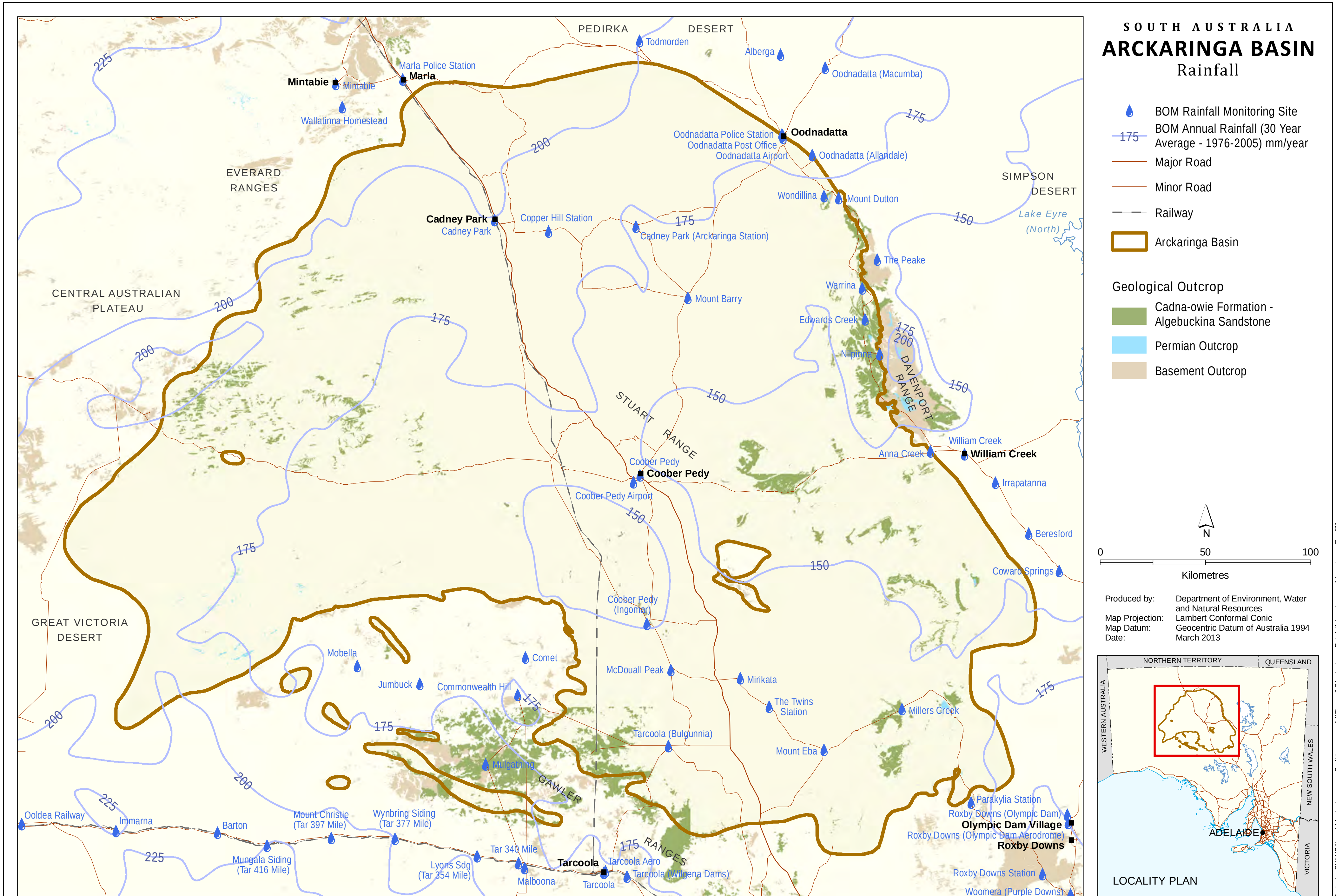

Figure 2.7: Average Annual Rainfall, Arckaringa Basin

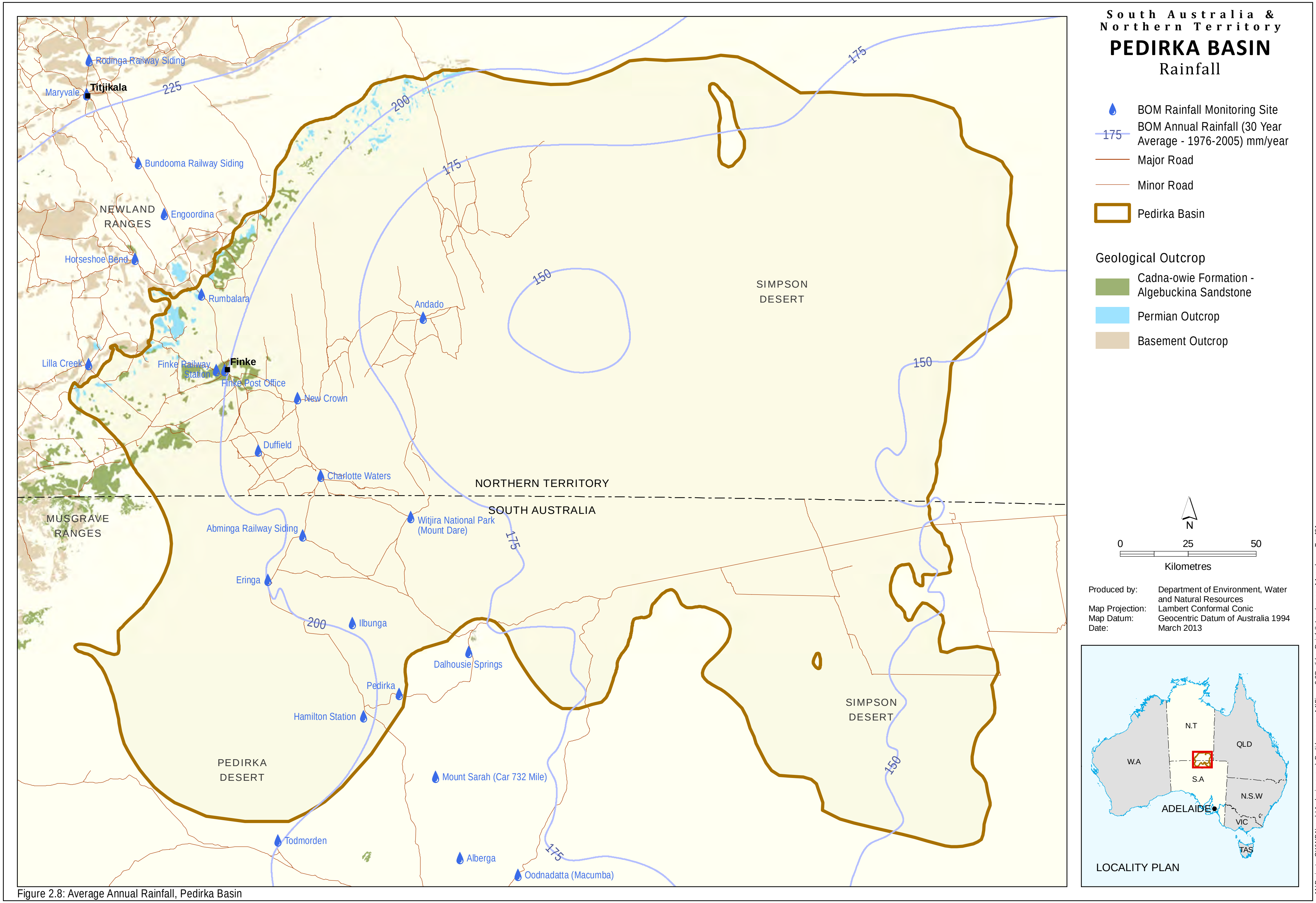

Figure 2.8: Average Annual Rainfall, Pedirka Basin

2.5. SURFACE WATER HYDROLOGY

As previously stated, although links between groundwater, surface water and GDEs are well established, the intent of this report is to focus only on hydrogeological considerations and therefore surface water and GDEs will only be discussed briefly; an in-depth discussion will be provided in reports.

Silcock (2010) notes that permanent surface water bodies are rare in this region and are generally associated with springs or rock-holes in discrete locations. Drainage in the region is characterised by a network of ephemeral rivers and creeks that drain concentrically east towards Lake Eyre or one of the other large playas in the region (Figures 2.1 and 2.3). Major ephemeral drainage lines include the Macumba, Neales, Alberga, Hale and Finke Rivers, as well as the Peake, Warriner, Goyder, Stevenson and Lilla Creeks. Not all of these rivers drain directly into Lake Eyre; in particular, rivers located in the Northern Territory terminate in ephemeral lakes and playas in the Simpson Desert. Headwaters of these rivers and creeks occur in highlands, with the Stuart and Newland Ranges of particular note given their proximity to Permian outcropping or sub-cropping sediments. Kotwicki (1986) notes that the major rivers draining into Lake Eyre have a typical fall of between 200–300 m between headwaters and their discharge point.

The majority of flow events are short lived, relatively small and occur on either an annual or bi-annual basis (Fulton, 2012). Kotwicki and Allan (1998) and Hutton (1984) state that, given the arid climate, stream flow conditions are only experienced after either heavy summer monsoonal rains or heavy winter rains that are typically caused by La Niña/Southern Oscillation events in the Pacific Ocean. Habermehl (1980) states that stream flow beyond the headwaters and middle reaches of rivers is rare due to the impact of low gradients, high evaporation and high infiltration rates. In support of this, Allan (1990) suggests that precipitation levels in excess of 400 % greater than the long-term annual average are required to provide sufficient floodwaters to reach their terminations in Lake Eyre. Consequently, the South Australian Arid Lands (SAAL) Natural Resources Management (NRM) Board (2006) characterised the surface water resources in this region as a 'boom and bust' cycle, where years of drought may be interspersed with a few weeks of intense rainfall and flooding. Quantifying the surface water recharge potential from such intermittent flood events has not been possible because all rivers are unregulated and are not relied upon as a source of water for stock, agriculture or domestic purposes. Sibenaler (2010) reported that early hydrological monitoring programs relied upon long-term recorders to measure water height and teams of researchers collecting flow data by hand, but difficulty in accessing areas during flood events and the reliability of recorders rendered such monitoring programs only partially successful at best. Alternative programs conducted since the 1980s have relied on either rain gauge data as a proxy or the use of newer, low-cost and more reliable water level recorders (e.g. the AridFlo program) (Sibenaler 2010).

2.6. BOUNDING AQUIFER FORMATIONS

2.6.1. CENOZOIC SEDIMENTS

The most recent phases of sedimentation may provide discrete aquifers in areas covered by the Lake Eyre Basin. These sediments were primarily deposited as episodic braided fluvial and lacustrine sediments. Cenozoic sedimentation may be divided into two depositional episodes; sedimentation that occurred during the Tertiary prior to upwarping at 15-5 Ma and those associated with the current hydrological system. The Cenozoic aquifers represent a known resource of stock and domestic water. Shepherd (1978) reported salinities vary from 1000 mg/L to greater than 100000 mg/L, while inferred transmissivities to be less than 100 m^2/d. In the Simpson Desert region, C. Bleys & Associates (1977) reported groundwater in several bores from a Cenozoic aquifer consisting of clean quartz sands. Salinities were approximately 8000 mg/L and yields varied from 5 L/s to 12.6 L/s. Groundwater quality from Cenozoic aquifers in the Northern Territory is variable, but potable supplies (less than 1000 mg/L) have been identified, particularly where these systems connect with modern-day drainage lines (e.g. Hale River).

2.6.2. GREAT ARTESIAN BASIN

The Great Artesian Basin (GAB) is one of the largest groundwater basins in the world, underlying approximately 1.7 million km^2, or 22% of the Australian continent (Habermehl, 1980). The GAB overlies the majority of the Arckaringa Basin (Figure 2.9) and Pedirka Basin (Figure 2.10) sediments. Except for the far north and far eastern parts, the GAB largely occurs in arid and semi-arid regions. Consequently, exploitation of the GAB groundwater resource has played and continues to play a vital role in supporting agriculture, mining, industry, civil and cultural communities in Australia (Ah Chee, 2002; Leek, 2002). Geologically, the GAB describes a terrestrial to marine Cretaceous–Jurassic hydrogeological super basin that covers much of eastern and central Australia. Although the name GAB may cover a number of smaller sedimentary basins, in South Australia and the southern Northern Territory, the GAB is synonymous with the Eromanga Basin. In the vicinity of the Arckaringa Basin and Pedirka Basin, the aquifer units of primary importance are the Cadna-owie Formation, Algebuckina Sandstone, DeSouza Sandstone and lateral equivalents (collectively referred to as the J aquifer), while the primary confining layers include the Bulldog Shale, Rumbalara Shale, Oodnadatta Formation and lateral equivalents within the Rolling Downs Group. Kellett et al. (1999) described typical yields in the vicinity of the non-artesian, south-eastern margin of the GAB of between 0.1 L/s to 6.0 L/s, although larger yields of up to 130 L/s have been reported Olympic Dam Well Field B.

More recent information and detailed summaries concerning the hydrogeology of the western GAB may be found in Smerdon et al. (2012), Keppel et al. (2013), Love et al. (2013a) and Love et al. (2013b).

2.6.3. SIMPSON BASIN

The Triassic Simpson Basin is an entirely subsurface intra-continental basin that was discovered as a result of seismic work and drilling (Moore, 1986). The Simpson Basin overlies the eastern extent of the Pedirka Basin and consists of two sedimentary formations: the Walkandi Formation and Peera Peera Formation.

The Peera Peera Formation overlaps conformably above the Walkandi Formation and consists of three main facies: the lowest facies type consists of grey shale, siltstone, minor sandstone and coal. This facies is overlain by fine-grained sandstone, which in turn is overlain by black carbonaceous silty shale. The depositional environment is interpreted to be a fluvial-floodplain-lacustrine and therefore will have an inherent heterogeneity (Questa, 1990). The Walkandi Formation is comprised of beds of red-brown shale, green siltstone and fine grained sandstone of possible lacustrine origin (Moore, 1986) and is largely restricted in extent to the Poolowanna Trough region at the centre of the Pedirka Basin. Goldstein et al. (2011) notes that sandstone inter-beds in the Walkandi Formation are fine-grained, with low porosity and permeability, although Questa (1990) reports that reservoir quality sands have been identified through log analysis. The overlying Peera Peera Formation is described by Goldstein et al. (2011) as containing laterally variable, poor quality reservoirs with a maximum measured porosity of 7.8%, although this is thought to improve up-dip from the central Poolowanna Trough. Due to the depth of the Simpson Basin and the accessibility of groundwater in overlying sequences, it has never been exploited for groundwater.

Work presented by Questa (1990), Ambrose and Heugh (2012) and Munson and Ahmad (2012) suggests that the Simpson Basin sequences should be included as part of the Pedirka Basin; abandonment of the name “Simpson Basin” is suggested, with Questa (1990) suggesting that group status within the Pedirka Basin sequence be more appropriate. However, as only Carboniferous and Permian units are discussed in this report, the definition of the Pedirka Basin described in Hibburt and Gravestock (1995), which treats the Simpson Basin succession as separate to that of the Pedirka Basin, is the definition adopted here.

2.6.4. WARBURTON BASIN

The Warburton Basin is a large pericratonic, epeiric to marine sedimentary basin that occupies a large portion of north and north-east South Australia and southern Northern Territory (Radke, 2009). The Warburton Basin underlies parts of the Arckaringa Basin and Pedirka Basin. Formation ages are primarily Cambrian to Ordovician, although Devonian-aged sediments within the Finke Group are present in the Northern Territory. The basin is generally divided into eastern and western sub-basins, with the demarcation structure being uplifted Proterozoic units that form the base of the Birdsville Track Ridge. Groundwater found within the Devonian Finke Group is exploited near the margins of the GAB within the Northern Territory; however, due to the depth of the Warburton Basin and accessibility of groundwater in overlying sequences, groundwater exploitation is otherwise very minimal. Consequently, the hydrogeological characteristics of formations within the Warburton Basin are poorly understood.

2.6.5. AMADEUS BASIN

A detailed description of the geology, basin architecture and structural development of the Amadeus Basin may be found in Wells et al. (1970) and Korsch and Kennard (1991). The Amadeus Basin is an intracratonic basin of largely Neoproterozic to early-Carboniferous marine siliciclastic and carbonate sediments that borders and underlies the western margin of the Pedirka Basin. The basin occupies much of the southern quarter of the Northern Territory, with a small section extending into Western Australia. Sequences of volcaniclastics and fluvial sediments define rifting events in the western part of the basin. Porous Ordovician and Devonian sandstone units are the main aquifers in the Amadeus Basin. In particular, the Hermannsburg Sandstone, the Mereenie Sandstone and the Pacoota Sandstone are important sources of groundwater (Jacobson et al. 1989; Lloyd & Jacobson 1987). Groundwater flow is predominantly eastward along synclinal axes (Cresswell et al. 1999). Recharge is largely through sandy riverbeds via episodic flooding (Calf, 1978).

The Amadeus Basin has also been the subject of exploration for conventional petroleum hydrocarbons since the early 1960’s (Pegum, 1997). Currently there are two major petroleum hydrocarbon producing fields in the Amadeus Basin. Both fields are associated with anticline structures and are located approximately 240 km and 120 km west of Alice Springs respectively.

2.6.6. OFFICER BASIN

The Officer Basin is a large pericratonic sedimentary basin that has similar origins to that of the Warburton Basin. The eastern Officer Basin occupies a large region of northern, central and western South Australia; it also borders and partly underlies the western margin of the Arckaringa Basin. Sediments are primarily Cambrian to Ordovician in age, although Devonian sediments (Mintabie beds) are known to occur within the Munyarai Trough region, located near the northern margin of the basin (Gravestock et al, 1995). Groundwater resources contained within it are generally described as highly saline (Alexander and Dodds, 1997). Given the sparse information available, regional groundwater was described simplistically by Lau et al. (1995a and b) as a single unconfined system with the Precambrian acting as the hydrogeological basement. Aldam (1993) mentions that there are a number of sandstone units within the Officer Basin that may contain useful supplies of groundwater, including the Murnaroo Formation, Relief Sandstone, Trainor Hill Sandstone and Mt Chandler Sandstone; however knowledge concerning these resources appears largely qualitative. In particularly, Alexander and Dodds (1997) suggest a semi-confined to confined aquifer may be present in the Murnaroo Formation in the south-eastern part of the basin. Recharge is described by Alexander and Dodds (1997) as primarily via Tertiary palaeochannels which extend southward from the Musgrave Block over the extent of the Officer Basin, as well as via points of localised recharge. Salt lakes along the basin's southern margin provide the only evidence for discharge from the basin. Read (1990) describes groundwater yields from Officer Basin sandstone units within the 1:250,000 EVERARD map sheet area as "moderate" (<0.1 L/s to 3 L/s), with recharge likely to be occurring along the southern margin of the Everard Ranges with groundwater flow primarily to the south. A number of localised groundwater studies (e.g. Dodds, 1997; Sheard, 1981; Sheard, 1982) have been conducted in the vicinities of townships and communities that describe groundwater resources possibly derived from the Officer Basin.

The Officer Basin has also been the subject of exploration for conventional petroleum hydrocarbons, from which information concerning porosity and permeability of various strata can be inferred.

A summary of the petroleum geology of the Officer Basin may be found in Morton and Drexel (1997). Additionally, further information concerning groundwater resources in the Officer Basin may be found in Lau (1995).

2.6.7. PROTEROZOIC-ARCHAEAN BASEMENT

Crystalline metasediment and igneous units of the Proterozoic and Archaean basement sequences primarily outcrop within the Peake and Denison Inlier, in the vicinity of the Mount Woods Inlier and to the south and south-east of Cooper Pedy. A number of localised fractured rock aquifers occur within crystalline Precambrian basement rocks. Groundwater is recharged either by direct infiltration of rainwater or via drainage channels. Groundwater yields within fractured rock aquifers are greatest near faults, although good yield may also be obtained from limestone aquifers within the Proterozoic sequences. Groundwater yields are highly variable and are correlated with the fracture density and aquifer composition. Groundwater quantity and quality for the SAAL NRM region, which covers a large portion of the Arckaringa Basin, is estimated at 400000 GL of freshwater, 925000 GL of brackish water and 1300000 GL of saline waters (SAALNRMB, 2006). In the vicinity of the Mount Woods Inlier (Figure 2.2), groundwater extracted for mining has salinities ranging between 5000 and 10000 mg/L and yields ranging between 400 and 4000 gph (~0.5–5 L/s) (Belperio, 2005).

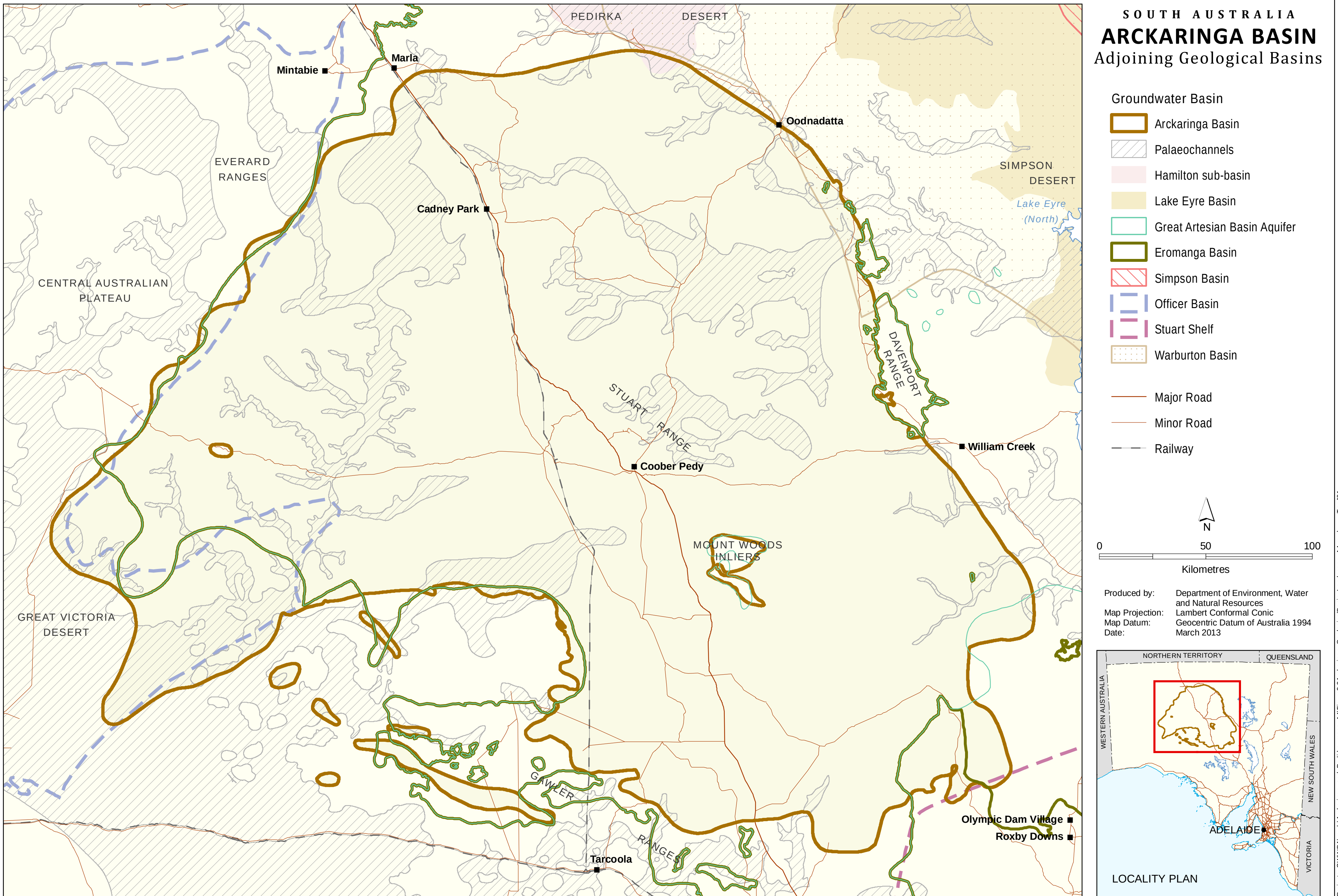

Figure 2.9: Adjoining Geological Basins, Arckaringa Basin

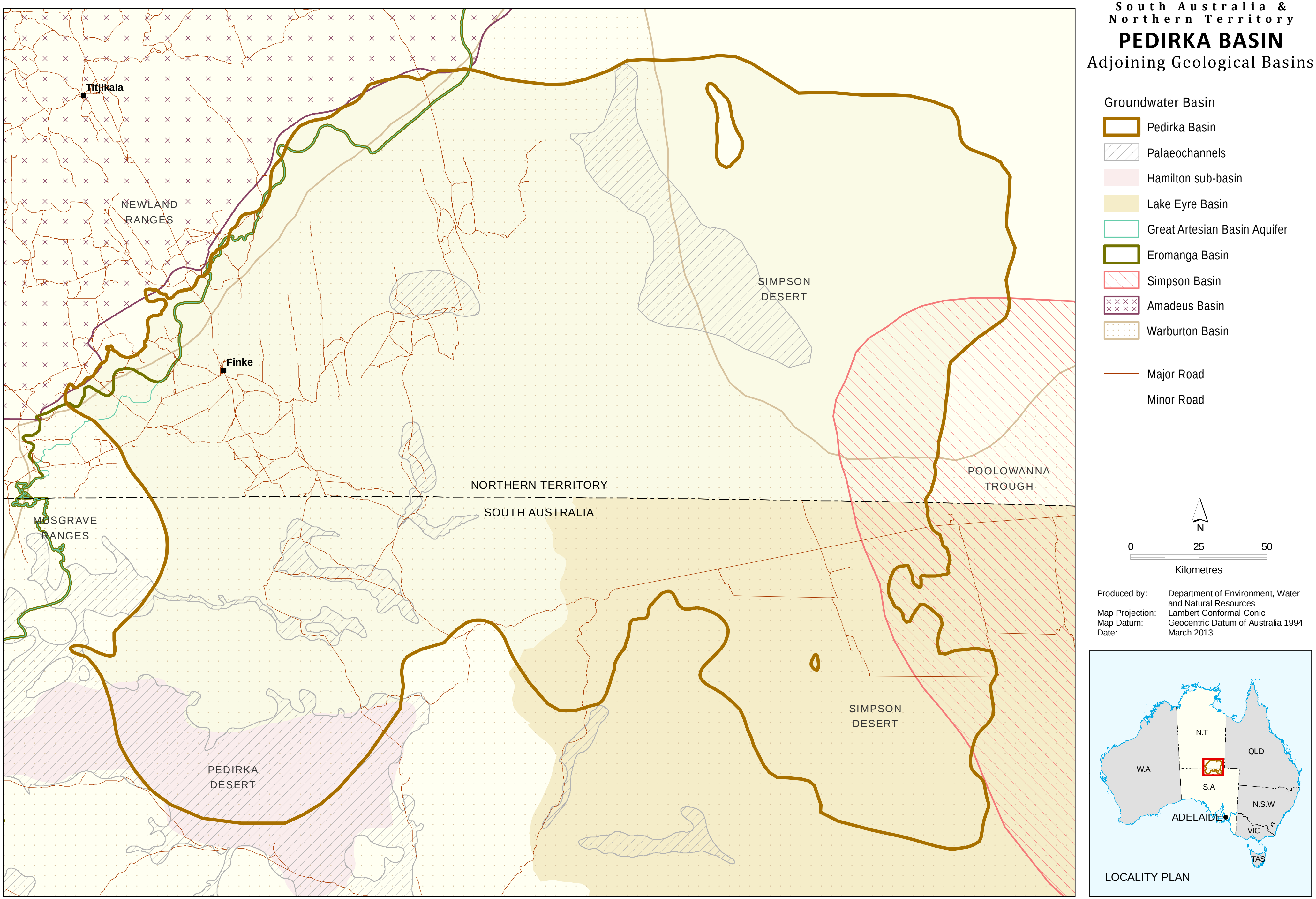

Figure 2.10: Adjoining Geological Basins, Pedirka Basin

2.7. STRUCTURAL AND TECTONIC SETTING

The development of conceptual models describing the hydrodynamics and flow characteristics of hydrogeological basins such as the Arckaringa Basin and Pedirka Basin require an understanding of their structural and tectonic history. Such an understanding provides important insights into the origins of basin architecture, deformation responsible for the development of sub-basins or preferential flow paths and the origins of sedimentary successions. The following provides a brief summary of pertinent information concerning the structural and tectonic history of the Arckaringa Basin and Pedirka Basin.

After a number of Archaean cratons amalgamated to form the Australian continent (Powell and Pisarevsky, 2002; Powell et al., 1993), a series of tectonic events commencing in the Late Cambrian resulted in the development of the structural architecture underpinning the Arckaringa Basin and Pedirka Basin. Permian basin architecture is largely controlled by Proterozoic and early Phanerozoic tectonics and the deep seated structures that formed during these times.

During the late Proterozoic to early Phanerozoic, plate divergences formed complex continental margins; the inception of a number of basins have been interpreted as aulacogens (failed arms) of deeply penetrating triple rift junctures that formed along these plate margins. Such basins include (but are not restricted to) the Officer, Amadeus and Warburton (Figures 2.9 and 2.10). The eastern Australian margin at that time was defined by a complex rift system. An interpreted triple rift junction in the vicinity of this margin is inferred to have occurred in close geographic proximity to the present day Pedirka Basin and southern Cooper Basin (Questa, 1990); while Preiss (2000) interpreted five major successive rift cycles, each with its own locus and orientation, in relation to deformation events associated with the Adelaide Geosyncline, located to the southeast and east of the Arckaringa Basin.

Deformation associated with the Delamerian Orogeny (Late Cambrian) saw the conversion of eastern Australia to a convergent plate margin; development of the eastern plate margin proceeded via the episodic accretion of magmatic arcs as terranes. The Delamerian Orogeny was associated with a number of west-north-west compressive tectonic events that produced a number of north-south trending thrusts, north-west trending transgressive shears, recumbent folds, igneous intrusions and metamorphism (Cotton et al, 2006), as well as inverting parts of the Adelaide Fold Belt. Cotton et al. (2006) also suggest that the deep crustal scale, length and planar form of these structures were favourable for reactivation during several later phases of tectonism.

Following the Delamerian Orogeny, deposition of sediments within a forearc basin associated with terrane accretion occurred during the Late Cambrian/Ordovician, resulting in the clastic sedimentary deposits associated with the Early Palaeozoic basins which, in part, underlie Permian sediments in Central Australia. The Pertnjara Orogeny during the Late Ordovician to Late Silurian resulted in uplift and erosion in the Pedirka Basin region; in particular uplift during these times formed the Black Hills Range which forms the north-western boundary of the Eringa Trough and provided a source of sediment during the Late Devonian (Finke Group sediments).

Cotton et al. (2006) suggest that north-west/south-east orientated compression and uplift associated with the Alice Springs Orogeny (Devonian and Carboniferous periods), had a great influence on the structural grain of the Permo-Carboniferous Basins (Cooper, Pedirka and Arckaringa) of central Australia. In particular, the Alice Springs Orogeny resulted in further remobilisation of Achaean Basement and over-thrusting causing high amplitude folding of existing basinal sediments. This resulted in the formation of domal trends such as the Gidgealpa—Merrimelia—Innamincka (GMI) Ridge, Dalhousie-McDills-Ridge and Birdsville Track Ridge (Figures 1.1 and 2.4) that controlled the position of depocentres for Permo-Carboniferous sedimentation (Karlstrom et al., 2013; Questa 1990). Gravestock (1995) describes crustal shortening of up to 20 km and uplift of 3 km as a consequence of this event.

The period of stability following the Alice Springs Orogeny saw glaciogenic, quiescent marine followed by lacustrine, fluvial and backswamp sedimentation; resulting in the Boorthanna, Stuart Range and Mount Toondina formations in the Arckaringa Basin and the Crown Point and Purni formations of the Pedirka Basin.

Shearer (1994) suggests that parts of the Arckaringa Basin immediately south of the “Marla Overthrust Zone” are severely faulted, with the dominant strikes of north-east and north-west most notable, while Cotton et al. (2006) notes that syn-depositional faulting occurred during the Early Permian. An interpretation of a “top of Permian” map by Shearer (1994) suggests that the north-east faults have not been reactivated post-Permian, while the north-west fault system has been re-activated.

In contrast, Menpes et al. (2010) and Menpes (2012) argue that the Arckaringa Basin troughs are dominated by glacial geomorphology, rather than the creation of accommodation space via fault growth. The location and orientation of the glacial valleys appears to be controlled by pre-existing structural grain and rock types in the underlying basement. Minor contraction coincident with deposition culminated in gentle folding of the Early Permian succession, uplift and erosion.

Deposition in the Arckaringa Basin appears to have ceased during the Sakmarian (Early Permian) on the basis of palynological information (Alley, 1995; Menpes, 2012). Menpes et al. (2010) and Menpes (2012) have suggested that this break in deposition may correlate with breaks in deposition within the Patchawarra Formation, or alternatively may be related to the Daralingie Unconformity between the Early and Late Permian identified in the Cooper Basin.

In contrast, Munson and Ahmad (2012) suggest that sedimentation in the Pedirka Basin continued throughout the Permian period. The initial onset of the Hunter-Bowen Orogeny, at the end of the Early Permian, re-activated pre-existing structural features and caused subsidence in the Poolowanna Trough region to the east of the Pedirka Basin, to which sedimentation shifted during the Triassic, resulting in the Simpson Basin sequence of sediments (Figure 2.11). Sedimentation in the Pedirka Basin region ceased altogether during the Middle Triassic as a consequence of compression associated with the Hunter-Bowen Orogeny; this event is also identified (in Menpes et al, 2010 and Menpes, 2012) as a third possibility with respect to cessation of deposition in the Arckaringa Basin.

Since this time, further periods of tectonic quiescence and down-warping have resulted in basinal sedimentation during the Mesozoic (Eromanga Basin) and Palaeogene-Neogene (Lake Eyre Basin). PIRSA (2010) estimates that between 500 m and 1000 m of the Mount Toondina section was removed prior to the deposition of Mesozoic sediments. Compression and uplift events during the early-Cenozoic (approximately 50 Ma) and in the last 15–5 Ma have caused further deformation of Permo-Carboniferous sediments, as well as terminating periods of sedimentation associated with the Mesozoic and Cenozoic respectively (Senior & Habermehl 1980; Toupin et al. 1997, Karlstrom et al. 2013; Questa, 1990). Deformation included re-activation of pre-existing faults as well as associated folding (Figure 2.11). Current intra-plate tectonic activity is interpreted to be a function of compression caused by the continents northward drift and subsequent collision with the Indonesian Archipelago, a regime that commenced approximately 43 million years ago (Sandiford et al., 2009).

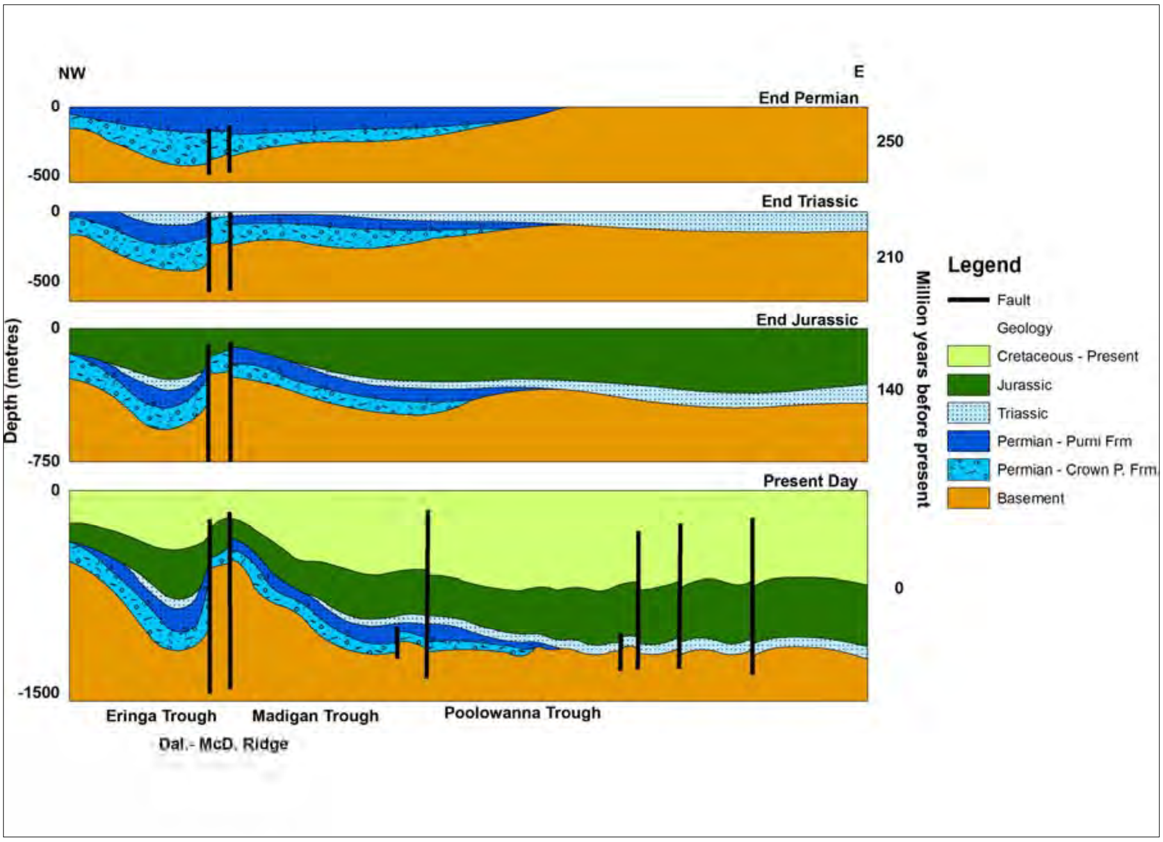

Figure 2.11: Schematic Structural History, Pedirka Basin Region. Modified after Questa (1990)

2.8. OVERVIEW OF COAL DEPOSITS WITHIN THE ARCKARINGA BASIN AND PEDIRKA BASIN

The summary of coal resources within the Arckaringa Basin and Pedirka Basin is primarily derived from the Roadmap for Unconventional Gas in South Australia (DMITRE, 2012).

The Arckaringa Basin contains thick, extensive Permian coal measures comprising a number of discrete deposits, primarily within the upper Mount Toondina Formation (refer to Section 2.1). In total, seven deposits (Wintinna, East Wintinna, Murloocoppie, Westfield, Weedina, Phillipson and Ingomar) of lignite A/sub-bituminous C rank coal have been measured, indicated or inferred within the Arckaringa Basin (Figure 2.12). These deposits are multi-seam deposits with individual seams up to 10 m in thickness and cumulative thicknesses of up to 35 m. In total, the Arckaringa Basin coal resource has been estimated at 20 Gt. Organic-rich marine shales and hydrocarbon shows are also evident within the Arckaringa Basin.

Within the Pedirka Basin, coal seams are a characteristic of the upper member of the Purni Formation. Coal plays associated with the Purni Formation may be found in both the western (Eringa Trough) and eastern (Madigan Trough) depocentres (Figure 2.13). The western depocentre contains up to 1000 m thickness of Permo-Carboniferous sediments at depths of less than 1500 m; in contrast, the eastern depocentre contains a Permo-Carboniferous sedimentary package between 300 and 400 m thick, at depths exceeding 2000 m. Thermogenic coal seam gas plays may be present within the eastern depocentre; in contrast, coals within the western depocentre are too immature for thermogenic gas generation. However, connectivity with the overlying Algebuckina Sandstone may allow for biogenic coal seam gas generation. Despite this potentially important relationship between the Algebuckina Sandstone aquifer and biogenic coal seam gas generation in Permian coals, there is currently only a limited understanding of connectivity between the Arckaringa Basin and Pedirka Basin coal seams and the Algebuckina Sandstone aquifer of the GAB.

Based on palynological studies, the age of the coal units within the upper Mount Toondina Formation of the Arckaringa Basin has been placed as late Sakmarian epoch within the Early Permian (~290 Ma) (Alley, 1995; Menpes, 2012). In contrast Munson and Ahmad (2012) summarise palynological work that suggests the Purni Formation covers a time period inclusive of most of the Permian, with coal seams in the upper member of the Purni Formation more likely to be Guadalupan epoch (270.6 ± 0.7–260.4 ± 0.7 Ma), while coal seams of the lower member of the Purni Formation are likely to be of Sakmarian age. Consequently, although there is some lateral correlation with respect to age between coal seams in the Arckaringa Basin and Pedirka Basin, this correlation is restricted to the older coal seams of the Purni Formation. Information from structural and tectonic studies (refer to Section 1.4.7) suggests that sedimentation associated with the Arckaringa Basin ceased during the Sakmarian with the onset of uplift, while sedimentation within the Pedirka Basin continued for longer, eventually shifting eastward and continuing through the Triassic to form the Simpson Basin succession. Likewise, as discussed in Section 3.2.2, correlation between the host units of the Purni Formation and the Mount Toondina Formation has been inferred by Alexander and Jensen Schmidt (1995); however this is currently restricted to sequences found in the Eringa Trough.

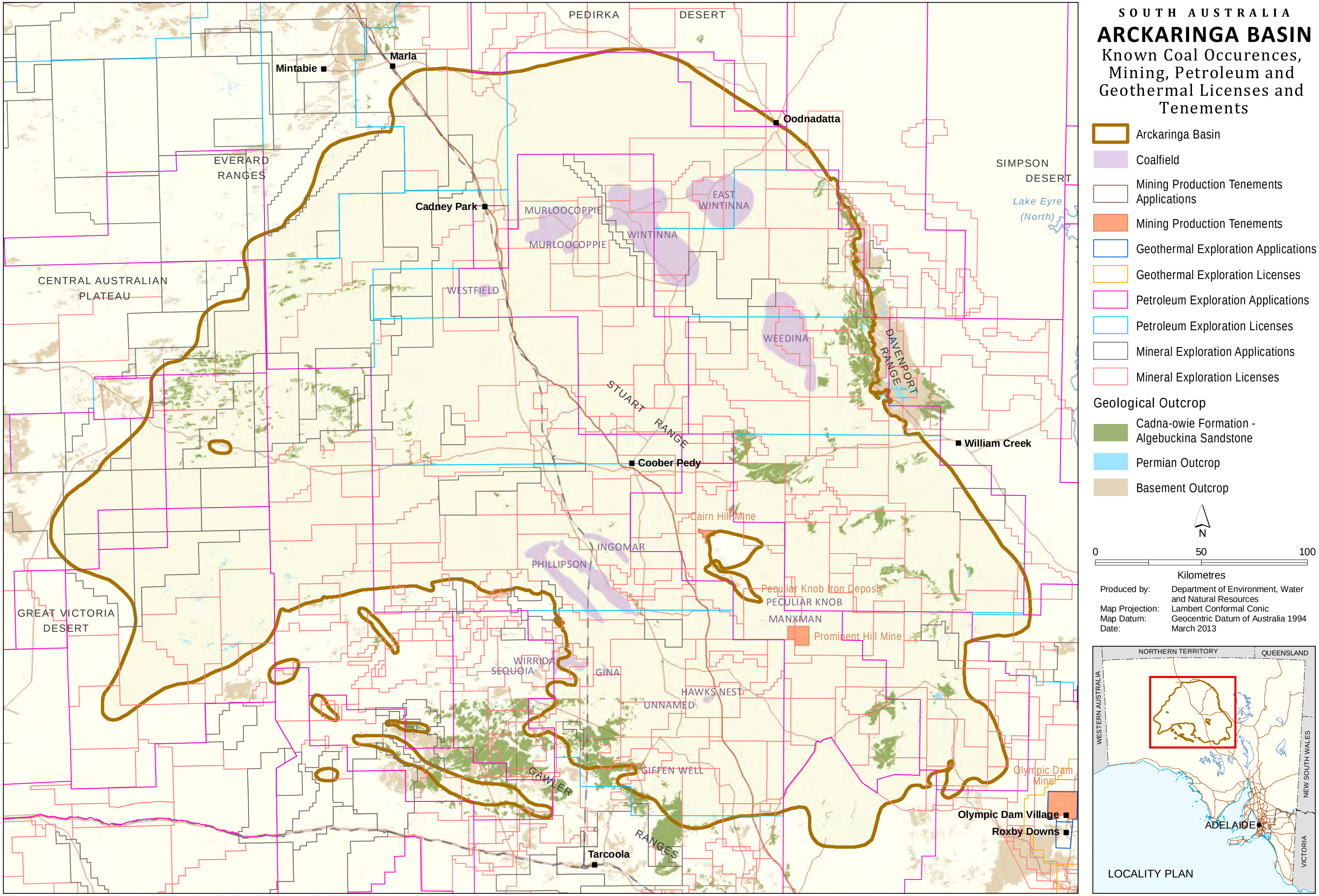

Figure 2.12: Known Coal Occurrences and Exploration Licences, Arckaringa Basin

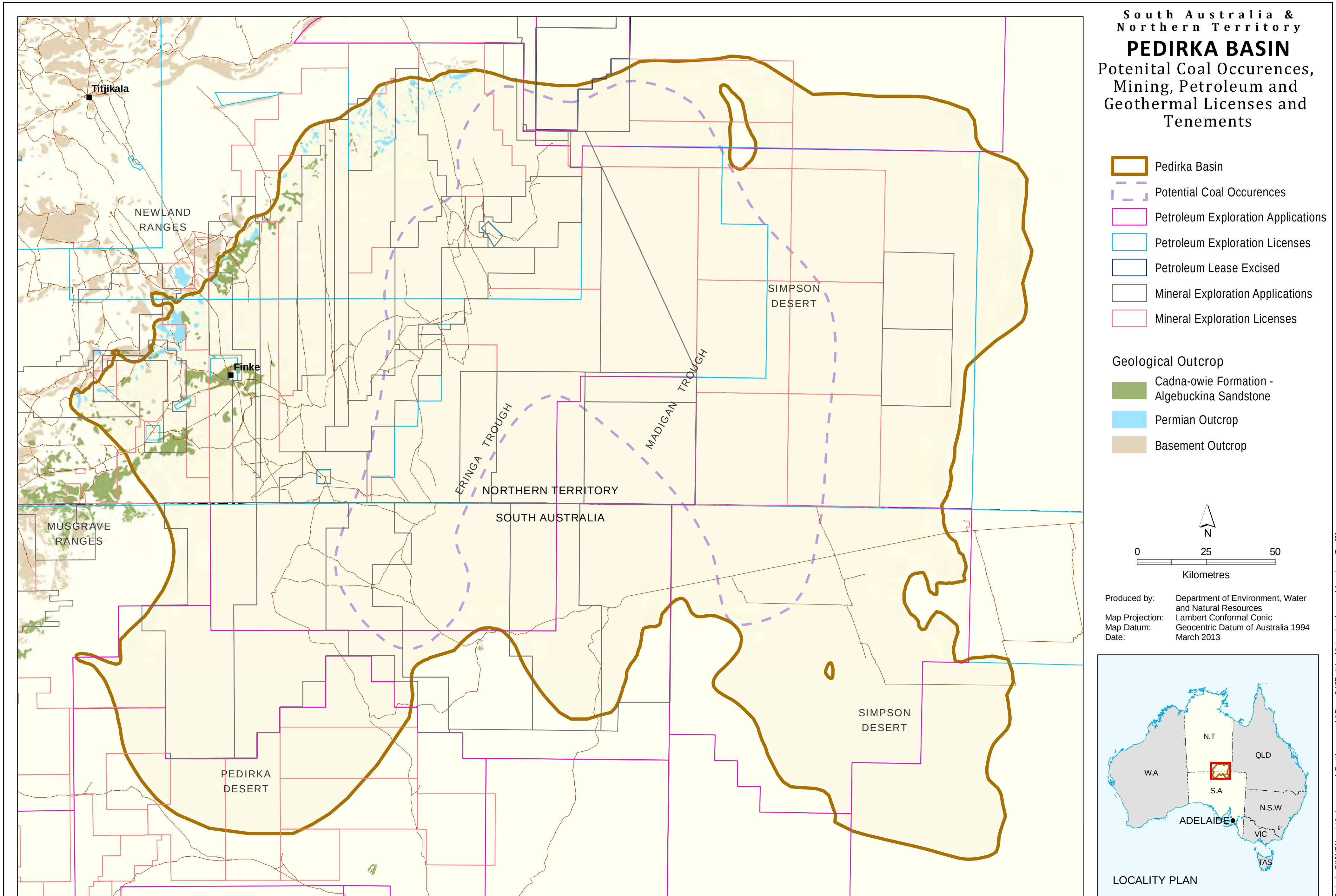

Figure 2.13: Potential Coal Occurrences and Exploration Licences, Pedirka Basin

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2.9. CURRENT EXPLORATION AND DEVELOPMENT ACTIVITY

2.9.1. ARCKARINGA BASIN

Currently joint venture partners, Altona Energy and China National Offshore Oil Corporation (CNOOC) New Energy Investment Co. Ltd are investigating the feasibility of mining part of the Wintinna coal deposit (Arckaringa Coalfield) to supply coal for a coal-to-liquids plant to produce liquid fuels and a co-generation power plant. Approximately 2500 Mt are estimated to be contained within the deposit. In addition, the joint venture partners also have exploration licences in the nearby Murloocoppie and Westfield coal fields.

WPG Resources Ltd has recently presented plans to mine the sub-bituminous black coal deposit associated with the Penrhyn Trough within the southern Arckaringa Basin. The current measured coal resource is estimated at 185.4 Mt, with a total coal resource currently estimated at 352.4 Mt. An additional 200–300 Mt is currently targeted in future exploration. Development of this coal resource is expected to provide fuel for an energy station that accompanies an iron ore development project located approximately 100 kms to the south east.

With respect to CSG exploration, Linc Energy currently holds petroleum exploration licences (PELs) covering the majority of the Arckaringa Basin (Linc Energy, 2013). Linc Energy is assessing coal deposits for in-situ gasification and CGS prospectivity. In addition, Linc Energy is also investigating the Arckaringa Basin for conventional oil and gas, shale oil and shale gas plays.

2.9.2. PEDIRKA BASIN

A number of companies currently hold exploration interests within the Pedirka Basin.

Central Petroleum Ltd and its wholly-owned subsidiary Merlin Energy Pty Ltd are assessing the Pedirka Basin for conventional hydrocarbon as well as unconventional CSG. The company currently holds exploration licences, or exploration licence applications, for areas covering the majority of the Pedirka Basin in the Northern Territory and South Australia. Recently, Central Petroleum entered into a $150M joint venture agreement with Santos Ltd to explore, and potentially develop, up to 13 areas within the Pedirka Basin and neighbouring Amadeus Basin over the next three years (Santos, 2012).

In the western portion of the Pedirka Basin in the Northern Territory, Tri-Star Petroleum are acquiring and re-analysing existing seismic, water well and other geological and geophysical data to identify shallow coal resources. They have initiated a drilling program to investigate the thickness of Purni coal measures along the western margin of the Pedirka Basin. Preliminary drilling identified an ironstone deposit, located between the De Souza Formation and Crown Point Formation, which is believed to be contemporaneous with the Purni Formation (Love, S. and Butler, J 2010). This formation is being investigated as a prospective iron ore deposit alongside the primary coal target.

2.10. INDUSTRY ENGAGEMENT

The project team has taken a proactive approach to engaging with industry in order to maximise the available information considered in assessing the groundwater resources in these two basins.

A communication strategy was put in place to gather information on companies that have an interest in the two basins in order to communicate the project scope and objectives. Data sharing and future work programs were discussed, which may lead to partnered drilling, groundwater sampling, aquifer testing and seismic programs.

These companies included:

- Altona Energy (Arckaringa Energy Pty Ltd) – Arckaringa Project: Joint venture with CNOOC New Energy Investment Co. Ltd
- Linc Energy
- OZ Minerals (Prominent Hill mine water supply)

The following companies will be approached during Stage 2 of the project:

- Central Petroleum Ltd
- Santos Ltd
- Tri-Star Petroleum Company
- WPG Resources

3. ARCKARINGA BASIN

The Arckaringa Basin is described by Hibburt (1995) as an intra-cratonic, sedimentary basin comprised of Carboniferous to Permian-aged rocks, the majority of which is sub-cropping. Thick depocentres of more than 1000m are associated with north-west lineament structures along certain basin margins (Hibburt, 1995).The basin comprises two main depocentres, the Boorthanna Trough in the east, and the southern Arckaringa troughs (West, Phillipson, Penrhyn and Wallira) in the south, separated by shallow basement with a thin veneer of Permian sediments (Menpes, 2012). There is very limited outcrop of Permian sediment within the Arckaringa Basin; the Permian formations are largely obscured by overlying Mesozoic sediments associated with the Great Artesian Basin and Palaeocene to Holocene sediments associated with the current–day Lake Eyre Basin.

3.1. HYDROSTRATIGRAPHY

There are three main formations within the Arckaringa Basin: the Mount Toondina, Stuart Range and Boorthanna Formations. A summary of hydrostratigraphic and hydrogeological properties is provided in Table 3.1.

3.1.1. MOUNT TOONDINA FORMATION

The Mount Toondina Formation was defined by Townsend and Ludbrook (1975) as comprising an upper section of grey carbonaceous shales, coals and interbedded grey sandstones, siltstones and sandy shales, and a less carbonaceous and slightly sandier lower section. The depositional environment was interpreted to have been non-marine lagoons and swamps with intermittent deposition of fluvial sands.

Three deep petroleum wells were drilled in 1986–87, Arkeeta 1 in the Phillipson Trough, and Birribiana 1 and Hanns Knob 1 in the Boorthanna Trough (Figure 3.1). These wells provide valuable information for comparing the Mount Toondina Formation in the Phillipson Trough with that intersected in the Boorthanna Trough.

The Mount Toondina Formation in Arkeeta 1 was divided into upper and lower units based on the presence of carbonaceous sediments in the upper unit including thin coals, and the absence of coals and general decrease in other carbonaceous material in the lower unit. The Upper Mount Toondina Formation in Arkeeta 1 is described as interbedded siltstone, shale, clay and thin coal seams (<3 m) with minor sandstone (very fine to coarse grained, with grain size decreasing with depth). The Lower Mount Toondina Formation in Arkeeta 1 is described as interbedded clay and siltstone with minor very fine to fine grained sandstone. The Arkeeta 1 gamma-ray log indicates the Mount Toondina Formation comprises an overall coarsening–upward succession with coals at the top, consistent with deposition in a prograding delta system (Menpes, 2012). A recent palynological study indicates that the base of the coarsening upward succession was deposited in lacustrine-brackish conditions whilst the remainder of the succession is described as non-marine (Menpes (DMITRE) 2013, pers. comm. March).

Coals were also intersected in the upper part of the Mount Toondina Formation in Birribiana 1 and Hanns Knob 1. The Mount Toondina Formation is described in both the Birribiana 1 and Hanns Knob 1 well completion reports as a massive deltaic unit of interbedded siltstone, sandstone and coal. The Lower Mount Toondina Formation in Hanns Knob 1 and Birribiana 1 is much sandier and generally coarser grained than that described in Arkeeta 1, suggesting that the wells in the Boorthanna Trough are located closer to the sediment source.

Menpes (2012) also sub-divided the Mount Toondina Formation into two sub-units. The Upper Mount Toondina Formation is described as a fluvio-lacustrine succession with intermittent coal swamp development, and includes the coal deposits described in Section 2.8. The Lower Mount Toondina Formation encompasses retrograde sedimentation above the maximum flooding surface (mfs) associated with the marine phase of Permian sedimentation. In the Boorthanna Trough, seismic reflectors within the Lower Mount Toondina Formation form clinoforms downlapping on to the mfs, indicating progradation, whilst reflectors within the Upper Mount Toondina Formation appear to be aggradational (Menpes (DMITRE) 2013, pers. comm. March). Clinoforms suggest an eastern sediment source area.

Coal seams within the Mount Toondina Formation have been described as well jointed (Coffey and Partners, 1983, Dames and Moore, 1986).

Table 3.1: Summary of Formation properties within the Arckaringa Basin

Formation	Deposition Age	Maximum Recorded Thickness	Lithology	Hydrogeology
Mount Toondina Formation	295.0-290.1 Ma	Total sediment package up to 1,300m thick	Grey carbonaceous shales, coals and interbedded grey sandstones, siltstones and sandy shales	Sandstone and coal units: potential aquifers. Clay and shale layers, particularly of the Lower Mount Toondina Formation: potential aquitards.
Stuart Range Formation	298.9-290.1 Ma		Homogenous marine shale with minor siltstone and sandstone	Potential regional scale aquitard
Boorthanna Formation	298.9-295.0 Ma		Predominantly sandstone and conglomerate, with sandy clays and boulder to pebble clays (diamictites)	Sandstone and conglomerate layers: potential aquifers. Shale, siltstone and diamictite layers: potential aquitards

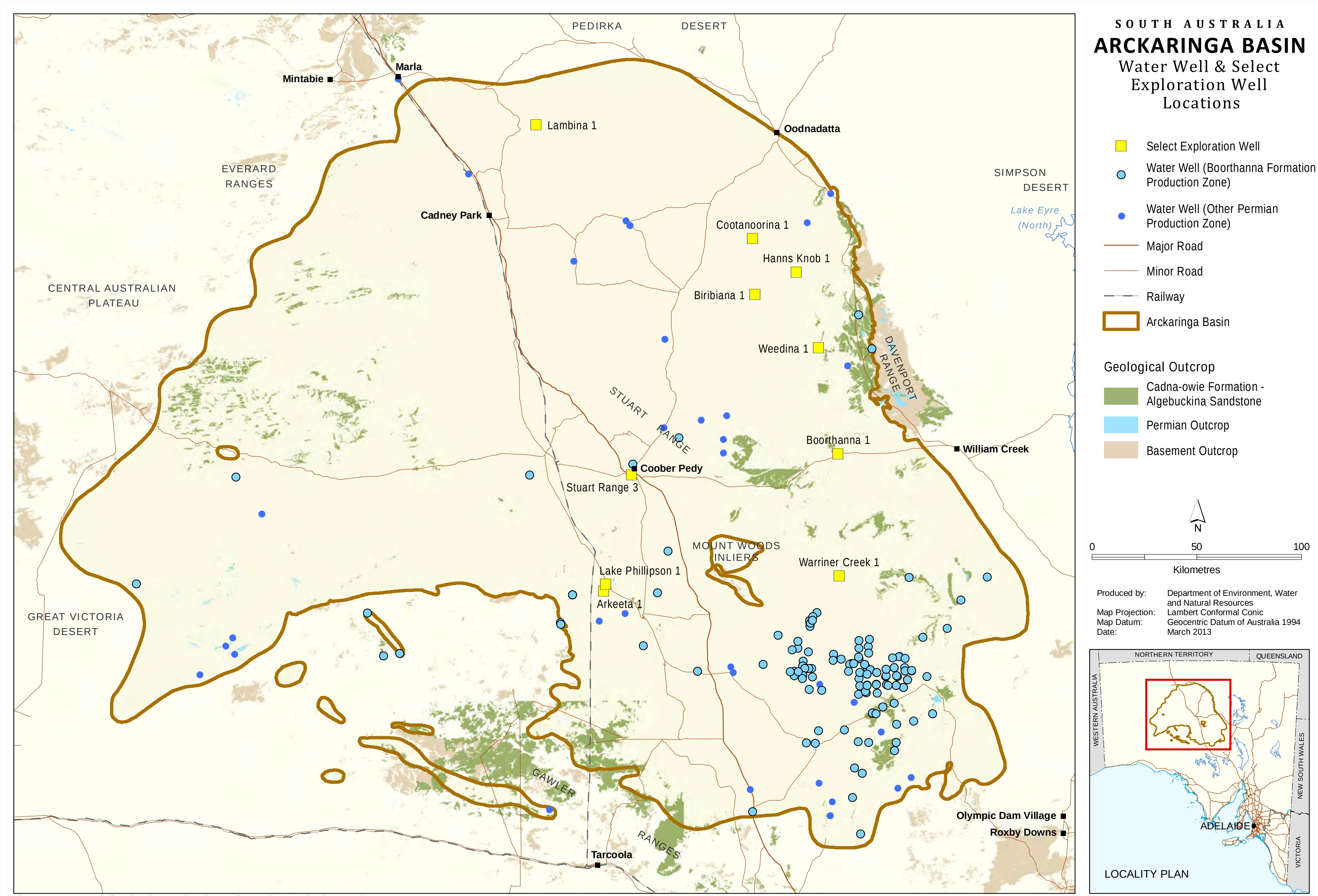

Figure 3.1: Water Well and Select Exploration Well Locations, Arckaringa Basin

3.1.2. STUART RANGE FORMATION

Ludbrook (1967) proposed the name Stuart Range Beds for the partly marine mudstones and siltstones between the basal glacial unit and the Mount Toondina Beds (now Mount Toondina Formation), using Lake Phillipson 1 in the Phillipson Trough and Stuart Range 3 as reference sections. In Lake Phillipson 1, the Stuart Range Beds were described as blue-grey mudstones with foraminifera overlain by a thick succession of sandstones and siltstones. In Stuart Range 3, the Stuart Range Beds were described as containing an abundant and persistent fauna of foraminifera with rare molluscs, ostracodes and vertebrate remains. In 1975, Townsend and Ludbrook formally named the Stuart Range Formation and determined that it was better represented in Cootanoorina 1, comprising a shale unit, greenish grey when wet and pale grey when dry. High concentrations of alginite, the dominant form being a small tasmanite, have been described in Stuart Range Formation (Cook, 1981).

Menpes (2012) and Menpes et al. (2010) undertook a sequence stratigraphic analysis of the Arckaringa Basin focused on understanding the distribution of the organic rich marine shales of the Stuart Range Formation. This work identified a mfs that chronostratigraphically represents the top of the Stuart Range Formation at the base of the prograding Mount Toondina delta succession. A prominent corresponding gamma ray peak was identified in the Weedina 1, Hanns Knob 1, Birribianna 1, Boorthanna 1 and Arkeeta 1 wells, while down–lapping clinoforms present in seismic profiles within the overlying Mount Toondina Formation are representative of prograding delta sediments and highlights the flattened seismic lines characteristic of the mfs. The organic rich shales of the Stuart Range Formation were determined to have been deposited during a marine transgressive phase, with the thickest successions present in the deepest parts of the troughs. The mfs was therefore considered a reasonable marker for the top of the Stuart Range Formation.

A wireline log correlation across the basin (Figure 3.2, after Menpes et al., 2012) highlights the difference between the chronostratigraphic mfs, and the highly variable lithological picks for the top of the Stuart Range Formation from well completion reports.

The Stuart Range Formation underlies the Mount Toondina Formation, with a conformable to disconformable relationship between the two and consists of homogenous marine shale with minor siltstone and sandstone (Barnes and Pitt, 1977; Hibburt, 1995; Wopfner et al., 1970). Menpes et al. (2010) point out that palynological and Rock-Evalorganic geochemistry data indicate lacustrine to brackish-restricted marine environments, with periods of anoxic bottom–water conditions. An analogy with the present-day Baltic Sea is drawn as a likely depositional environment, where high volume fresh-water runoff into a restricted seaway results in density stratification of the water column.

Shearer (1994) notes that the Stuart Range Formation is largely restricted to the areas south of the “Marla Overthrust Zone” suggesting that this may be influenced by different geological interpretation of drill hole cuttings. Consequently in some contexts the identification of this formation during logging may be difficult.

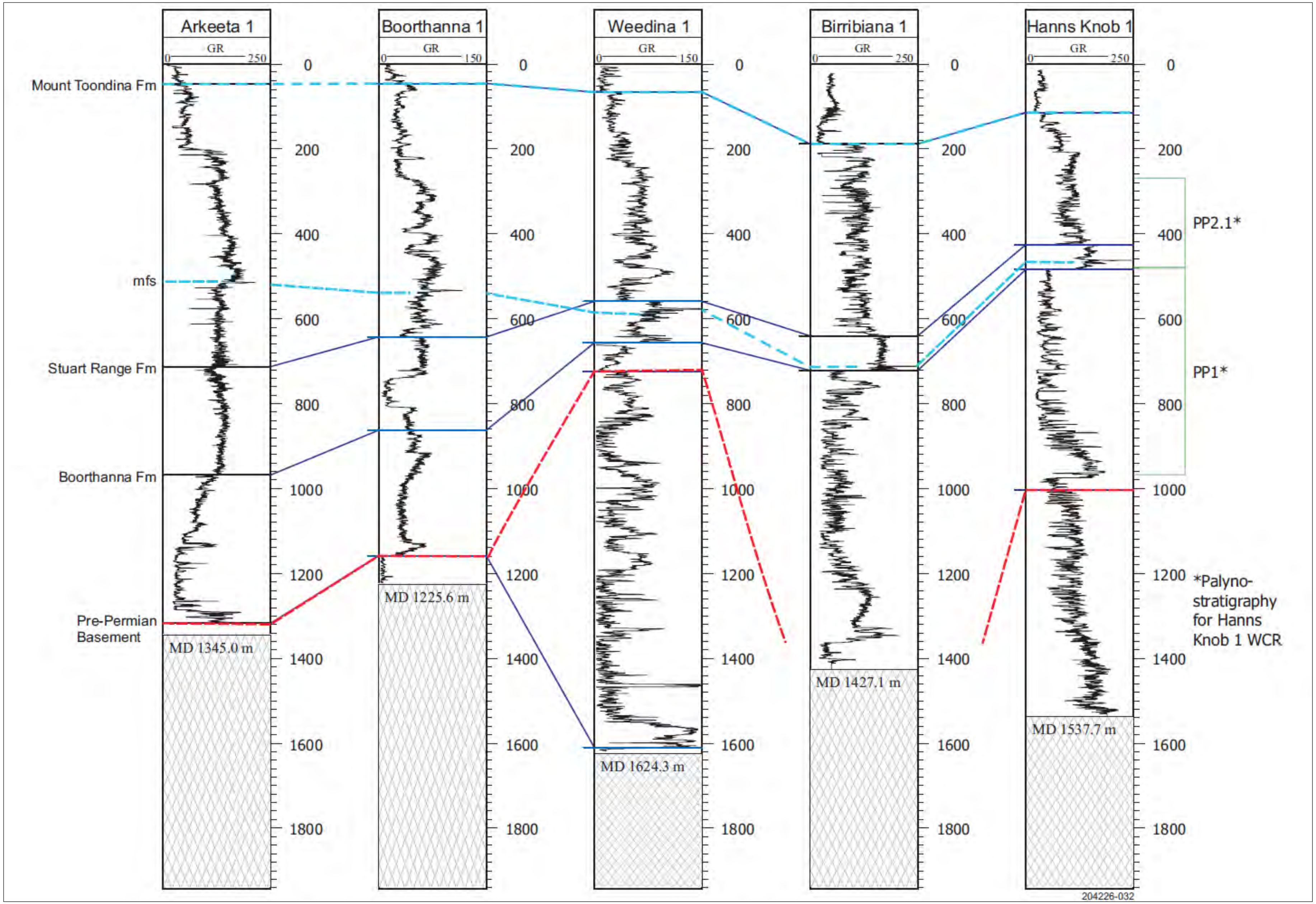

Figure 3.2: Wireline Log Correlation, Arckaringa Basin (after Menpes et al., 2012)

3.1.3. BOORTHANNA FORMATION

The Boorthanna Formation was defined by Townsend and Ludbrook (1975) using Boorthanna 1 as the subsurface type section, where it consists predominantly of sandstones and conglomerates but also includes sandy clays and boulder to pebble clays (diamictites). Townsend and Ludbrook (1975) noted that erosion of basement highs produced basal conglomerates that grade out to pebbly sandstones and homogenous sandstones overlying the diamictite in depressions.

The Boorthanna Formation consists of two units: the upper unit consists of interbedded marine clastics, with grain sizes ranging from silt to boulders, while the lower unit is comprised of a glaciogene sandy to bouldery claystone diamictite with shale and carbonate intercalations. Occurrences of the lower unit appear restricted to deeper parts of the basin, including the Wallira, West, Penrhyn and Phillipson Troughs and the southern half of the Boorthanna Trough. Boorthanna Formation sediments are described by Kellett et al. (1999) as weakly indurated, with localised calcareous, ferruginous and pyrite cementation.

Over 500 m of Boorthanna Formation was intersected in Hanns Knob 1 in the Boorthanna Trough. The sediments were described as being predominantly glacial in origin, comprising diamictites with minor siltstones and sandstones representing periods of varying glacial activity. The diamictites consist of a silt to very fine sand matrix with abundant coarser pebble to boulder size fragments. The siltstones are arenaceous and sucrosic in appearance. The sandstone shows a number of distinct facies indicative of glacial activity and proximity to the glacial outwash zone.

The contact between the Boorthanna Formation and the overlying Stuart Range Formation is described as typically conformable and occasionally disconformable. Variations to this are notable in the Boorthanna Trough where the contact between the two formations is unconformable, while near the south–western boundary of the basin, the two formations are inter-fingered (Hibburt, 1995). However, Menpes (2012) and Menpes et al. (2012) has identified a sequence boundary that cuts down into the Boorthanna Formation in the Boorthanna Trough, but appears to have been an exposure surface with marine sediments overlying marine sediments and minimal loss of section in the Phillipson Trough. The Boorthanna Formation unconformably overlies Cambrian and Pre-Cambrian Basement rocks.

Alluvial and colluvial sediments consisting of coarse sand and gravel were interpreted as Permian palaeovalleys cutting down into Proterozoic basement underlying the Boorthanna Formation in the vicinity of the Mount Woods Inlier (Belperio, 2005). The headwaters of the palaeovalleys appear to occur on the flanks of the Mount Woods Inlier. The palaeochannel deposits unconformably overlie Proterozoic basement and reported palynological dates of Early Permian (Sakmarian) with either little or no marine influence.

Menpes et al. (2010) and Menpes (2012) also interpret the deep troughs of the Arckaringa Basin as a palaeovalleys scoured by the Late Carboniferous–Early Permian Gondwana glaciation. The location and orientation of the palaeovalleys appears to be controlled, at least in part, by structural grain and rock types in the underlying basement. With respect to palynological interpretation, the Boorthanna Formation and lower Stuart Range Formation are assigned to zone PP1 (Asselian), and the upper part of the Stuart Range Formation and the Mount Toondina Formation are zone PP2 (Sakmarian) (Menpes et al. 2010; Price et al., 1985).

The stratigraphic relationship between each of the formations described is provided in Figure 3.3.

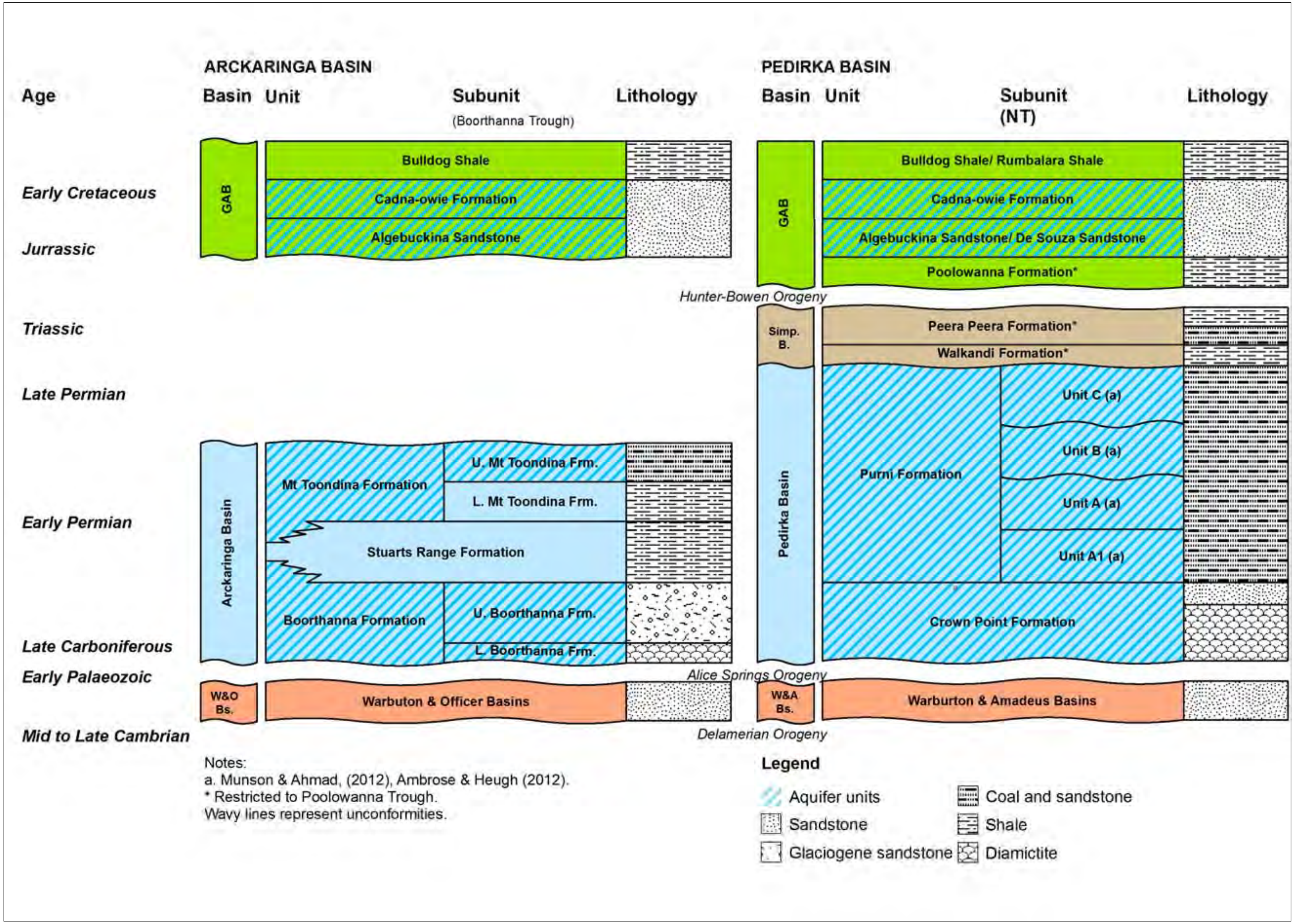

Figure 3.3: Simplified Cretaceous to Cambrian Stratigraphy, Arckaringa Basin and Pedirka Basin

3.2. HYDROGEOLOGY

The following provides a summary of pertinent hydrogeological information as found in publically available literature concerning the Arckaringa Basin. A summary of these key information resources are provided in Appendix A (Summary of critical information sources). Information has been discriminated based on hydrostratigraphy. In addition, relevant findings pertaining to the hydrogeology and basin architecture of the Arckaringa Basin are encapsulated in Table 3.7 in Section 3.3.5 of this report.

3.2.1. DESKTOP REVIEW

3.2.1.1. Mount Toondina Formation (P-t)

Sandstone units in the Mount Toondina Formation encountered during petroleum exploration work have been described as having porosities from as low as 4% (Wopfner and Allchurch, 1967) to as high as 36.6% (Linc Energy, 2010b), while shale and siltstone units have been interpreted as potential seals for petroleum (Cotton et al., 2006; Tucker, 1997). Six packer permeability tests conducted on coal seam and coal seam interbeds in the Wintinna Coal Field by Coffey and Partners (1983) found coal seams to be of low to moderate hydraulic conductivity, while interbedded sediments were found to have a very low to low hydraulic conductivity; the greater permeability in the coal seams was attributed to observed fracturing (fissility). Tucker (1997) notes that feldspar within sandstone units within the Mount Toondina Formation can appear to be partially dissolved, indicating the development of secondary porosity.

Hydrogeological investigations conducted by Australian Groundwater Consultants (AGC) (1975) identified three discrete aquifers within the Upper Mount Toondina Formation in the Lake Phillipson region. These were called the P (Permian sediments), S (S coal seam) and T (T coal seam) aquifers. Thicknesses of the coal seams ranged between 5–10 m and 2–8 m respectively. The P aquifer is composed of sandy clay to silty sand with increasing sand content and grainsize with depth; thickness of the P aquifer ranged between 0.6–5.3 m. The specific yield for these aquifers were estimated at 1%, which lead to estimates of 8×10^4 m^3 of groundwater held in storage in the P aquifer and 1.3×10^4 m^3 held in storage for each of the S and T aquifers. Although AGC (1975) considered it impossible to determine the hydraulic gradient for the Permian aquifers, they predicted flow-conditions to be “possibly stagnant”.

AGC (1975) described water quality from the bores installed as ranging from saline to ultra-saline (73198–155065 mg/L TDS), extremely hard (13,862-24,125 mg/L $CaCO_3$) and slightly acidic (pH 6.5–7.0), while Coffey and Partners (1983) described groundwater from the Mount Toondina Formation as saline. Hydrochemistry data indicates groundwater from the Mount Toondina Formation aquifers in the Lake Phillipson region are Cl and Na + K dominant, with relatively high Mg and SO_4; although salinities were generally much higher, this chemical characterisation was found to be similar to groundwater from the overlying GAB aquifer (AGC, 1975).

Reported hydrogeological properties are provided in Tables 3.2 and 3.3.

3.2.1.2. Stuart Range Formation (P-s)

No aquifers of any significance are known to occur in the Stuart Range Formation. Read (1984) noted that Stuart Range Formation sediments in the vicinity of the Stuart Highway between Gosses and Mirikata were saturated but did not contain aquifers.

The limited scope and spatial extent of many studies pertaining to the hydrogeology of the Arckaringa Basin has resulted in what appear to be at times contradictory results or interpretations. This is particularly evident with respect to the hydrogeological properties of the Stuart Range Formation. For example, in the south-east region of the Arckaringa Basin, Kellett et al. (1999) and Belperio (2005) described the Stuart Range Formation as a leaky aquitard that separates the GAB and Boorthanna Formation aquifers, while SKM (2009) and Aquaterra (2009) suggest that the Stuart Range Formation potentially provides sufficient leakage to enable drawdown stability in groundwater production wells located in the underlying Boorthanna Formation. Conversely, Aquaterra REM (2005a) and Sinclair Knight Merz (SKM) (2009) used head differences between groundwater in the Boorthanna Formation and the overlying watertable to suggest that the Stuart Range Formation acts as an effective barrier to downward leakage.

In addition SKM (2009) and Lyons et al. (2010) used data from short-term aquifer-testing to highlight the limited connectivity between Boorthanna and unconfined GAB aquifers within a study area associated with the Prominent Hill Mining operation. It should be noted that a decline in head was observed in the GAB aquifer from data obtained from these aquifer tests, however the change observed was very small; the detection of even a small changes as the one presented suggests that data from longer term aquifer stress tests is required to more fully understand the degree of interconnectivity between the GAB and Arckaringa aquifers. Reported hydrogeological properties are provided in Tables 3.2 and 3.3.

3.2.1.3. Boorthanna Formation (CP-b)

Most information concerning the hydrogeological characteristics of the Boorthanna Formation is sourced from the south-eastern Arckaringa Basin, where a number of wells have been completed and several studies undertaken (e.g. Kellett et al., 1999; Rogers and Zang, 2006; Belperio, 2005; Howe et al., 2008; Lyons et al., 2010; Enesar, 2006; SKM, 2009). SKM (2009) and Aquaterra REM (2005) refer to this area as the Billa Kalina sub-basin. A summary of conceptual models developed for the hydrogeology of the Billa Kalina sub-basin, including interpretations of recharge and discharge characteristics and flow dynamics is provided in Section 3.3.5.

The shale and siltstone units have been interpreted as a potential seal for petroleum (PIRSA, 2010), while SKM (2009) have described the diamictite facies as a leaky aquitard unit. In contrast, Tucker (1997) suggests that several thick sandstone units in the Boorthanna Formation have relatively high porosity (up to 25%, Table 3.2), while Kellett et al. (1999) states that such sandstone units are capable of producing significant supplies of brackish to moderately saline groundwater in the south-eastern Arckaringa Basin (Kellett et al., 1999). These sandstone units can be separated from each other by the lower-permeability shale and siltstone units (SKM, 2009). Results from a shutdown test conducted at a production bore within the Boorthanna Formation, near the Prominent Hill mining operation, suggested that multiple aquifers with only weak hydraulic connectivity occur within the Boorthanna Formation (SKM, 2009). This supports the notions put forward by Kellett et al. (1999) that variations in groundwater yield are facies dependent; and by SKM (2009) that the Boorthanna Formation is highly-heterogeneous at a local scale. This heterogeneity is reflected in stated lateral hydraulic conductivity figures for the Boorthanna Formation, which varies from 0.02–5 m/d (Table 3.3). Kellett et al. (1999) also suggests that secondary porosity development is important in assessing the unit’s viability as a reliable groundwater supply. Secondary porosity development occurs primarily via fracturing, while primary porosity is described as only providing a minor contribution to overall porosity, due to the weakly indurated nature of the unit.

Applying an infiltration rate of 0.5 mm/y and an unsaturated zone of 45 m Kellett et al. (1999) used a CMB approach to estimate an infiltration time of 4400 years for a combined sequence of Cadna-owie Formation and Boorthanna Formation. In contrast, Aquaterra REM (2005b) used a constant recharge rate of 0.18 mm/y for numerical modelling of the Boorthanna Formation in the south-eastern portion of the Arckaringa Basin, stating that this value was within the range of long–term rainfall recharge (0.16 ± 0.08 mm/y) reported by Love et al. (2000) for the south-western GAB.

Hydraulic gradients for the Boorthanna Formation within the south-eastern corner of the Arckaringa Basin were calculated by Kellett et al. (1999) at between 1:300 and 1:1100, with a modal value of 1:600, where unconfined aquifer conditions exist. According to Kellett et al. (1999), these gradients are slightly lower compared to the overlying GAB aquifer (modal value of 1:700). Howe et al. (2008) suggests transmissivity to be highly variable (<5-

180 m^2/d, Table 3.3); a result of structurally controlled variations in formation thickness. An average groundwater velocity in the Boorthanna Formation aquifer within the south-eastern corner of the Arckaringa Basin was calculated by Kellett et al. (1999) at 1.4 m/y. Residence times for groundwater in the Boorthanna Formation aquifer in the vicinity of the Billa Kalina sub-basin may reach up to 200000 years (Kellett et al., 1999).

Aquaterra REM (2005a), Howe et al. (2008), SKM (2009) and Lyons et al. (2010) all used hydrochemistry to differentiate between groundwater sources and groundwater systems pertaining to Boorthanna Formation aquifers and others located within the Billa Kalina sub-basin. Aquaterra REM (2005a) state that GAB-related groundwater east of the Billa Kalina Fault and Arckaringa Basin, and GAB-related water west of the Billa Kalina Fault, can be differentiated via major ion concentration signatures. Aquaterra REM (2005a) also report that some differentiation can also be made between groundwater north of the Boorthanna Fault and groundwater to the south, indicating limited interaction. However, Aquaterra REM (2005a) and SKM (2009) conclude that GAB and Arckaringa Basin groundwater west of the Billa Kalina Fault cannot be differentiated based on either major ion hydrochemistry or salinity. In general, groundwater from the Boorthanna Formation aquifers can be described as having a Na/Cl dominated ionic composition. Howe et al. (2008), SKM (2009) and Lyons et al. (2010) used stable isotope and ^{36}Cl data to differentiate between Arckaringa Basin sourced groundwater from the Billa Kalina sub-basin and groundwater from the western GAB. Chloride-36 data were also used to indicate that groundwater from the Boorthanna Formation aquifer in the Billa Kalina sub-basin was younger than that from the western GAB. Finally, SKM (2009) suggested that the decrease in salinity down-gradient of flow lines in the vicinity of the south-eastern Arckaringa Basin may either indicate multiple groundwater recharge zones or alternatively be a function of palaeoclimate variation.

Kellett et al. (1999) observed that yields from the Boorthanna Formation aquifer within the south-east portion of the Arckaringa Basin varied between <0.1 L/s to 5 L/s; groundwater yields are generally described as gradually increasing down hydraulic gradient (west to east), however facies variations and well depth provide variations to this trend. Working in a comparable area, Rogers and Zang (2006) briefly described useful supplies of groundwater (100–140 kL/d; 7000–25000 mg/L) in the northern KINGOONYA 1:250000 map sheet; fresher groundwater supplies were described to be in the vicinity of recharge areas (swamps). Additionally, groundwater from a number of interpreted gravelly to sandy palaeochannels at the base of the Boorthanna Formation and in the vicinity of the Mount Woods Inlier were found to be brackish (between 7000 and 50000 mg/L TDS) and provided yields between 0.4 and 1.1 L/s (Belperio, 2005; Howe et al., 2008). Finally, Hillwood (1965) reported the total salinity of water obtained from a drill stem test in sediments thought to be representative of Boorthanna Formation to be 12300 mg/L.

Table 3.2: Reported porosity and permeability for the Arckaringa Basin

Unit	Reference	Porosity (%)	Effective Porosity (%)	Permeability (cm^2)
Permian	Papalia (1970)	5.5-16[a]		
Mount Toondina Formation	Wopfner and Allchurch (1967)	4-8		
	Allchurch and Wopfner (1967)	8 (sandstone unit)		
	DMITRE (2011a))	6-9 (sandstone units)		
	Linc Energy (2010a)	25.4-33.3[b]		$3.06 \times 10^{-12} – 1.5 \times 10^{-9}$ [c]
	Linc Energy (2010b)	22-36.6[b]		$1.48 \times 10^{-12} – 1.39 \times 10^{-8}$ [c]
Boorthanna Formation	CRAE (1987)	3.6-23[a]	1.9-22.7	
	Tucker (1997)	20-25		$2.96 \times 10^{-9} – 1.97 \times 10^{-8}$
	Kellett et al. (1999)			
	DMITRE (2011a) (undated)	13.5	5	

a) Calculated from density

b) Determined in a laboratory using helium and a porosimeter

c) Determined in a laboratory using a permeameter

Table 3.3: Reported hydrogeological properties for the Arckaringa Basin

Unit (sub–unit)	Reference	Source	Kh (m/d)	Kv (m/d)	Transmissivity (m^2/d)	Storativity	Specific Yield (%)
Upper Mount Toondina Formation (P)	AGC (1975)	Slug Test			38.14 (P)[a]		1
Upper Mount Toondina Formation (T)					22.066 (T)		1
Upper Mount Toondina Formation (S)					0.073–0.34 (S)		1
Upper Mount Toondina Formation (S&T)					15.4–22.5 (S & T)		1
Upper Mount Toondina Formation (P, S&T)		Aquifer Test			24.3 (P, S & T)	$4.5x10^{-3}$	1
Upper Mount Toondina Formation (T)					22.1 (T)	$2x10^{-7}$	1
Upper Mount Toondina Formation (S)					0.4 (S)	$1.3x10^{-6}$	1
Upper Mount Toondina Formation (S&T)					21	$2.6x10^{-5}$	1
Upper Mount Toondina Formation	Coffey and Partners (1983)	Packer test	$0.9\text{-}9x10^{-3}$ (coal seams)				
			$9x10^{-4}\text{-}9x10^{-5}$ (sedimentary interbeds)				
Stuart Range Formation	Howe et al. (2008)	Aquifer tests		$1x10^{-4}$		$1x10^{-5}$	
Boorthanna Formation	Howe et al. (2008)	Aquifer tests	1-5		<5-180	$1x10^{-4}$ $1x10^{-5}$	
	SKM (2009)	Aquifer tests			2-150	$1x10^{-4}$	

a) Results are thought to be affected by slumping of P aquifer and partial blockage of underlying S and T aquifers

b) Aquaterra (2009) state that the use of two layers for the Boorthanna Formation is to allow for spatial variations in hydrogeological properties

c) Low conductivity zone

3.3. NEW KNOWLEDGE

3.3.1. BASIN ARCHITECTURE

The following discussions and interpretations in this section are based upon the architecture and composition of the Arckaringa Basin as currently understood at the time of this report. Work determining the architecture of the Arckaringa Basin is ongoing and subsequent information may alter interpretations of the structure, extent, basin architecture and hydrogeology of the Arckaringa Basin in the future.

3.3.1.1. Seismic and Log Interpretation

To improve our understanding of the regional hydrogeology of the Arckaringa Basin, an extension of the work completed by Menpes (2012) was undertaken to regional map the chronostratigraphic framework of Permian strata and Permian coal measures in the Arckaringa Basin.

Three-dimensional subsurface datasets highlight areas of coal potential and connectivity to associated groundwater resources. In addition, the relationship to younger, overlying and surrounding basins and groundwater systems is also presented. The interpreted basin architecture is based on a logical process of compilation and integration of over 5500 line km of seismic data and 4480 stratigraphic control points (formation top data from wells and a spatial coverage of 1:100000 surface geology). Five surfaces, including fault constraints, have been constructed. These include:

- Base Permian
- Top Boorthanna Formation
- Top Stuart Range Formation
- Top Lower Mount Toondina Formation
- Top Upper Mount Toondina Formation

For each surface the formation extent has been determined, with the base Permian extent providing the absolute extent of the Arckaringa Basin. Additionally, four isopachs are provided; these include:

- Boorthanna Formation
- Stuart Range Formation
- Lower Mount Toondina Formation
- Upper Mount Toondina Formation

The development of the chronostratigraphic framework improves our understanding of basin development and architecture. In particular, knowledge concerning the following basinal and hydrogeological features of the Arckaringa Basin has been advanced:

- The extent and thickness of the major regional hydrostratigraphic units including their spatial relationship and interconnectivity
- The identification of sub-basinal areas or discrete intra-formational aquifer units. Such areas may be formed via basinal subsidence during the deposition stage, channel erosion via alluvial or glacial activity or later stage structural deformation
- The identification of sedimentation heterogeneity. For instance, sand filled palaeochannel features in contact with basin formations; and gradation of sands from basin margins towards the centre of the basin. Similarly, deltaic depositional features highlight the heterogeneous nature of sedimentation within parts of the basin.

Sequence stratigraphic model

Figure 3.4 presents a summary diagram showing the seismic, well, wireline and facies characteristics of the Permian section in the Arckaringa Basin. The sequence stratigraphic model based on this interpretation divides the Permian basin-fill into two sequences:

- Sequence 1: comprises the basal, sandstone-prone glaciogenic facies of the Boorthanna Formation and parts of the Stuart Range Formation. The lower Boorthanna Formation is interpreted as a low-stand deposit. The top of Sequence 1 is the unconformity originally interpreted as the top Stuart Range Formation. The actual top of the formation is shown by the dotted pink horizon higher in the section, but this is a less important surface chronostratigraphically.
- Sequence 2: overlies the older sequence and comprises marginal marine to lacustrine-deltaic facies of the Stuart Range Formation and Mount Toondina Formation. The majority of Sequence 2 comprises a thick, sedimentary cycle, becoming coarse and sandy towards the top of the sequence,, as deltaic facies change upwards into fluvio-lacustrine depositional environments. The thickest and most extensive coals within the basin are formed within the Upper Mount Toondina Formation.

This model largely conforms to that of Menpes (2012), with two notable although minor addendums. First, the top Stuart Range Formation is not identified as consistent with a sequence stratigraphic surface and second, the lower Boorthanna Formation has been assigned to a low-stand deposit. The seismic and wireline examples used in the summary diagram are from the southern region within the Phillipson Trough. The same model can be applied across the region.

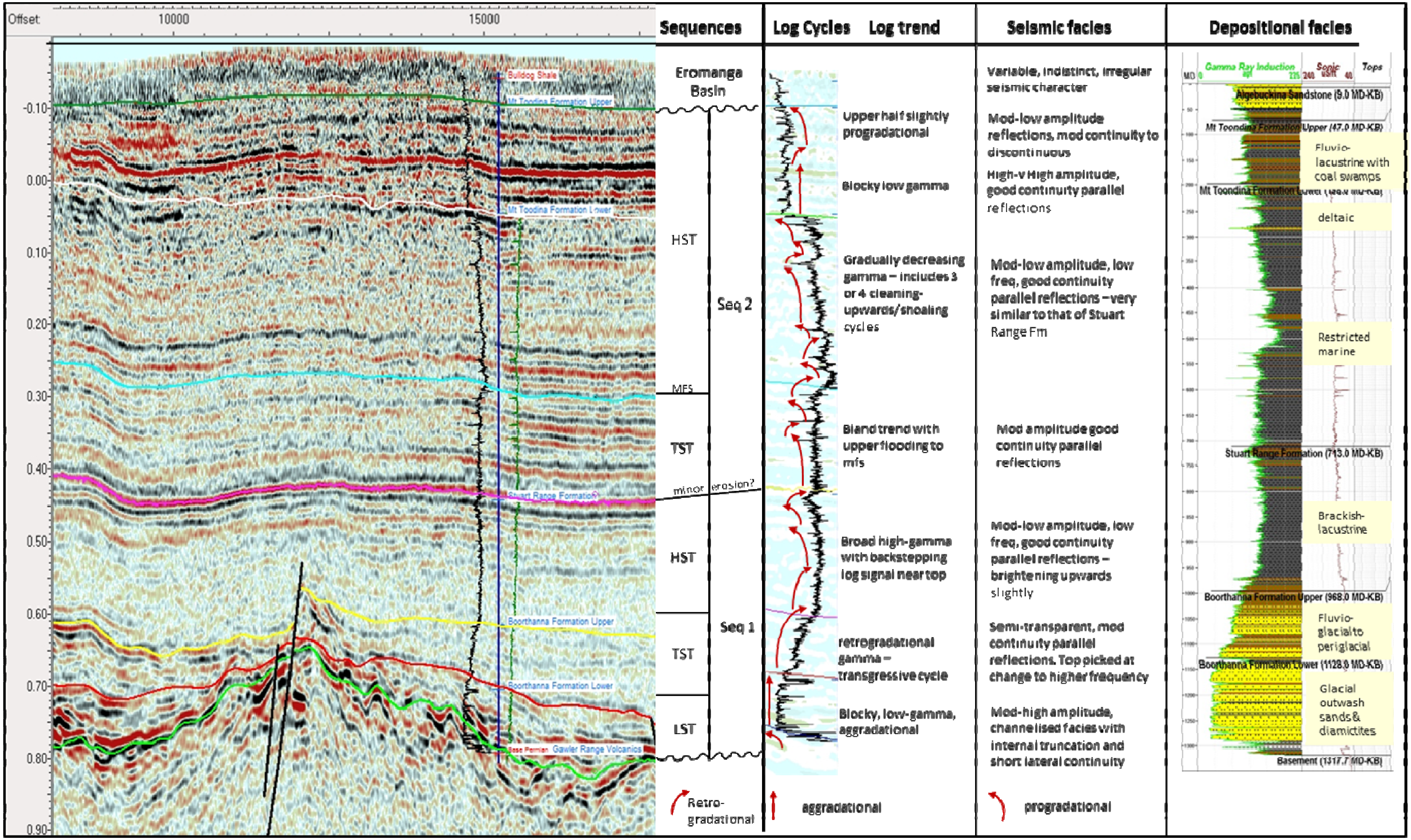

Figure 3.4: Sequence Stratigraphic Model, Arckaringa Basin

(HST: Highstand Systems Trend. TST: Transgressive Systems Tract. LST: Lowstand Systems Tract. MFS: Maximum Flooding Surface)

Key findings

Using this stratigraphic model as a basis, a number of key findings pertaining to the Arckaringa Basin succession and the coal measures contained within the Upper Mount Toondina Formation were made:

- The base of the Permian strata forms a complex, glacially-scoured surface with significant erosional relief (Figures 3.5, 3.7 and 3.8).
- The Early Permian coarse-grained, sandstone-dominated glacial facies of the Boorthanna Formation exhibit clear mappable seismic facies in most areas and their distribution is mostly restricted to the main depocentres. Given observations by Tucker (1997), Kellett et al. (1999) and Aquaterra REM (2005) concerning the groundwater resources inherent in such units within the south–east portion of the Arckaringa Basin, the ability to map these sandstone units within a regional context is considered important.
- As highlighted in Section 3.1.2, the Stuart Range Formation is potentially an important regionally extensive aquitard. Results from this study suggest that the seismic character of the Stuart Range Formation (maximum flooding surface) is variable and interpretation relies on wireline correlation and recognition of downlap geometries. This is possible in the Boorthanna Trough and the Phillipson Trough (Figures 3.5, 3.6, 3.7 and 3.12) but not elsewhere due to lack of preservation and/or poor seismic quality, or lack of seismic data.
- Coals are best developed in the northern half of the Boorthanna Trough, where they have distinct, high-amplitude seismic reflection character. Additionally, there is a strong influence on coal development from old, basement-related faults. Such faults have influenced the amount of accommodation space and the edges of the coal swamps – this is particularly evident in the northern Boorthanna Trough (Figures 3.5, 3.6 and 3.7). Such features suggest a correlation between coal development and syn-depositional subsidence and faulting. Consequently, thick coal seam development may occur in areas where the sedimentary package is generally thickest or modified by syn or post-depositional faulting. There is a regional trend to thinner and less connected coal seam development to the south along the Boorthanna Trough (Figure 3.8). Thin, patchy, local coals have a less distinct seismic character but are mappable throughout most of the Boorthanna Trough. Likewise, in the north-west part of the basin towards the Officer Basin, the Permian section thins regionally. Here, the lower section is preferentially preserved (typically the Boorthanna Formation and lower Stuart Range Formation) (Figures 3.9, 3.10 and Figure 3.11). Much of the younger Permian section is missing through erosion at the base Eromanga Basin unconformity. Permian coals are thin, patchy or absent in this region. The identification of erosion of units overlying the Boorthanna Formation sandstones is potentially significant with respect to identifying areas of recharge to Arckaringa Basin aquifers.
- Major incision and erosion is evident at the base of the Eromanga Basin regional unconformity, particularly within the northern and north-western parts of the basin. The large channels incised into the Permian succession are filled with chaotic, semi-transparent seismic facies identical to that of the Algebuckina Sandstone and are therefore likely to be sand filled (Figure 3.9). This has important implications with respect to inter-aquifer connectivity.
- There is clear seismic evidence of gentle tilting, low angle truncation and erosion of Upper Mount Toondina Formation coals below the base Mesozoic unconformity. As part of this process, coals are absent or thin in the far northern and north-western parts of the basin (Figures 3.9, 3.10 and Figure 3.11). In the south, coals are only preserved within the main troughs (e.g. Phillipson Trough). The identification of erosion of units overlying the Boorthanna Formation sandstones is potentially significant with respect to identifying areas of recharge to Arckaringa Basin aquifers.
- The top of the Lower Mount Toondina Formation has been interpreted at the base of the main, highly reflective coal-bearing interval and this interpretation has been calibrated by wire-line and core analysis. As the Lower Mount Toondina Formation has similar sedimentological characteristics to the underlying Stuart Range

Formation and therefore potentially similar hydrogeological characteristics, the identification and mappability of the Lower Mount Toondina Formation is important with respect to identifying confining layers to underlying aquifer units.

- The main regions of coal accumulation are outside of the strongly deltaic-influenced parts of the Mount Toondina Formation. The deltaic areas have distinct clinoform seismic geometries and are potentially indicative of a heterogeneous distribution of sediment type with respect to aquifer development within the Mount Toondina Formation, via syn-depositional stream channel avulsion and delta lobe switching (Koltermann and Gorelick, 1996).

Seismic interpretation examples

The chronostratigraphic characteristics of the central Boorthanna Trough are depicted using seismic interpretation (Figure 3.5). The high amplitude, parallel, good–continuity seismic reflections correlate to coals in the Upper Mount Toondina Formation. Also note the scoured regional unconformity at the base of the Permian section.

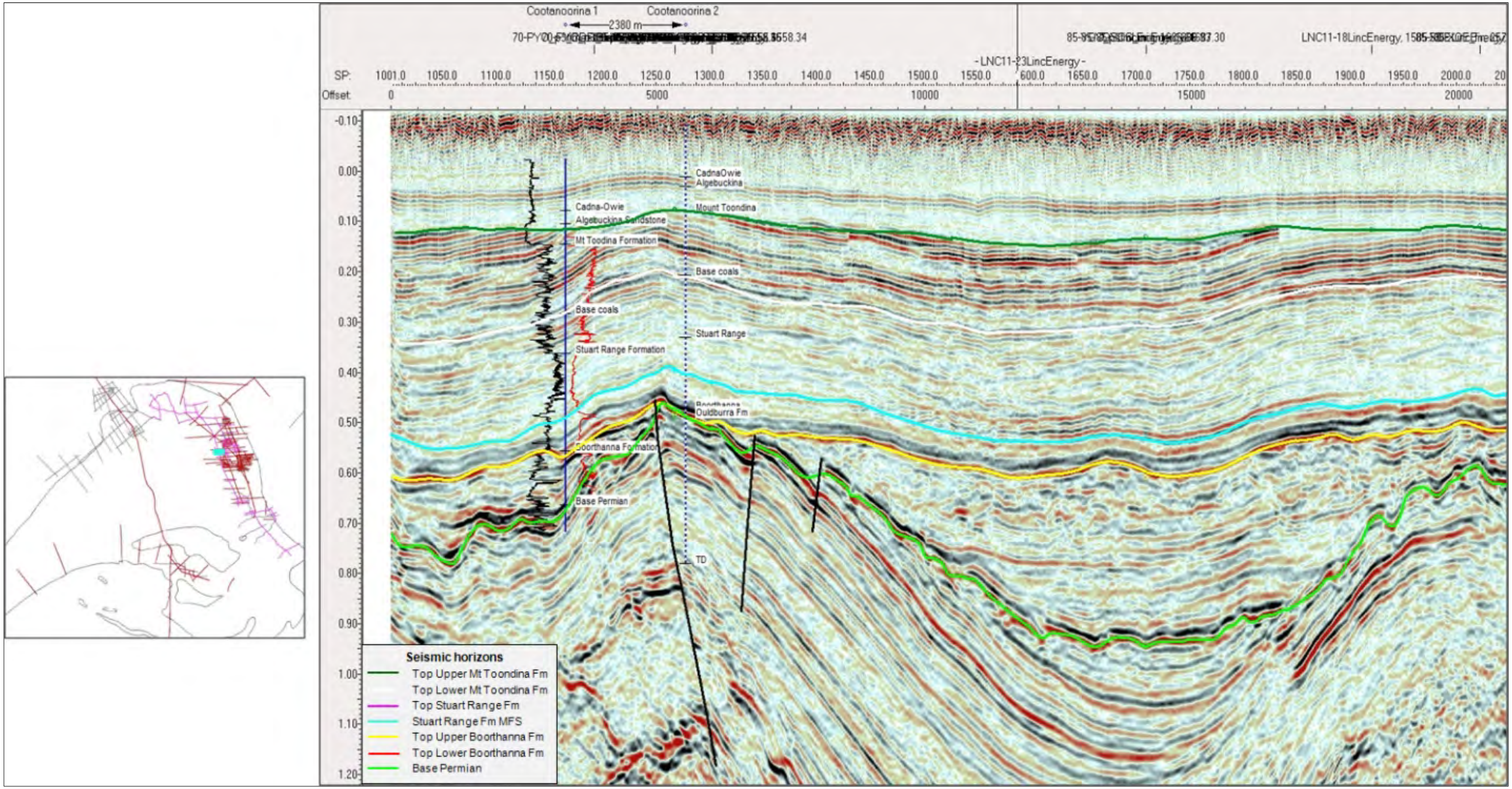

Figure 3.5: Central Boorthanna Trough

The seismic strike line image shown below in Figure 3.6 provides an example of sequence stratigraphy from the west-central Boorthanna Trough. Minor faulting with small throws within the Mount Toondina Formation is evident.

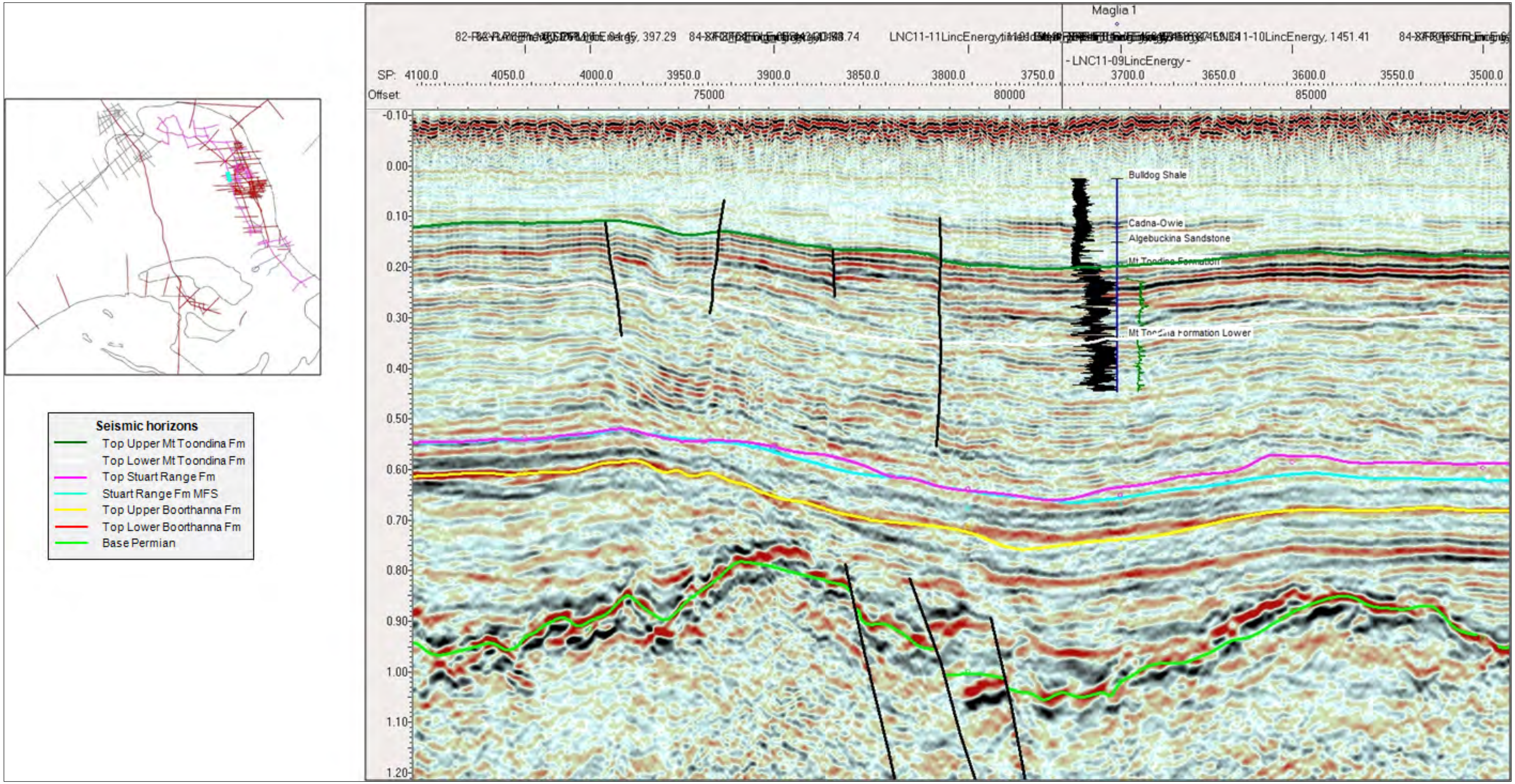

Figure 3.6: Western Boorthanna Trough

Figure 3.7 is representative of a seismic dip line across the eastern margin of the Boorthanna Trough. The entire Permian section is bounded by a major north-south striking fault system. The Upper Mount Toondina Formation is truncated beneath the major regional unconformity at the base of the Eromanga Basin before the eastern fault boundary.

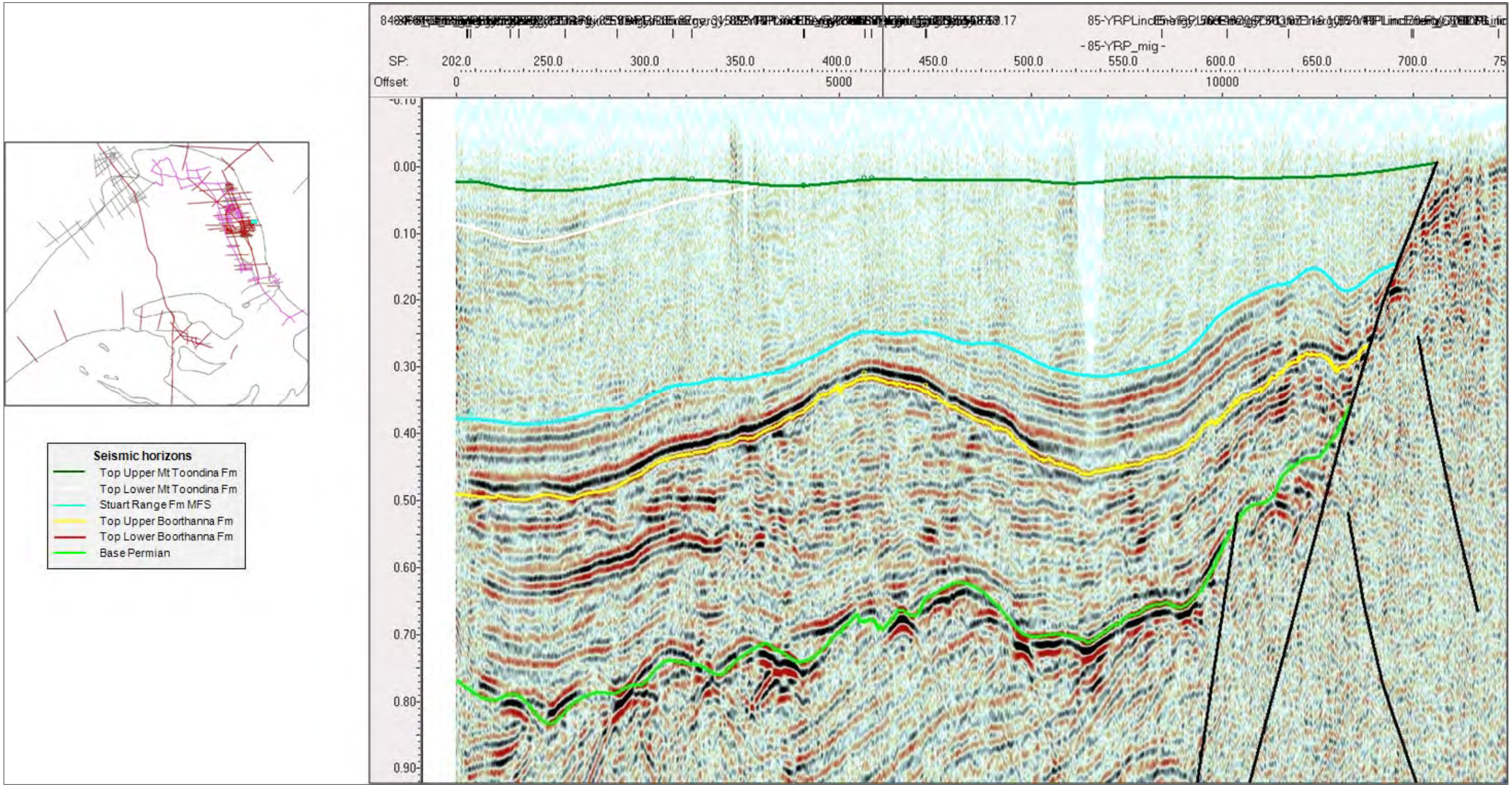

Figure 3.7: Eastern Boorthanna Trough

An interpreted seismic strike line from the southern Boorthanna Trough is shown in Figure 3.8 below. The entire Permian section gradually thins to the south. Coals within the Upper Mount Toondina Formation are locally developed and become progressively truncated beneath the base Eromanga Basin unconformity.

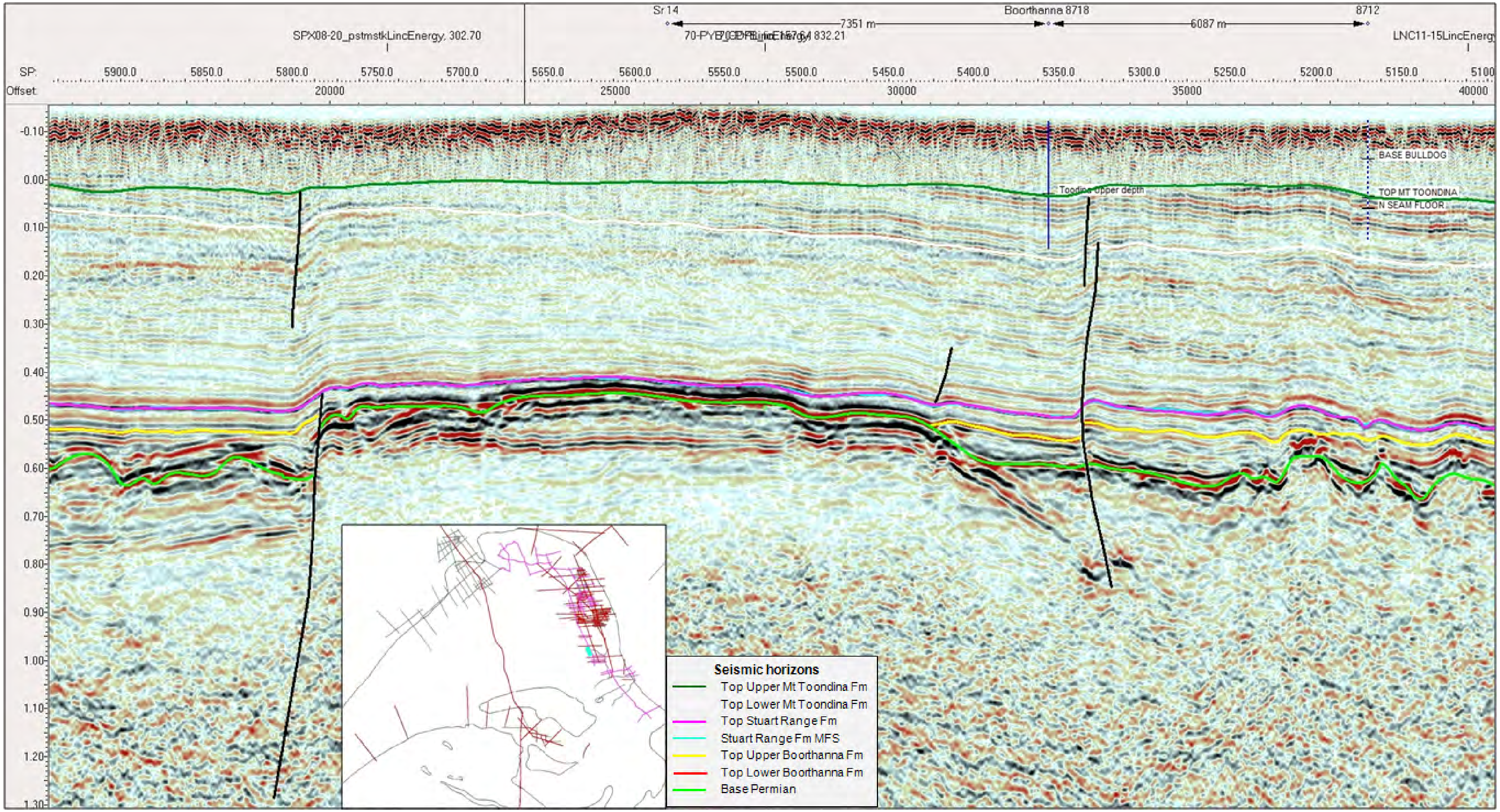

Figure 3.8: Southern Boorthanna Trough

Figure 3.9 shows the seismic interpretation across the northern margin of the Boorthanna Trough. The Permian section is thin and largely comprises older parts of the Permian stratigraphy (Boorthanna Formation and Stuart Range Formation). Major incision and erosion is evident at the base of the Eromanga Basin regional unconformity. The large channels incised into the Permian succession are filled with chaotic, semi-transparent seismic facies identical to that of the Algebuckina Sandstone. These large channels are most likely sand-filled and therefore have important implications with respect to inter–basin and inter–aquifer connectivity between overlying GAB and the Mount Toondina Formation. The base of the Permian section is defined by an angular unconformity.

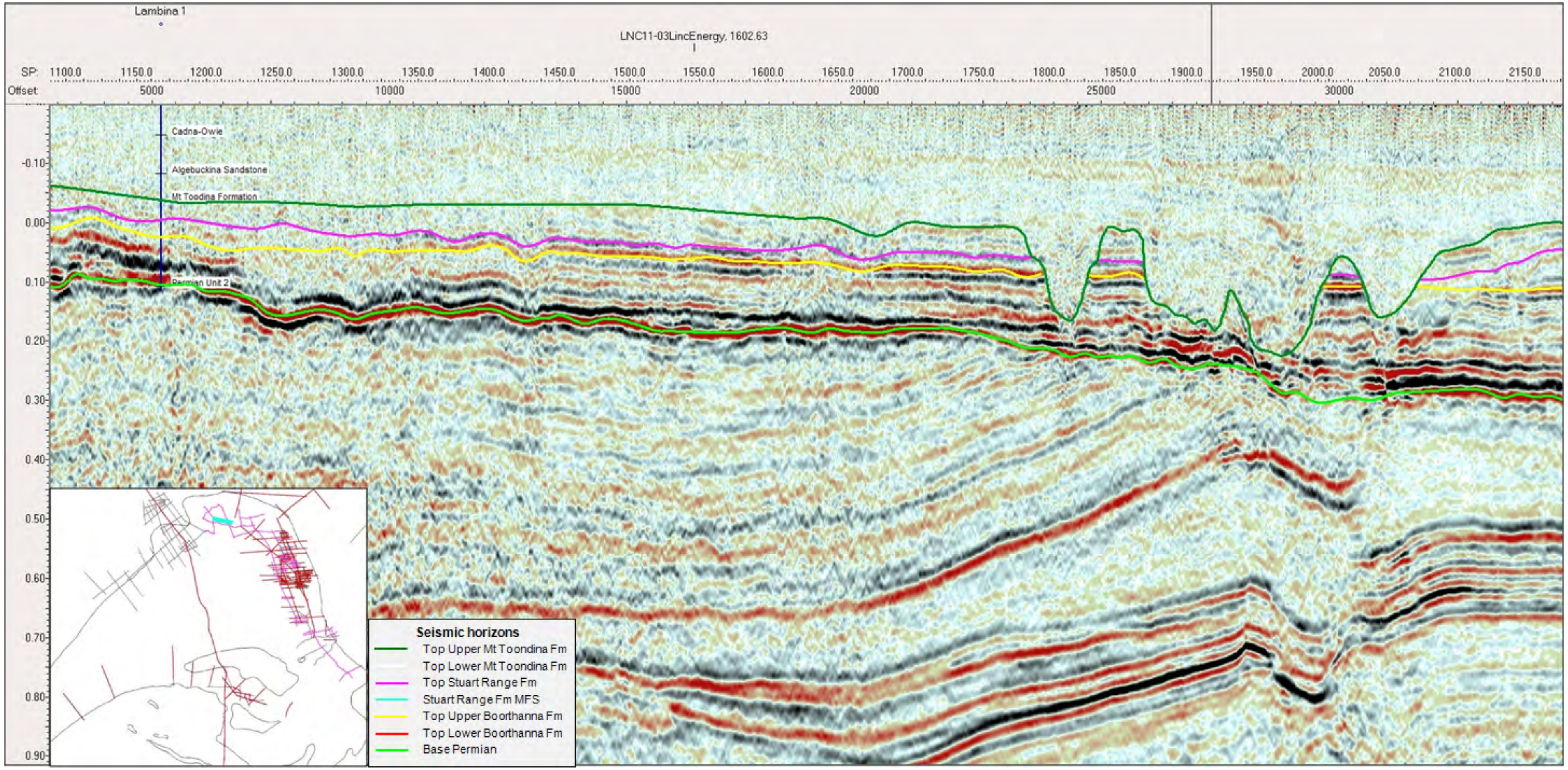

Figure 3.9: Northern Boorthanna Trough

Figure 3.10 below presents the interpreted chronostratigraphy across the far north-east margin of the Boorthanna Trough. A steep major fault offsets the Permian stratigraphy and defines the edge of the Permian coal measures. The preserved Permian section is considerably thicker to the east of the fault.

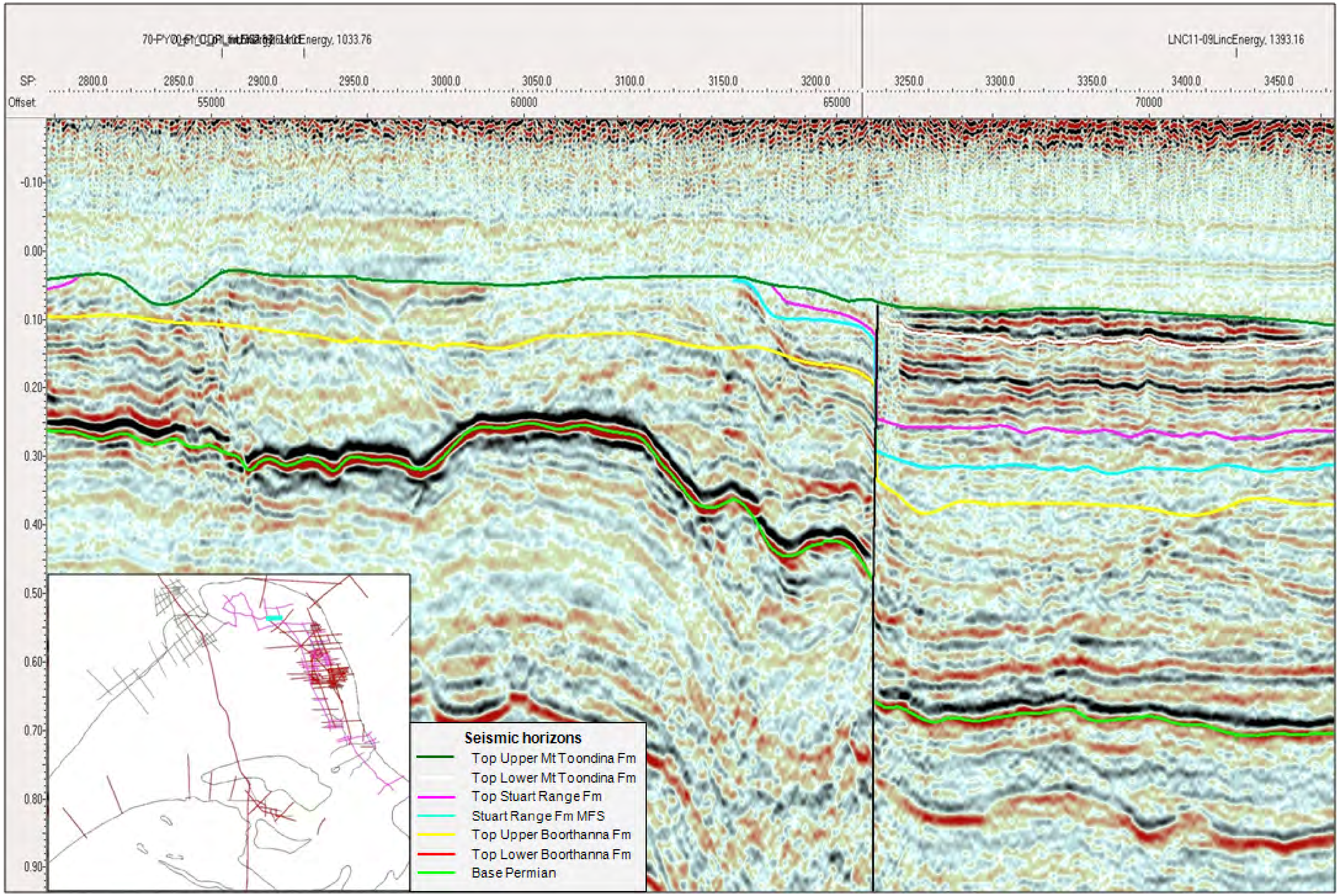

Figure 3.10: Northern basin

Along the north-western margin of the Arckaringa Basin, towards the Officer Basin, basement is somewhat shallow and the Permian section very thin (Figure 3.11). The Permian section is largely comprised of basal Boorthanna Formation and some erosional remnants of the Stuart Range Formation. There is no seismic evidence for coals or much preserved strata of the Mount Toondina Formation. Note that the seismic data quality is poor to fair in this area - hindering confidence in the seismic interpretation; this likely to be because the age of the seismic data, which is approximately 30 years old.

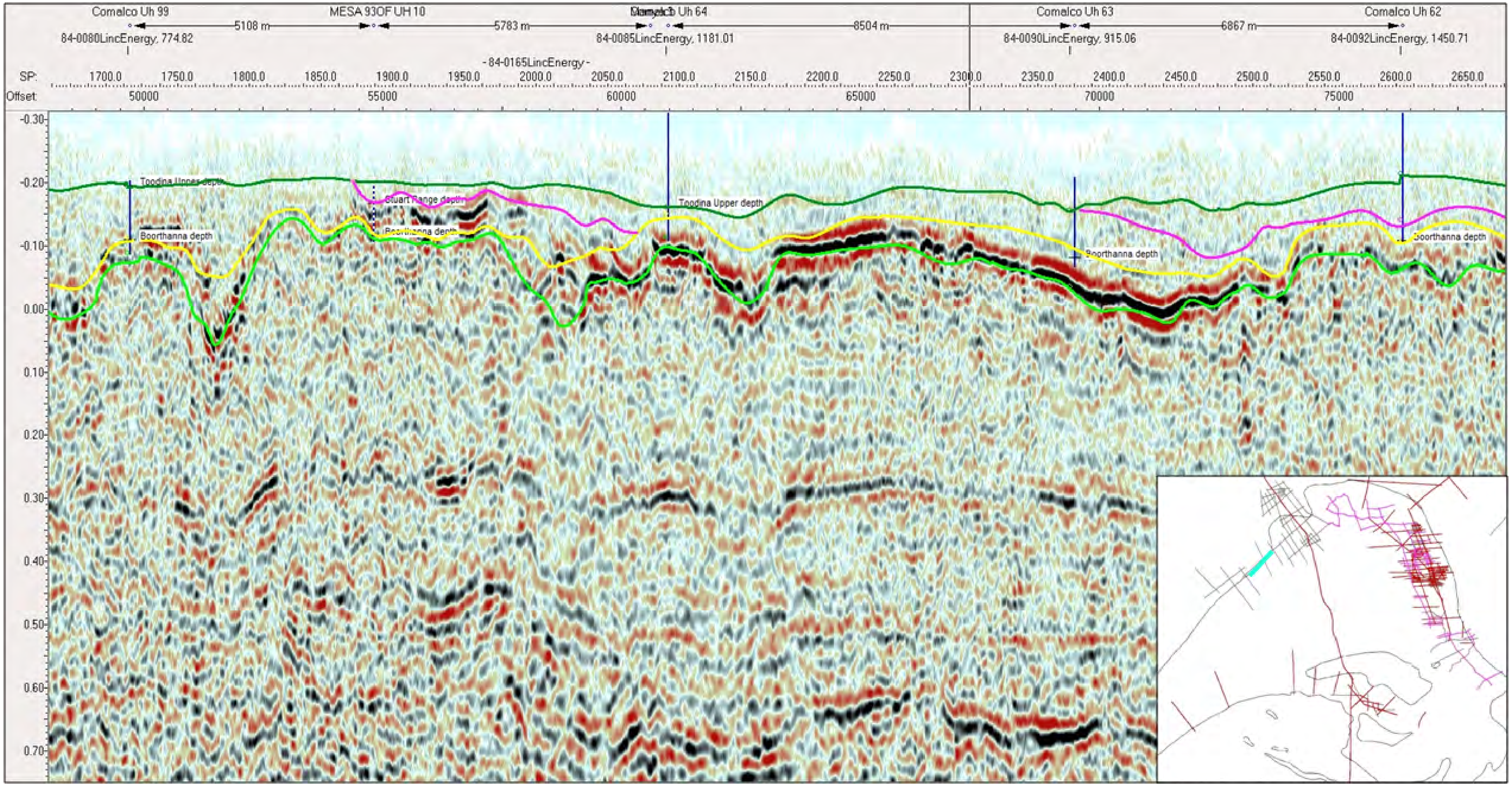

Figure 3.11: North-western basin

Figure 3.12 represents a strike line along the Phillipson Trough. Clear seismic facies of the Boorthanna Formation are notable, while coals in the Upper Mount Toondina Formation are distinguished by bright amplitude reflections. The pick horizon of the Stuart Range Formation is not actually the top, but does represent an intra-Stuart Range Formation horizon that is correlated around the southern depocentres.

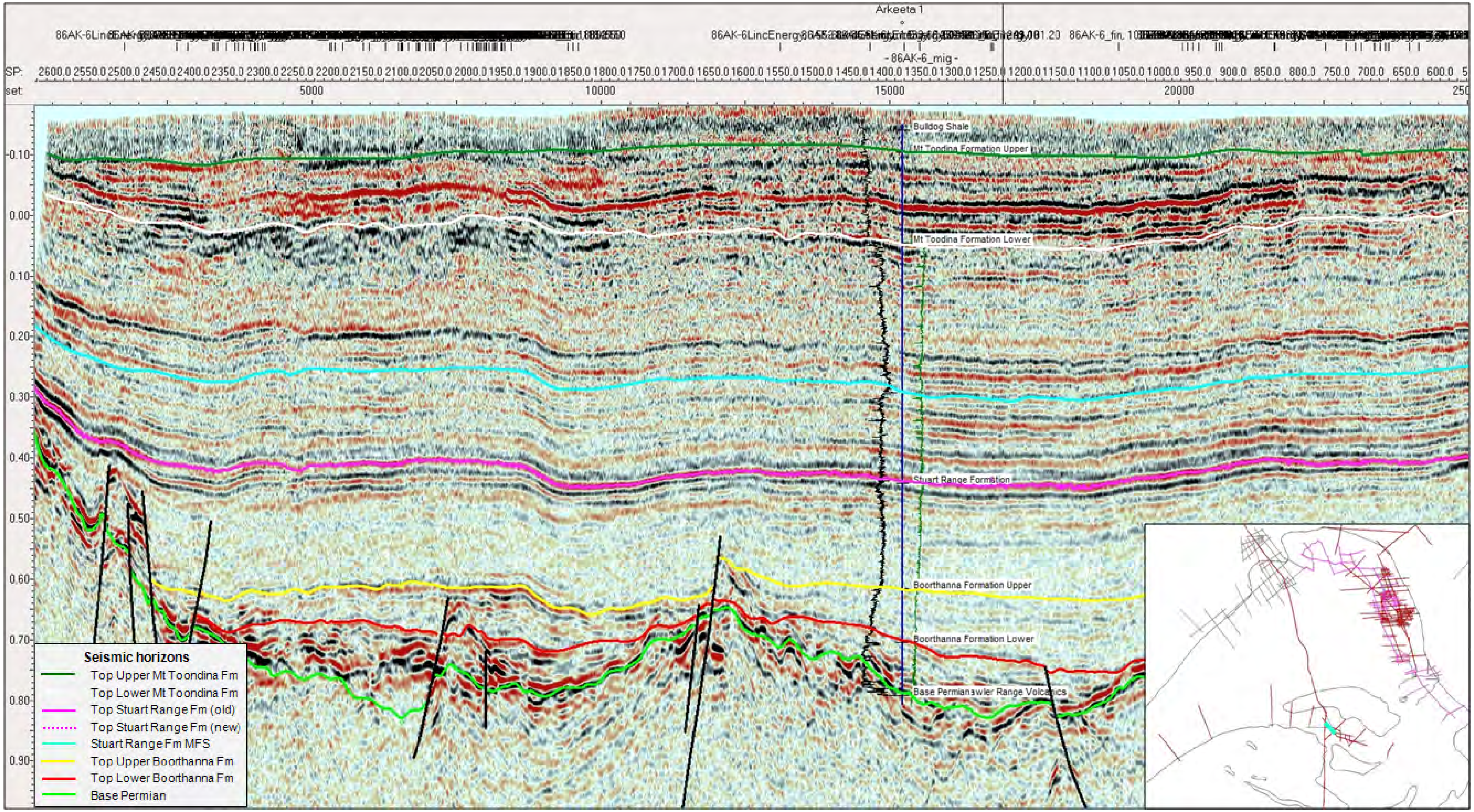

Figure 3.12: Southern troughs

3.3.1.2. Basin cross-sections

The basin-wide cross-sections (Figure 3.13) constructed from the surface layers, as well as a number of the seismic cross-sections highlight important architectural features in the Arckaringa Basin, including:

- The influence of pre, syn and post depositional faulting in shaping the basin and potentially demarcating sub-basinal areas (section C-C', Figure 3.13). Of note are the Billa Kalina sub-basin area (section B-B' and C-C', Figure 3.13), the Boorthanna Trough and areas in the vicinity of the north-western margin. In most instances, fault activity has resulted in a highly variable thickness of the Permo-Carboniferous formations, particularly relative to the overlying Mesozoic and Quaternary sediments. The identification of faulting is important to defining hydrogeological sub-basins, the development of secondary porosity and assessing the interconnectivity of Permo-Carboniferous aquifers with overlying and/or underlying sediments.
- Faulting has the potential for connecting Arckaringa Basin aquifers with the surface environment. The potential for deep-seated faults to connect GAB aquifers with the surface via the formation of springs has been discussed on a number of occasions (e.g. Aldam and Kuang, 1989; Karlstrom et al. 2013; Krieg, 1989). The structural architecture and tectonic history of these faults suggest that they potentially have a similar relationship with Arckaringa Basin aquifers (Figure 3.13).
- Cross sections highlight the differences in basinal characteristics between the eastern and western Arckaringa Basin. While the western Arckaringa Basin is thin, hydrostratigraphically simple and only moderately faulted, the eastern Arckaringa Basin is deep, hydrostratigraphically complex (most notably with the demarcation of Upper Mount Toondina Formation, Lower Mount Toondina Formation and Boorthanna Formation) and highly faulted (sections A-A' and C-C', Figure 3.13).
- The areal extent of the Stuart Range Formation is important to determine areas of potential aquifer recharge, or where Permian aquifers are confined. Considering there are two key aquifer units within the Arckaringa Basin, the Mount Toondina Formation and the Boorthanna Formation, the presence or absence of confining layers may indicate that recharge mechanisms and flow dynamics within the respective aquifers are different. For example, near the western margin of the basin, the absence of Stuart Range Formation suggests that Arckaringa sediments may form a single aquifer unit, whereas in the vicinity of the Boorthanna Trough and central Arckaringa Basin, the presence of the Stuart Range Formation suggests a significant barrier to interconnectivity (Figure 3.13).
- Similarly, the areal extent and thickness of the Bulldog Shale as highlighted by previous seismic reinterpretation work (Keppel et al., 2013), is important when determining regions of potential recharge. Areas where thinning or removal of Bulldog Shale has occurred may coincide with recharge zones for the Mount Toondina Formation or Boorthanna Formation. Such areas include the region east of the Stuart Range, where recent stream activity has removed much of the overlying Bulldog Shale and potentially formed an area of intra-basinal recharge to both the underlying GAB aquifers and Mount Toondina Formation (sections A-A' and C-C', Figure 3.13).
- The importance of potential connectivity between the Mount Toondina Formation and the overlying GAB. In areas where sandier or more porous units within the Mount Toondina Formation come into direct contact with GAB aquifer units, such as in the vicinity of the western and north-western margins of the basin (sections A-A' and C-C', Figure 3.13), the two formations may operate as a single hydrogeologic unit. Such areas may also operate as important zones of recharge to Mount Toondina Formation aquifers.
- The development of palaeodrainage at the contact between the Eromanga Basin and Arckaringa Basin represent zones of potential inter–aquifer connectivity, highlighted in Figure 3.9. Such channels may

intersect multiple units within the Permian sequence and provide pathways for groundwater flow, irrespective of the low porosity and permeability of specific formations.

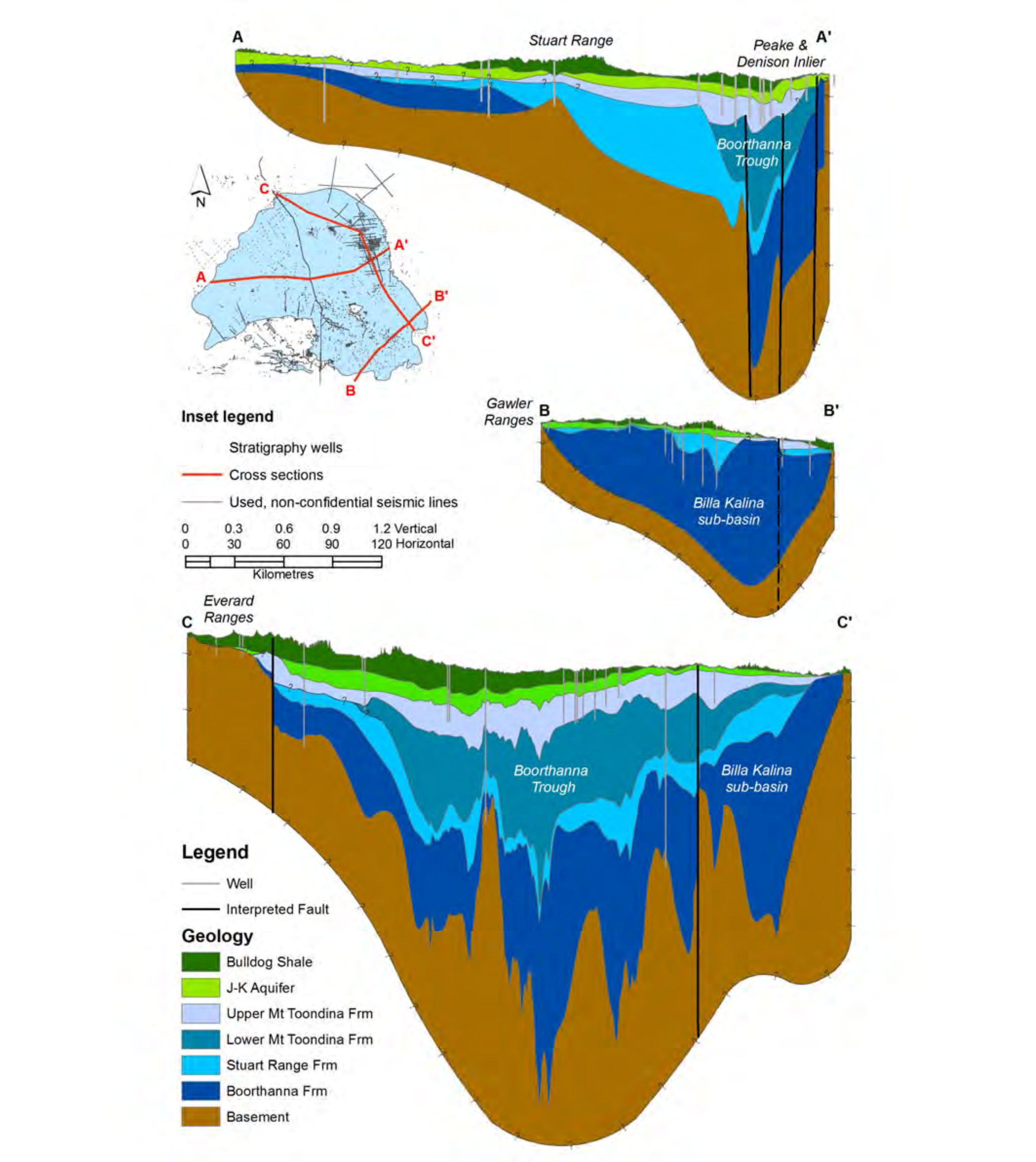

Figure 3.13: Interpreted cross-sections based on surfaces from seismic and well data

3.3.1.3. Potential Basin Connections

There is potential hydraulic connection between the GAB and the Arckaringa Basin. In particular, interconnectivity between GAB aquifers and sandier units within the Mount Toondina Formation is likely to be reasonably common in marginal areas of the basin where sandier units are more commonly encountered. This appears to be the case in the west and north-west of the Arckaringa Basin, where apparent difficulty in discriminating between sands from either the Mesozoic or Palaeozoic is evident in existing logs. In addition, the development of palaeochannels within the unconformity between the Eromanga Basin and Arckaringa Basin; particularly the north and north-west of the basin are zones where potential exists for both cross-formational flow and recharge to the Permian aquifers.

For deeper aquifers, such as those found within the Boorthanna Formation, the cross sections provide evidence for the removal of younger sedimentary horizons by erosion, in particular the Stuart Range Formation, prior to the deposition of the GAB or younger sedimentary units. Where this has occurred, interconnectivity between the Boorthanna Formation and overlying aquifer units is possible. Furthermore, sections A-A' and C-C' (Figure 3.13), draw attention to the potential for connectivity through basement units within the extent of the Arckaringa Basin. Further data acquisition and detailed analysis is required to confidently describe these processes. This is particularly the case with aquifer units that abut the Arckaringa Basin laterally, such as those found within the Officer Basin to the west or the Stuart Shelf to the south and east. Such basins may be important to recharge and discharge processes within Arckaringa Basin aquifers. Although there is circumstantial evidence for a potential connection (e.g. head data from Arckaringa Basin aquifers suggests flow between basins) this is yet to be established with any confidence.

3.3.1.4. Confidence

The integrated seismic and log interpretation, and mapping provides a consistent regional three-dimensional chronostratigraphic framework for the Arckaringa Basin. This framework provides the basis for further studies investigating the stratigraphic, hydrostratigraphic and structural relationships between the Permian coals and shales, and the overlying Mesozoic units that contain significant groundwater resources.

The basin architecture mapping task aimed to integrate all formation top data from groundwater, mineral exploration and petroleum bores with seismic interpretations to provide an initial synthesis of both geological and hydrogeological data sets. Every effort was made within the timeframe given to not only verify seismic interpretation against existing geological and hydrogeological data sets, but to also check the veracity of data and to re-interpret logging information appropriately when discrepancies between seismic and logging data became apparent. The coverage of seismic and stratigraphic logging data used to compile this interpretation of basin architecture and regional scale cross sections is provided with the inset map of Figure 3.13.

It is important to note that the seismic project and interpretations may need to be revised and refined by the inclusion of additional data. Likewise, drilling logs used to tie and verify seismic interpretation may need additional review, or where possible with the existence of archive material, re-logging and re-interpretation. Suggested recommendations to improve the accuracy of interpretation include the following:

- There are very few defined formation tops for the Lower Mount Toondina Formation. Therefore, away from seismic control, mapping of all known coal areas of the Mount Toondina Formation is limited. Where possible, all bores through the known coal deposit areas require re-assessment to discriminate formation top picks for the Lower Mount Toondina Formation which would allow for a revision of the formation extent and associated isopach.
- A second phase of more detailed seismic and well interpretation is recommended for the upper part of the Permian section and the lower part of the Eromanga Basins succession to allow for more detailed assessments of the extent and nature of connectivity between Permian coals relative to the Algebuckina Sandstone. In addition, seismic facies analysis would aid in mapping aquifer transmissivity.

3.3.2. FIELD AUDIT

The Arckaringa Basin (according to SA Geodata records and the basin extent as presented in Section 1.3.2.1) contains approximately 1974 drill holes classified as water wells. An additional 70 wells have been backfilled. These 1974 water wells form the basis of the field audit commenced under this project (Stage 1).

The objective for the field audit team was to produce a field survey report (Appendix B) for each water well whether located or not. During the initial field surveys a number of water wells were found to be:

- New – for which a new record was generated in SA Geodata and referral to the State Drilling Inspector provided
- Not located – for which the status on SA Geodata has been updated
- Backfilled – for which the status on SA Geodata has been updated.

As part of the initial Stage 1 field surveying, 365 water wells have been audited within the Arckaringa Basin. Of these, 31 were confirmed as new water wells previously not recorded in SA Geodata, 147 were able to be measured for water level (typically limited to accessible well columns, i.e. not equipped with a pump or windmill) and 77 were not located. Approximately 39 wells are located on mine site boundaries which are yet to be surveyed due to access.

Salinity samples were collected from equipped water wells where possible.

Figure 3.14 shows the general spatial coverage of the initial Stage 1 bore audit (to March 2013) and represents approximately 20% of the total wells originally identified for the program. Table 3.4 provides a summary of the available bore audit data collected for the Arckaringa Basin. These results are preliminary and subject to update upon the completion of the overall program

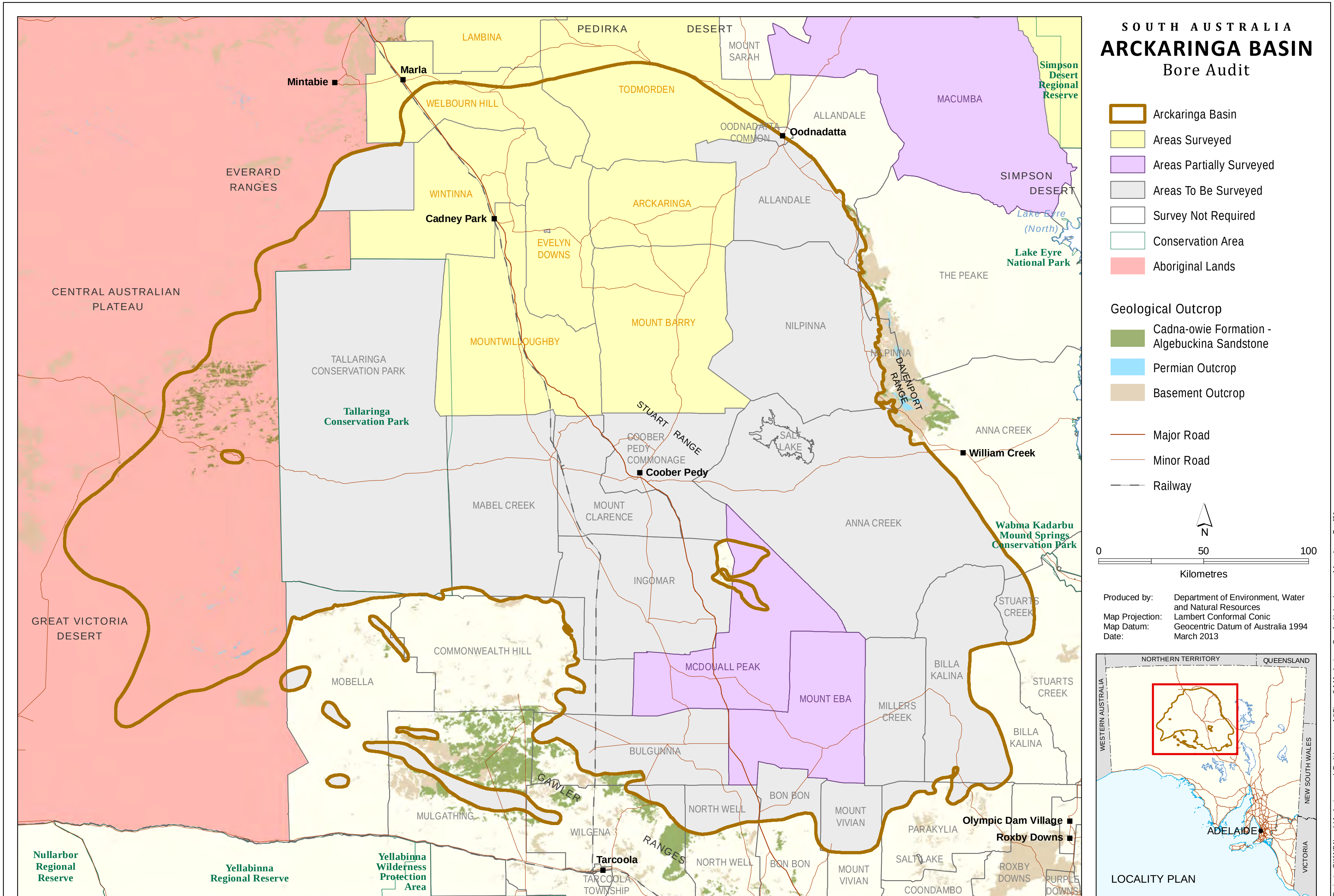

Figure 3.14: Initial Bore Audit Program, Arckaringa Basin (areas surveyed prior to March 2013)

Table 3.4: Summary of surveyed wells, Arckaringa Basin

Trip No.	Date of Trip	Pastoral Stations	Water Wells per Station	Water Wells Surveyed per Station	New Water Wells Found	Water Wells Not Located	Water Wells where WL Obtained	Comments
1	Sep 12	Mount Eba	175	71	6	1	20 (8 dry)	39 wells yet to be surveyed (i.e. on mine site) Survey to be competed
1	Sep 12	McDouall Peak	111	23	3	1	12 (3 dry)	Survey to be completed
2	Sep 12	Arckaringa	37	37	2	9	23 (1 dry)	
2	Sep 12	Cooper Hills	1	1	0	0	0	
2	Sep 12	Evelyn Downs	35	35	7	13	16 (2 blocked, 8 dry)	
2	Sep 12	Mount Barry	40	40	0	5	21 (2 dry)	
2	Sep 12	Mount Willoughby	47	47	5	15	16 (3 dry)	
3	Oct 12	Lambina	3	3	0	0	2 (1 dry)	
3	Oct 12	Todmorden	41	40	4	9	8 (2 dry)	1 well not visited
3	Oct 12	Welbourn Hill	30	26	4	5	13	4 wells not visited
3	Oct 12	Wintinna	43	42	0	19	16 (2 dry)	1 well not visited
Total		11	563	365	31	77	147	

3.3.3. DATABASE REVIEW AND PRELIMINARY ANALYSIS

A review of drill hole information (SA Geodata) was undertaken to identify available groundwater information associated with Arckaringa Basin aquifers. Table 3.5 provides a summary of that well information.

Table 3.5: Summary of well data, Arckaringa Basin

Number of wells	Production zone partially within Permian-Carboniferous sediments*	Production zone solely within Permian-Carboniferous sediments
Total	182	148
With SWL	148	119
With Yield	116	95
With TDS	73	49
With Temperature	6	3

*Production zone may also incorporate aquifer units within overlying GAB or underlying basement units

The majority of wells are located in the south-east of the basin, are associated with production and groundwater monitoring for the Prominent Hill mine and are constructed in the Boorthanna Formation. There are a small number of wells in the vicinity of the Phillipson Trough near the margins of the Mount Woods Inlier and the Peake and Denison Inlier. The density of water wells is lowest in the northern and western potions of the basin. Additionally, three well completion reports identified archival drill–stem test data (Weedina 1, Stuart Range 3 and Cootanoorina No.1).

3.3.3.1. Yield

Most yield data for bores screened in the Permian Formations are identified within the Boorthanna Formation and associated with the Prominent Hill mining operation. Yields from the Boorthanna Formation aquifer vary between 0.01 L/s and 31 L/s. The remaining yield data are for either the Mount Toondina Formation or undifferentiated Permian with yields varying between 0.1 L/s and 9.1 L/s (Table 3.6).

3.3.3.2. Water Levels

Considering only wells with production zones solely within Permo-Carboniferous aquifers; the majority of standing water level (SWL) measurements are from aquifers contained within the Boorthanna Formation and are associated with groundwater abstraction for the Prominent Hill mining operation. Spatially, SWL data for the Mount Toondina Formation covers a larger area. Combined, the depth to groundwater ranges from at surface near the Peake and Denison Inlier and south-east margin of the basin, to 155 mbgs around the headwaters of the Margaret Creek catchment and 133 mbgs near the centre of the basin to the west of the Mount Woods Inlier (Figure 3.15). SWL values are variable and not spatially correlated; it is possibly affected by variations in topography and effects of abstraction associated with the Prominent Hill Mine water supply.

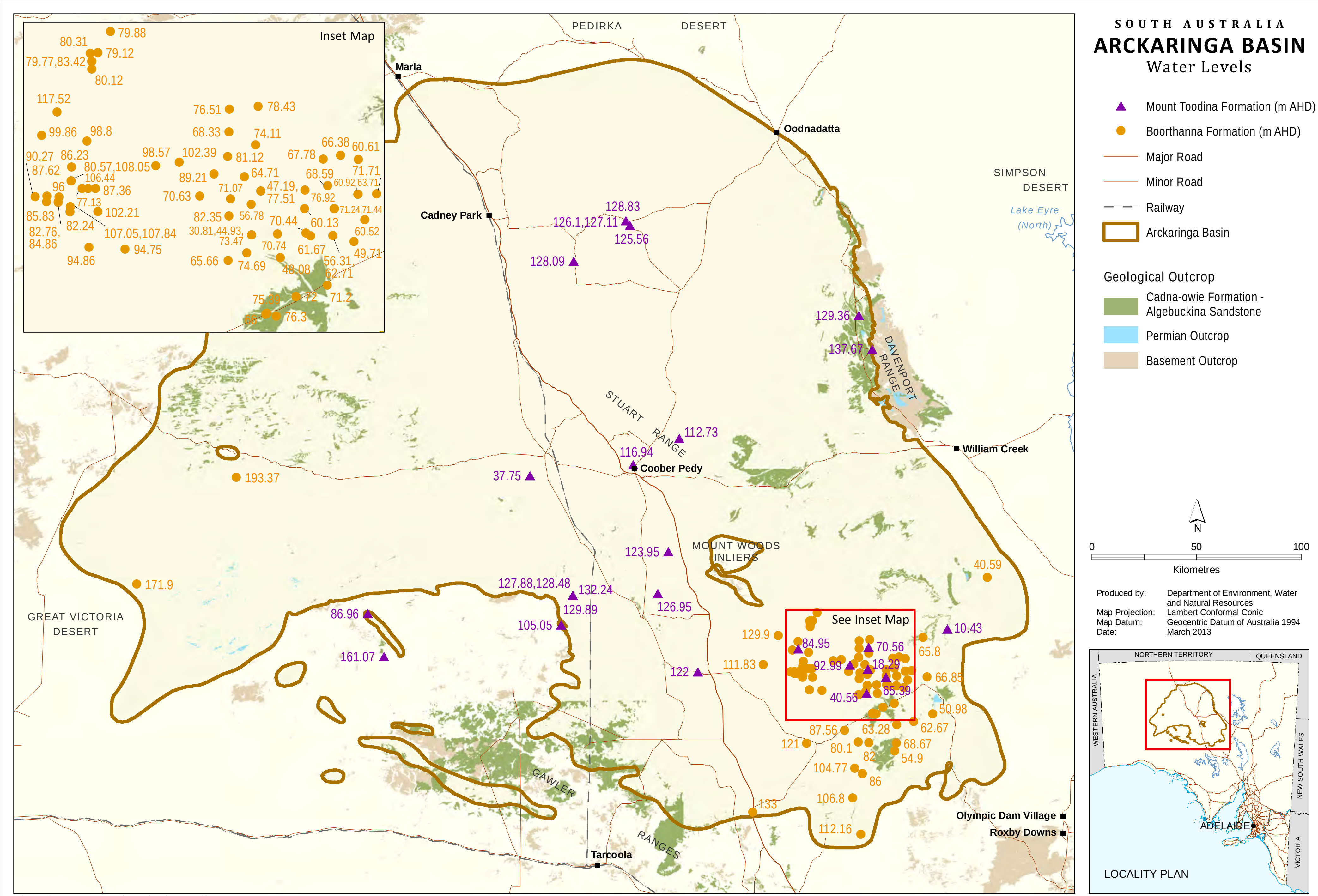

Figure 3.15: Water Levels, Arckaringa Basin

3.3.3.3. Salinity and Hydrochemistry

Salinities in the Permo-Carboniferous aquifers range between 625 mg/L and 25024 mg/L. Four higher values of between 108560 and 150710 mg/L occur near the southern margin of the basin and are associated with groundwater abstracted from thick coal bearing units within the Mount Toondina Formation. In general, fresher groundwater occurs near the south-eastern and eastern margins of the basin, in the vicinity of the Gawler Ranges, southern Stuart Ranges and Peake and Denison Inlier. Increases in salinity occur between these two areas, east of the Mount Woods Inlier and the Stuart Range, and also in the vicinity of the Phillipson Trough south of the Mount Woods Inlier. From very limited data, temperatures were found to vary between 25°C (non-artesian wells located within the far south-west corner of the Arckaringa Basin) and 26.5°C (artesian well located in the vicinity of the Wintinna Coalfield). As the non-artesian wells were not drilled for water monitoring purposes, the integrity of this data cannot be confirmed.

Table 3.6: Minimum, maximum and average SWL, yield and salinity measurements, Arckaringa Basin (source, SA Geodata)

Data Type	Aquifer	No. Data points	Minimum Value	Maximum Value	Average Value
SWL (mbgs)	Boorthanna Formation	92	0	125.27	73.02
	Mount Toondina Formation/ Stuart Range Formation/ combined Permian	27	0	154.84	50.11
Yield (L/s)	Boorthanna Formation	75	0.01	31.25	0.33
	Mount Toondina Formation/ Stuart Range Formation/ combined Permian	20	0.01	9.09	1.37
Salinity (mg/L)	Boorthanna Formation	21	3382	17,024	8491
	Mount Toondina Formation/ Stuart Range Formation/ combined Permian	28	625	150,710	25,189

3.3.3.4. Diffuse Recharge Estimation

A saturated chloride mass balance (CMB) approach, as described by Gee et al. (2004), was used to derive an estimate of diffuse recharge to the Permian aquifer where possible. The CMB method is commonly used to estimate recharge because it is conceptually simple, the data requirements are generally readily available and where data acquisition is required, analysis is inexpensive relative to other techniques. Gee et al. (2004) notes that the CMB technique can provide reliable estimates of diffuse recharge for rates below a few mm/y. The CMB method assumes that all chloride in the target aquifer is derived from atmospheric inputs and that the chloride ion behaves conservatively as it travels through the unsaturated zone to the watertable. If the loss of chloride to overland flow and evapotranspiration are considered negligible and the addition of chloride from rock weathering is insignificant then recharge can be estimated using the following relationship:

$$R = \frac{p \times Cl_p}{Cl_{gw}}$$

Where:

R is recharge (mm/y)

p is precipitation (mm/y)

Cl_p is the chloride concentration in precipitation (mg/L)

Cl_{gw} is the chloride concentration in groundwater (mg/L)

Chloride deposition can take the form of wet (rainfall) or dry (aerosols) deposition, where the mass of wet and dry chloride deposition is known the recharge relationship can be further simplified to:

$$R = \frac{Cl_{dwdf}}{Cl_{gw}} \times 100$$

Where Cl_{dwdf} is the chloride deposition from wet and dry fallout (kg/ha/y).

The CMB method also assumes that the chloride deposition rate has not varied over time and that steady state conditions exist in the aquifer.

Twelve wells completed in the Boorthanna Formation and located where the overlying GAB aquifer is unsaturated, have historical chloride data. All of these wells were found in the vicinity of the Billa Kalina sub-basin. Point estimates of chloride deposition at each of the well sites were estimated using the Australian 0.05° gridded chloride deposition spatial coverage (Davies et al., 2011). Estimated mean chloride input for well localities ranged between 3.15 and 3.87 kg/ha/y. Based on these estimates of chloride input and historical chloride data from selected groundwater wells, diffuse recharge to the Permian aquifers range between 0.05 mm/y and 0.22 mm/y, with an average rate of 0.09 mm/y. Kellett et al. (1999) used a similar chloride mass balance approach to obtain a recharge rate of 0.5 mm/y through a combined GAB/Boorthanna Formation profile within the Billa Kalina 1:100000 map sheet. Kellett et al. (1999) estimated chloride input using an average annual rainfall of 180 mm/y and an average chloride concentration in rainfall of 4 mg/L to calculate recharge rates. Both results indicated that diffuse recharge at the well locations assessed is small. During the same study, Kellett et al. (1999) found that diffuse recharge rates to either GAB or Stuart Shelf aquifers varied between 0.1 and 5 mm/y, with variation interpreted to be dependent on the presence and thickness of Bulldog Shale. It should also be noted that there is uncertainty associated with the chloride deposition rate as these values were obtained from a national interpolated surface with only one data point in the vicinity of the study area and very limited data coverage in central Australia. Given the generalisations and uncertainties characteristic of the data used to undertake this CMB-based assessment of diffuse recharge, it must be emphasised that the rates obtained are order of magnitude estimates only.

3.3.4. HYDROGEOLOGICAL MAP

The accompanying Arckaringa Basin hydrogeological map (part 1 and part 2) is a first edition for the Arckaringa Basin.

The information displayed on these maps includes:

- A location plan depicting administration boundaries, land elevation and hydrological features
- A plan of geological provinces detailing geological and groundwater sub-basins. This includes the location of the following:
    - Precambrian basement units within the Peake and Denison Inlier and Mount Woods Inlier, as well as the Musgrave and Gawler Ranges to the north-west and south respectively.
    - The Officer and Warburton Basins to the north-west and north east respectively.
    - The GAB and Lake Eyre hydrological basin, which largely overlie the Arckaringa Basin.
- Groundwater salinity for the Permian formations within the Arckaringa Basin that display the following characteristics:
    - Fresher groundwater occurs near the south-eastern and eastern margins of the basin, in the vicinity of the Gawler Ranges, southern Stuart Ranges and Peake and Denison Inlier respectively.
    - Salinity concentrations are highest east of the Mount Woods Inlier and the Stuart Range, and in the vicinity of the Phillipson Trough south of the Mount Woods Inlier. Increases in salinity east of the Mount Woods Inlier may reflect the input of mineral dissolution along flow paths, while high salinity in the vicinity of the Phillipson Trough is reflective of the provenance of groundwater from a coal seam aquifer.
- Uncorrected water level data for the Permian formations within the Arckaringa Basin. Groundwater levels are highest near the southern, eastern and western margins of the basin and are generally lowest in the south-east corner of the basin, with discharging groundwater entering aquifers within the Stuart Shelf. It should be noted that the data for the Boorthanna Formation is largely restricted to the Billa Kalina sub-basin, while for the Mount Toondina Formation; the number of data points is small.
- As requested by the Office of Water Science, a phreatic watertable surface–being an interpolated groundwater surface of the first recorded groundwater intersection, be that from Tertiary, Cretaceous, Jurassic or Permian formations. When compiling data for the production of this map, care was taken to remove any data points that were obviously artesian or sub artesian. Although the phreatic watertable is ubiquitous across the landscape, this surface does not necessarily imply continuous groundwater movement between formations. The phreatic watertable surface has the following characteristics:
    - In general, the phreatic surface reflects the regional topography, with areas of high groundwater elevation found in the vicinity of the Musgrave Ranges and the Central Australian Plateau to the north-west and west respectively. Areas of low phreatic elevation occur in the vicinity of Lake Eyre and Lake Torrens, located to the east and south-east respectively.
    - Groundwater elevations vary from >800 m AHD in the vicinity of the Musgrave Ranges to approximately 0 m AHD near Lake Eyre, with flow generally from the north-west to east and south-east. Small variations to this flow direction occur in the vicinity of the southern flanks of the Gawler and Ooldea Ranges near the southern margin and south-west corner of the Arckaringa Basin, where groundwater flows toward the south and south-west respectively.
    - Areas of apparent localised mounding occur in the vicinity of the Stuart and Gawler Ranges, near the centre of the Arckaringa Basin, and in the vicinity of the north-western and southern margins of the basin.

- A plan of current monitoring networks and observation wells
- Structure surfaces and isopach contours for the Mount Toondina Formation, Stuart Range Formation, Boorthanna Formation and the combined Permian sequence
- Geological data sources, including location of seismic lines, wells, 1:1000000 surface geology and faults used in the interpretation of all stratigraphic surfaces and isopachs
- Three cross-sections through the extent of the Arckaringa Basin highlighting the following:
    - The important influence of faulting and Permo-Carboniferous glacial scouring on basin architecture, the highly variable isopach of Permo-Carboniferous formations and the development of potential hydrogeological sub-basins. These basinal characteristics are particularly highlighted when comparing the western and eastern halves of the Arckaringa Basin.
    - The potential location of areas of recharge in the vicinity of the margins of the basin and along the eastern flank of the Stuart Range
    - The relationship between the Mount Toondina Formation and the overlying GAB aquifers
    - The development of palaeodrainage channels within the unconformity between the Eromanga and the Arckaringa Basins, which has potentially important ramifications for inter aquifer connectivity.

3.3.5. CONCEPTUAL MODEL

3.3.5.1. Existing Conceptual Model

The most comprehensive hydrogeological conceptual model describes the Boorthanna Formation in the south-eastern Arckaringa basin, where a number of studies have been conducted (e.g. Aquaterra REM, 2005a; Kellett et al. 1999; Rogers and Zang, 2006; Belperio, 2005; Howe et al., 2008; Lyons et al, 2010; Enesar, 2006).

The area is referred to by Aquaterra REM (2005a) as the Billa Kalina sub-basin. The region is structurally defined, being bound to the east and north by the Billa Kalina Fault and the Boorthanna Fault respectively. As previously described in Section 3.2.1.3, Aquaterra REM (2005a), Howe et al. (2008), SKM (2009) and Lyons et al. (2010) used hydrochemistry to differentiate between groundwater from Boorthanna Formation aquifers and other aquifers located in the Billa Kalina sub-basin. GAB aquifer units within the region are thin and are either unsaturated or contain sub-artesian groundwater. Consequently, groundwater exploration in this region has focussed on the underlying Boorthanna Formation and fractured rock aquifers (Belperio, 2005).

SKM (2009) suggested that productive aquifer units may occur as relatively isolated semi-discontinuous “pods” related to sporadic turbitite flows within an otherwise quiescent glacio-marine environment and that further discontinuity may arise from syn and post depositional faulting. Large drawdowns (>50 m) observed within bore fields located within the western half of the basin were interpreted by REM (2007) and presented in SKM (2009) as evidence for a limited lateral aquifer extent.

With respect to recharge, a number of proposed recharge mechanisms have been discussed in the literature. Kellett et al. (1999) proposed that recharge in this region occurs via diffuse discharge through the main GAB aquifers of the Cadna-owie Formation and Algebuckina Sandstone. Modelling completed by Aquaterra REM (2005b) suggested that parts of the overlying GAB aquifer units and Stuart Range confining layer may be unsaturated; this appears to have been confirmed after a review of well completion data undertaken by Love et al. (2013b), as well as drilling results discussed in SKM (2009).

As well as recharge via the overlying GAB, Howe et al. (2008) suggested possible direct recharge to the Boorthanna Formation where the formation subcrops near the southern basin margin and north of the Boorthanna Fault. Aquaterra REM (2005) inferred groundwater mixing from multiple recharge zones as an explanation for apparent contradictions in groundwater gradients, ^{36}Cl age and groundwater salinity trends.

Groundwater flow is generally eastward to south-eastward, where discharge occurs into the Andamooka Limestone and groundwater is transmitted towards Lake Torrens and the Olympic Dam mine (Kellett et al., 1999; Howe et al., 2008; Lyons et al., 2010). Despite previous difficulties using hydrochemistry data to discriminate between GAB and Boorthanna Formation related groundwater within the Billa Kalina sub-basin (Kellett et al., 1999; REM et al., 2005; Aquaterra REM, 2005b), SKM, (2009) and Lyons et al. (2010) suggest that GAB-related groundwater flow is primarily north-east towards Margaret Creek, whereas Boorthanna Formation related groundwater flow is more radial, flowing to the north-east, east and south-east. This difference may be explained by Aquaterra REM (2005a), who suggested that the north-south striking Billa Kalina Fault that defines the eastern margin of the Billa Kalina sub-basin deflects groundwater flow from a predominantly east-north-east direction to one with a prominent southerly direction. Finally, SKM (2009) also anticipate the existence of a deeper flow field associated with the Boorthanna Trough that flows through the sub-basin from the north to the south-east.

Kellett et al. (1999) and Howe et al. (2008) proposed that groundwater discharges from the Arckaringa Basin into the underlying Andamooka Limestone in the Stuart Shelf, which is described as highly transmissive. Aquaterra REM (2005a) and SKM (2009) also intimate that upward leakage from the Boorthanna Formation aquifer into the overlying GAB, salt pan and saline environments in the vicinity of the western margin of the Billa Kalina Fault is possible on the basis of hydraulic gradient data, although they note that the Stuart Range Formation may limit this capacity.

3.3.5.2. Proposed Conceptual Model

Based on previous research and new work presented in this report, any new conceptual model for the hydrogeological characteristics of the Arckaringa Basin should consider the following general concepts:

- Kellett et al. (1999) suggested that the dependence on fracture related secondary porosity development within the Boorthanna Formation imposes scale-dependent limitations on aquifer continuity.
- Evidence from the south-east Arckaringa suggests that groundwater resources in the basin may be best described as a series of semi-interconnected, structurally controlled sub-basins. Work by Aquaterra REM (2005a) and SKM (2009) have identified the Billa Kalina sub-basin in the vicinity of the south-east corner of the Arckaringa Basin (sections B-B' and C-C', Figure 3.12); others areas where hydrogeological sub-basins might exist include north of the Boorthanna Fault (section C-C', Figure 3.12) and west of the Stuart Range (Figure section A-A', Figure 3.12).
- There is also a likelihood that vertically discrete aquifer units may exist in the same areas. SKM (2009) presented evidence for the existence of multiple aquifers with only weak hydraulic connectivity within the Boorthanna Formation in the Billa Kalina sub-basin. With respect to a more regional scale, the separation of the Mount Toondina and Boorthanna Formations by the Stuart Range Formation may lead to the existence of two regionally extensive aquifers with restricted or spatially heterogeneous connectivity that have determinably different hydrodynamics and flow characteristics.

It is considered likely that a number of recharge sources contribute to groundwater within the eastern Arckaringa Basin and the Billa Kalina sub-basin. Kellett et al. (1999) suggests recharge is likely to occur where the watertable is elevated and where salinity levels are low. A review of uncorrected head data from the eastern Arckaringa Basin suggests an important zone of recharge may occur where the Arckaringa Basin abuts the Stuart Ranges and the northern margin of the Gawler Ranges; a number of freshwater swamps are noted to occur in the general vicinity of this boundary. Additionally, a review of uncorrected head (RSWL) data suggest that recharge may be occurring near the Peake and Denison Inlier from where groundwater migrates south towards the south-east corner of the basin. The distribution of salinity within groundwater of the south-eastern Arckaringa Basin is consistent with the gradient evident in uncorrected head data. Recharge via cross formational flow from the overlying GAB aquifer units is considered a potential inflow to the Permian aquifers, particularly where confining layers such as the Stuart Range Formation are absent.

Estimates of diffuse recharge presented by Kellett et al. (1999) and in this report suggest that this recharge source is negligible. That being said; recharge to Permian aquifers may be heterogeneous in nature; for example, recharge from surface may occur via preferential flow through fractures associated with polygonal faulting or via ephemeral river recharge. In the case of the former, polygonal fault systems have previously been identified in Mesozoic sediments within deeper parts of the GAB to the east of the Arckaringa Basin (Watterson et al., 2000). In the western Arckaringa Basin, based on very limited head data, recharge is thought to occur along the western margin of the Arckaringa Basin, in the vicinity of the Musgrave and Everard Ranges and Central Australian Plateau. Groundwater is interpreted to flow in an easterly direction towards the Stuart Range, which might act as a zone of recharge for the eastern Arckaringa Basin.

With respect to discharge processes, previous interpretations concerning outflows to the Stuart Shelf and to salt-pans and playa regions to the south-east are considered feasible, albeit requiring further work to move beyond a conceptual stage. Additionally, although a detailed argument against spring discharge has been made for the Billa Kalina sub-basin (e.g. SKM, 2010); a review inclusive of any new data and within the confines of a regional assessment is warranted. Also, such detailed studies cannot be used to exclude other areas in the wider Arckaringa Basin, such as the spring discharge area associated with the Weedina Fault to the west of the Peake and Dennison Inlier, where little to no work has been undertaken.

Finally, the hydrostratigraphy and therefore the hydrogeological characteristics of the trough regions of the basin are expected to be more complex, with the deposition of more diverse and thicker aquifers and confining layers.

Table 3.7 presents a summary of the conceptual groundwater model for the Arckaringa Basin, including a summary of knowledge gaps and information required to develop a more rigorous characterisation of the system.

Table 3.7: Conceptual groundwater model, Arckaringa Basin

	COMPONENT	SUMMARY OF CURRENT INFORMATION	KNOWLEDGE GAPS
Scale of model		A conceptual model exists for the Billa Kalina sub-basin (BKSB) , located within the south-eastern corner of the Arckaringa Basin	No conceptual model that incorporates the entire Arckaringa Bain exists.
Basin Architecture	Basin Architecture	This report presents the following information for either the first time, or in a detail not previously obtained: •The base of the Permian strata forms a complex, glacially-scoured surface with significant erosional relief. •The Early Permian coarse-grained, sandstone-dominated glacial facies of the Boorthanna Formation exhibit clear mappable seismic facies in most areas and their distribution is mostly restricted to the main depocentres. •The Stuart Range Formation and Lower Mount Toondina Formation are potentially important regionally extensive aquitards. •Coals are best developed in the northern half of the Boorthanna Trough and there is a strong influence on coal development from old, basement-related faults. •Major incision and erosion is evident at the base of the Eromanga Basin regional unconformity, particularly within the northern and north-western parts of the basin. •There is clear seismic evidence of gentle tilting, low angle truncation and erosion of Upper Mount Toondina Formation coals below the base Mesozoic unconformity.	It is important to note that the seismic project and interpretations may need to be revised and refined by the inclusion of additional data. Potential work to improve the accuracy of interpretation presented in this report include the following: •There are very few defined formation tops for the Lower Mount Toondina Formation. Therefore, away from seismic control, mapping of all known coal areas of the Mount Toondina Formation is limited. •Existing seismic and well interpretation could be improved upon to with respect to assessing the extent and nature of connectivity between Permian coals relative to the Algebuckina Sandstone. In addition, seismic facies analysis would aid in mapping aquifer transmissivity.
Recharge	Recharge Zones and Mechanisms	Kellett et al (1999) proposed that recharge in the BKSB occurs via diffuse discharge through the main GAB aquifers of the Cadna-owie Formation and Algebuckina Sandstone. Howe et al. (2008) suggested possible direct recharge to the Boorthanna Formation where the formation subcrops near the southern basin margin and north of the Boorthanna Fault. Additional recharge zones include freshwater stream and wetland environments located near the south-eastern margin of the basin. In the western Arckaringa Basin, based on very limited head data, recharge is thought to occur along the western margin of the Arckaringa Basin, in the vicinity of the Musgrave and Everard Ranges and Central Australian Plateau.	Previous interpretations concerning recharge zones and mechanisms are considered feasible, albeit requiring further work to move beyond a conceptual stage. Additionally, recharge to Permian aquifers may be heterogeneous in nature; for example, recharge from surface may occur via preferential flow through fractures associated with polygonal faulting or via ephemeral river recharge.
	Recharge Rates	Diffuse recharge rate of between 0.05 and 0.5 mm/y estimated using CMB approach. Aquaterra REM (2005b) used a constant recharge rate of 0.18 mm/y for numerical modelling of BKSB based on reported recharge rates for the overlying GAB.	High uncertainty surrounding CMB estimates of diffuse recharge The rate of ephemeral river recharge or other preferential flow pathways is not known

	COMPONENT	SUMMARY OF CURRENT INFORMATION	KNOWLEDGE GAPS
Aquifer Parameters	Transmissivity	Mount Toondina Formation: 0.073 (coal seam) - 38.14 m^2/d (clastic sediments) Boorthanna Formation: 2-150 m^2/d	Howe et al. (2008) suggests transmissivity is highly variable as a result of structurally controlled variations in formation thickness. Current transmissivity, hydraulic conductivity and storativity data come from one or two discrete locations. Permeability measurements are primarily based on core analysis of small formation intervals and should be viewed as indicative only with respect to estimations of hydraulic conductivity and transmissivity.
	Storativity	Mount Toondina Formation: $2x10^{-7}$ - $4.5x10^{-3}$ Stuart Range Formation: $1x10^{-4}$ Boorthanna Formation: $1x10^{-4b}$ - $1x10^{-5}$	
	Permeability and Hydraulic Conductivity	Permeability Mount Toondina Formation: $1.48x10^{-12}$ – $1.5x10^{-9}$ cm^2 Boorthanna Formation: $2.96x10^{-9}$ - $1.97x10^{-8}$ cm^2 Hydraulic Conductivity Mount Toondina Formation: Kh: 0.9-9x10-3 m/d (coal seams), 9x10-4-9x10-5 m/d (sedimentary interbeds) Stuart Range Formation: Kv: $1x10^{-4}$ m/d Boorthanna Formation: Kh: 0.2-5 m/d	
	Porosity	Mount Toondina Formation: 4-36.6% Boorthanna Formation: 3.6-25% Kellett et al. (1999) suggests that secondary porosity development is important in assessing the unit's viability as a reliable groundwater supply.	
Hydrodynamics	Aquifer Composition and Extents	SKM (2009) suggested that productive aquifer units may occur as relatively isolated semi-discontinuous "pods" related to sporadic turbitite flows within an otherwise quiescent glacio-marine environment and that further discontinuity may arise from syn and post depositional faulting. Large draw downs (>50 m) observed within bore fields located within the western half of the basin was interpreted by REM (2007) and presented in SKM (2009) as evidence for a limited lateral aquifer extent.	Outside of the BKSB and other discrete areas of previous hydrogeological investigation, the hydrogeological characteristics of the Mount Toondina, Stuart Range and Boorthanna Formations are unknown. It is anticipated that the shale units of the Stuart Range and lower Mount Toondina Formations may act as an aquitard between the upper Mount Toondina and Boorthanna Formations within the deeper parts of the basin, however the relationship and composition of sediments near the basin margins is still unclear in places.

	COMPONENT	SUMMARY OF CURRENT INFORMATION	KNOWLEDGE GAPS
	Groundwater Flow and Flow scale	Groundwater flow in the BKSB is generally eastward, where discharge occurs into the Andamooka Limestone (Kellett et al., 1999; Howe et al., 2008; Lyons et al, 2010). SKM (2009) also anticipate the existence of a deeper flow field associated with the Boorthanna Trough that flows through the sub-basin from the north to the south-east. An average groundwater velocity of 1.4 m/y and a residence time up to 200000 years was estimated by Kellett et al. (1999) for Boorthanna Formation groundwater. Groundwater within the western Arckaringa speculated to flow in an easterly direction towards the Stuart Range, which might act as a zone of recharge for the eastern Arckaringa Basin. Based on hydrogeological studies completed within the BKSB, the possibility that the Arckaringa Basin to be partitioned to a series of semi-discrete sub-basinal areas exists. It is currently assumed that a regional groundwater flow regime also exists.	There is very little information outside of the BKSB to make a confident assessment of groundwater flow and flow scales. Evidence from the BKSB suggests the partitioning of the Arckaringa Basin into semi-discrete sub basins is a feasible theory but there is inadequate data to confirm this hypothesis.
	Potentiometric surface	Density-uncorrected groundwater levels are highest near the southern, eastern and western margins of the basin and are generally lowest in the south-east corner of the basin, where water is interpreted to discharge into aquifers contained within the Stuart Shelf.	There are insufficient water quality data for existing wells to determine whether density variation is affecting flow. Likewise there is insufficient well coverage to interpret the potentiometric surface on a regional scale, or to adequately determine a head difference between the GAB and Arckaringa groundwater, or between aquifers in the Mount Toondina and Boorthanna formations.
	Cross-formational flow	Kellett et al. (1999) and Belperio (2005) described the Stuart Range Formation as a leaky aquitard that separates the GAB and Boorthanna Formation aquifers, while SKM (2009) and Aquaterra (2009) suggest that the Stuart Range Formation potentially provides sufficient leakage to enable drawdown stability in groundwater production wells located in the underlying Boorthanna Formation. Conversely, Aquaterra REM (2005a) and SKM (2009) infer that the Stuart Range Formation acts as an effective barrier to downward leakage. Pump test data presented in SKM (2009) and Lyons et al. (2010) were used to highlight the limited connectivity between Boorthanna and unconfined GAB aquifers	The limited scope and spatial extent of many hydrogeology studies of the Arckaringa Basin results in what appear to be at times contradictory interpretations of cross-formational flow. Additionally, in areas where sandier or more porous units within the Mount Toondina Formation come into direct contact with GAB aquifer units, such as in the vicinity of the western and north-western margins of the basin, the two formations may operate as a single hydrogeological unit. There is little information however to provide evidence for this currently.

	COMPONENT	SUMMARY OF CURRENT INFORMATION	KNOWLEDGE GAPS
	Basin Dynamics	Basin dynamics refers to whether the flow system is in a transient or steady state (i.e. whether recharge is equivalent to discharge). No information is available.	No information is available about the relative magnitude of recharge and discharge or the basin dynamic
	Hydrochemistry	Groundwater from Arckaringa Basin aquifers is generally described as brackish to ultra saline, although fresh supplies are known in parts of the BKSB. Major ion hydrochemistry from Arckaringa Basin aquifers is very similar to that found within the overlying GAB, being predominantly Cl and Na + K dominant, with relatively high Mg and SO_4. Some differentiation between GAB and Boorthanna Formation groundwater suggested via use of ^{36}Cl and stable isotopes (e.g. Lyons et al., 2010).	Although there has been an extensive review of hydrochemistry from the BKSB, there is very little reliable data outside of this. Additionally a detailed review of hydrochemistry with respect to a regional standpoint is lacking
Discharge	Discharge Zones and Mechanisms	Kellett et al (1999) and Howe et al., (2008) proposed that groundwater in Boorthanna Formation aquifers in the BKSB discharges into the underlying Andamooka Limestone in the Stuart Shelf, which is described as highly transmissive. Aquaterra REM (2005a) and SKM (2009) also indicate that upward leakage from the Boorthanna Formation aquifer into the overlying GAB, salt pan and saline environments in the vicinity of the western margin of the Billa Kalina Fault is possible on the basis of hydraulic gradient data, although they note that the Stuart Range Formation may limit this capacity.	Previous interpretations of discharge zones and mechanisms are considered feasible, albeit requiring further work to move beyond a conceptual stage. Additionally, although a detailed argument against spring discharge has been made for the Billa Kalina sub-basin (e.g. SKM, 2010), a review inclusive of any new data and within the confines of a regional assessment is warranted. Also, such detailed studies cannot be used to exclude spring discharge within the wider Arckaringa Basin.
	Discharge Rates	No information available on discharge rates from the Permian Formations	

4. PEDIRKA BASIN

4.1. INTRODUCTION

The Pedirka Basin is an intra-cratonic sedimentary basin comprising largely Early to Late Permian sediments and coal sequences. The basin is located in the north of South Australia and straddles the South Australian / Northern Territory border. The basin unconformably overlies the Early-Palaeozoic Amadeus and Warburton Basins and Proterozoic basement rocks; and unconformably underlies the Mesozoic Eromanga Basin (Great Artesian Basin). Much of the Pedirka Basin occurs subsurface at depths greater than 400 m; outcrop is confined to the Crown Point Formation and occurs exclusively along the north–west margin of the basin in the Northern Territory (Munson and Ahmad, 2012).

4.2. HYDROSTRATIGRAPHY

Jaques (1966) divided the Permian sequences of the Pedirka Basin into two formations that form the basis of currently accepted stratigraphic nomenclature; the Crown Point Formation and overlying Purni Formation. Wells drilled prior to this classification system may not utilise formal names for Permian sequences or may refer to all Permian strata as Crown Point Formation.

4.2.1. PURNI FORMATION

The Purni Formation (Youngs, 1975) disconformably underlies Jurassic sediments of the Eromanga Basin and consists of fluvial and paludal interbedded sands, silts and clays, as well as coal beds within the paludal sequences. Youngs (1975) and Hibburt and Gravestock (1995) suggest that the South Australian occurrence of the Purni Formation can be further subdivided into three sub–units based on the proportion of carbonaceous shale, lenticular or cross-bedded sandstone and coal seams. The upper and lower units are dominated by carbonaceous shale and coal respectively, while cross-bedded sandstone predominates in the middle facies.

Conversely, in the Northern Territory, Ambrose and Heugh (2012) and Munson and Ahmad (2012) describe four sub–units (Units A1, A, B and C) based on facies description, palynology and coal seam correlation.

- Unit A1 consists of a sandstone interbedded with siltstones and finer sandstones. Coal seams are thin but the presence of higher carbonaceous content is used to discriminate between the Purni Formation and underlying glacial sequences.
- Unit A consists of thick coal seams and interbedded clastics that conformably overly Unit A1.
- Unit B is thought to disconformably overly Unit A and consists of interbedded siltstones, sandstones and coals.
- Unit C contains a sequence of interbedded coals and clastics that are bound at the top and base by unconformities.

A similar characterisation of 4 sub units (Units I to IV) was first proposed by Faridi (1986). As well as discriminating between subgroups, Munson and Ahmad (2012) describe how palynological work has extended the Purni Formation to cover most of the Permian time period, whereas most previous interpretations had this unit restricted to the early Permian (Sakmarian). Consequently previous interpretations that broadly describe the Purni Formation as the lateral equivalent of the Mount Toondina Formation (e.g. Youngs, 1975) require review. They suggest that with further work, the Purni

Formation could be elevated to Group status, with the identified sub-units reclassified as formations in their own right.

The stratigraphic relationship between each of the formations described is provided in Figure 3.3 and a summary of hydrostratigraphic and hydrogeological properties is provided in Table 4.1.

Table 4.1: Summary of Formation properties within the Pedirka Basin

Formation	Deposition Age	Maximum Recorded Thickness	Lithology	Hydrogeology
Purni Formation	298.9-254.1 Ma	564 m	Fluvial and paludal interbedded sands, silts and clays, as well as coal beds within the paludal sequences.	Sandstone and coal units: potential aquifers. Clay and shale layers: potential aquitards.
Crown Point Formation	298.9-295.0 Ma	504 m	Glacio-fluvial and glacio-lacustrine sands and shales (diamictite)	Sandstone layers: potential aquifers.

4.2.2. CROWN POINT FORMATION

The Crown Point Formation (Wells et al., 1966) consists of glacio-fluvial and glacio-lacustrine sands and shales. The formation unconformably overlies sediments associated with the Early Palaeozoic Amadeus and Warburton Basins and underlies the Purni Formation. The formation comprises extensive diamictite, conglomerate, fluvioglacial and glacio-lacustrine sandstones, ripple-laminated sandstone and siltstone, and clay-rich rhythmites (Giuliano, 1988). Coarser grained strata such as conglomerate, coarse sandstone and diamictite are associated with depositional highs, whereas finer grained mudstone is more commonly associated with basinal lows such as the Eringa Trough (Hibburt and Gravestock 1995). The lithological similarity between the Crown Point Formation and the Boorthanna Formation in the Arckaringa Basin has led to the determination that these formations are lateral equivalents (Alexander and Jensen Schmidt, 1995).

A clean sand that occurs at the top of the Crown Point Formation is typically used as a marker for the end of glaciation; Ambrose and Heugh (2012), Ambrose (2006), and Munson and Ahmad (2012) regard this sand unit as a distinct formation and have named it the Tirrawarra Sandstone, suggesting it is the equivalent of the Tirrawarra Sandstone in the Cooper Basin. After logging of core from Mount Hammersley 1, New (1998) subdivided the Crown Point Formation into three sub-units on the basis of lithological variation and log character. The basal unit (Unit “C”) consisted of sandstone with interlaminated and interbedded siltstone. The middle unit (Unit “B”) consisted predominantly of siltstone and claystone, while the upper most unit (Unit “A”) consisted of sandstone and interbedded siltstone.

In distribution, the Crown Point Formation is widespread and outcrops along the north-western margin of the Pedirka Basin where it borders the Newland Ranges. With respect to palynological interpretation, the Crown Point Formation has been assigned to zone PP1 (Asselian), although a broader Late Carboniferous to Early Permian age has also been ascribed (Munson and Ahmad, 2012).

4.3. HYDROGEOLOGY

Groundwater extraction from the Pedirka Basin occurs exclusively along the western margin within the Northern Territory, where it is used as a source of stock water for pastoral enterprises and provides a water supply for several Aboriginal outstations west of Apatula (Finke) Community (Figure 4.1). In South Australia, the Pedirka Basin underlies the GAB and Tertiary Hamilton sub-basin in the south–west. There is limited development of Permian aquifers in this region as reliable groundwater resources exist within the Tertiary and GAB sequences. The availability of more accessible and plentiful water supplies from these overlying aquifers has limited the number of groundwater wells constructed in the Pedirka Basin within South Australia. Away from the western margin, the only registered well intersecting Permian aquifers is McDills No.1 – a failed petroleum investigation well drilled in the 1964 and controlled in 2002 (Humphreys and Kunde, 2008). As a consequence of limited groundwater infrastructure over much of the Pedirka Basin, little is known about the aquifer and groundwater characteristics of the Permian formations. This report draws on data from the petroleum and coal exploration industries to complement conventional hydrogeological information sources. A summary of key information resources are provided in Appendix A (Summary of critical information sources).

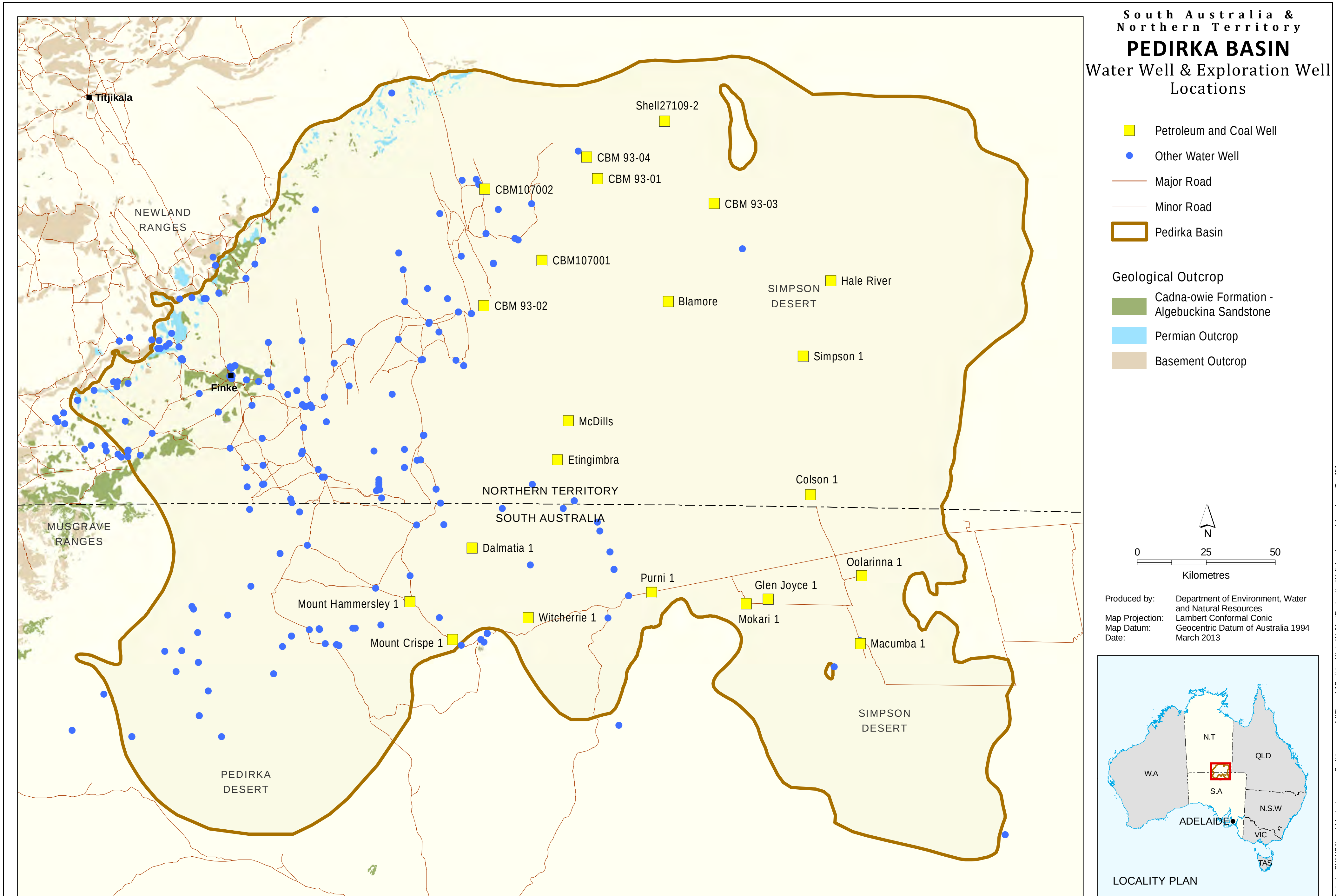

Figure 4.1: Water Well and Exploration Well Locations, Pedirka Basin

4.3.1. PREVIOUS WORK

The groundwater resources of the Pedirka Basin are poorly characterised and no published studies were identified that exclusively investigate the Permian aquifers. In a study of the central Amadeus Basin, Wells et al. (1970) reviewed the availability and quality of groundwater in the Crown Point Formation which is described as a medium to coarse grained sandstone with horizons of pebbles and conglomerate. Wells et al. (1970) identified 22 wells constructed in the Crown Point Formation with a salinity range of 397 to 3854 mg/L and an average depth of 135 m. Maximum well yields and the effects of long-term pumping from the formation were considered unknown. Further work on the groundwater resources of the Amadeus Basin by Lau and Jacobson (1991) identified 12 wells in the vicinity of outcrop areas along the margin of the Pedirka Basin accessing groundwater from the Crown Point Formation. They report an average aquifer depth of 89 m, a mean standing water level of 71 m and an average yield of between 0.1 and 2.0 L/s. Groundwater salinity was considered brackish, with a TDS of between 550 and 19050 mg/L.

Mathews (1995) and Radke et al. (2000) both undertook extensive field investigations of the overlying Great Artesian Basin system. Though not expressly discussed in the reports, both investigations included hydrochemical and isotopic analyses of groundwater from several Crown Point Formation wells located on the western margin of the Pedirka Basin. Fulton (2012) undertook a review of groundwater resources in the Great Artesian Basin Water Control District, an area which encompasses the north-west of the Pedirka Basin. Seventeen wells that screen the Crown Point Formation were identified. Reported groundwater quality for the Permian formation ranged between 100–8000 mg/L with an average salinity of 3100 mg/L. The discrepancy between the number of Permian wells studied relates to the large time gap between studies. In the ensuing decades between Wells et al. (1970), Lau and Jacobson (1991) and Fulton (2012) several Permian stock wells have been abandoned and in some cases replaced. It is not always explicit whether the count relates to active Permian wells or is inclusive of historic wells. Results from these studies are summarised in Table 4.2.

Table 4.2: Groundwater summary, Pedirka Basin (results from previous studies)

Unit	Reference	No. Wells	Mean Well Depth (mbgs)	Mean SWL (mbgs)	TDS Range (mg/L)	Mean TDS (mg/L)	Yield Range (L/s)
Crown Point Aquifer	Wells et al. (1970)	22	135	-	397–3854	-	-
	Lau and Jacobson (1991)	18	101	71	550–19050	7032	0.1 – 2.0
	Fulton (2012)	17	-	-	100–8000	3100	-

Since 1964 more than 20 conventional gas and oil wells, and more recently coal and coal bed methane exploration wells have been drilled in the Pedirka Basin. Due to the limited groundwater development of the Permian aquifers, data and testing conducted by petroleum and coal drilling investigations represents a key data source for this study.

4.3.2. DATA REVIEW

4.3.2.1. Drill hole database assessment summary

Both the South Australian database (SA Geodata) and the Northern Territory database (HYDSTRA) were interrogated to identify all drill hole data within the geographic extent of the Pedirka Basin. A total of

4.3.2. DATA REVIEW

4.3.2.1. Drill hole database assessment summary

Both the South Australian database (SA Geodata) and the Northern Territory database (HYDSTRA) were interrogated to identify all drill hole data within the geographic extent of the Pedirka Basin. A total of 352 water wells were identified in the Pedirka Basin; 127 in South Australia and 225 in the Northern Territory. This data set was reviewed to identify wells screened within the Permian formations on the basis of geological logs (where available), driller's logs, geophysical logs, surface geology maps and sub-surface aquifer extents from the GAB Hydrogeology map (Sampson et al., 2012).

A total of 27 water wells screening the Crown Point Formation were identified, there were no wells screening the Purni Formation and no wells located in the South Australian portion of the basin. In part, this reflects the great depth with which the aquifer occurs in the central and western parts of the basin and the availability of shallower water resources in these areas.

All wells identified as exclusively screening the Permian aquifers are located in the Northern Territory, along the north-west margin of the Pedirka Basin. It is estimated that of the 27 wells constructed in the Permian aquifer, only 12 are currently operational, with the remaining 15 having been abandoned. Well depths range from 12 to 192 mbgs with an average depth of 119 mbgs. Groundwater depth ranges from 5 to 159 mbgs, with an average depth of 77 mbgs. Groundwater levels are shallow (less than 10 mbgs) in the vicinity of the Finke River and outcropping Crown Point Formation, but deepen sharply to the east. Well yields range from 0.2 to 2.5 L/s with an average of 1.3 L/s. It is worth noting that the majority of wells are used for stock water supply and the estimated well yield generally reflects the water requirement rather than the true yield potential of the aquifer. Major ion chemistry and field parameters were available for groundwater samples from 21 wells. Salinity ranged from 93 to 7910 mg/L with an average water quality of 2470 mg/L; these results are discussed in more detail in the Hydrochemistry section. Histograms showing the distribution of well depth, standing water level, well yield and salinity are shown in Figure 4.3.

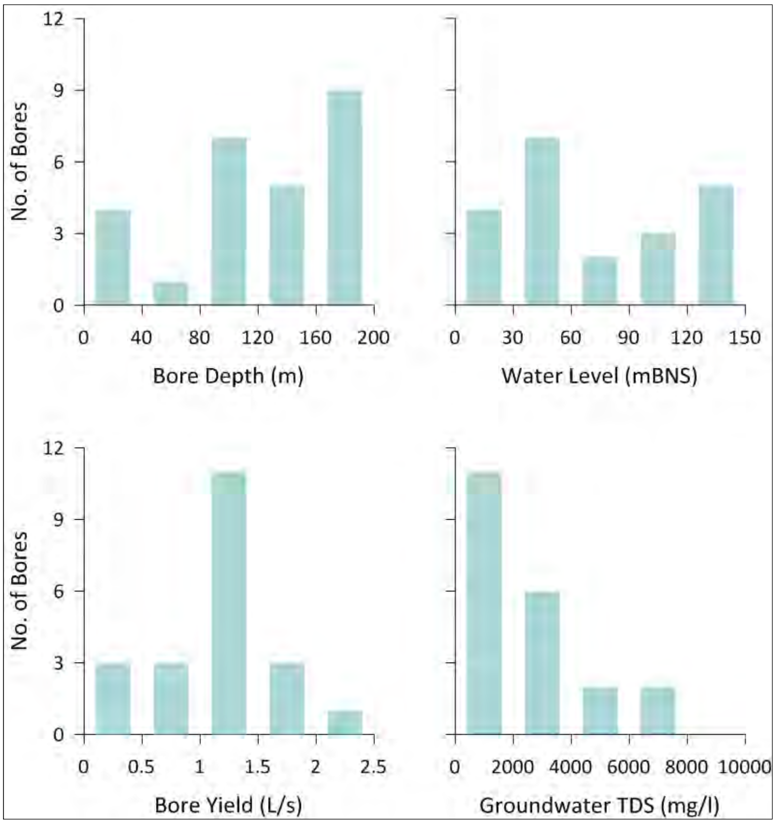

Figure 4.3: Histograms of well depth, water level, yield and salinity for Permian wells

4.3.2.2. Compilation of Petroleum and Coal Well Completion Reports

Fifteen conventional oil and gas exploration wells, in addition to seven coal and coal bed methane exploration holes that intersect the Permian sequence have been drilled and abandoned in the Pedirka Basin. Seventeen of these wells have open file well completion reports. Table 4.3 lists the name and abandonment date of each well, including the availability of data relevant to this hydrogeology study: porosity and permeability estimates, measurements of Permian formation pressure and samples of Permian formation water.

Table 4.3: Petroleum and coal exploration wells penetrating Pedirka Basin Sequence and associated data

Well Name	Completion/ Abandonment Year	Porosity Estimate		Permeability Estimate		Formation Pressure	Formation Water Sample
		Core Analysis	Geophysical Log Analysis	Core Analysis	Drill Stem Test		
Blamore	2008						
CBM 93-01	2008		YES		YES	YES	YES
CBM100701	2010				YES	YES	
Colson	1978		YES				
Etingimbra	1990		YES				
Glen Joyce	1985		YES				
Hale River	1966	YES	YES	YES			YES
Macumba	1977		YES		YES	YES	YES
McDills	1965	YES	YES	YES			
Mokari	1966		YES			YES	YES
Mt Crispe	1966						
Purni	1964	YES	YES			YES	
Simpson	2008						
Witcherie	1963	YES		YES		YES	
Mt Hammersley	1987	YES		YES			
Oolarinna	1985		YES				
Dalmatia	1988		YES				

4.3.3. AQUIFER PARAMETERS

No published aquifer tests were identified that tested the sequences of the Pedirka Basin, as a result no conventional estimates of aquifer transmissivity, hydraulic conductivity or storage coefficients are available for either the Purni Formation or Crown Point Formation. However, the Permian sequence has long represented a target for hydrocarbon and, more recently, coal exploration. Significant information on the porosity and permeability of the Purni Formation and Crown Point Formation is available in oil, gas and coal well completion reports.

4.3.3.1. Purni Formation (CP-p)

Questa (1990) report that excellent porosity and permeability were exhibited in extensive lateral sand deposits within the Purni Formation in the western part of the basin. These sands have an average thickness of 30 m east of the Dalhousie-McDills trend, while west of the structure the sandstone beds are thin but display increased permeability and porosity (Questa, 1990). Porosity measurements for the Purni Formation derived from geophysical logs range from 4–32%, while porosity measurements from core analysis range from 16–25%. Permeability estimates for the sand and sandstone intervals within the Purni Formation range from 135–2529 millidarcies (mD) (equivalent hydraulic conductivity range of 0.11–2.44 m/d). The permeability of the coal measures, estimated from drill stem testing, range from 0.2–66.7 mD (equivalent hydraulic conductivity range of 1.7×10^{-3}–0.03 m/d). The full range of porosity and permeability measurements are summarised in Table 4.4.

Table 4.4: Purni Formation porosity and permeability values extracted from well completion reports

Well Name	Reference	Porosity (%)	Permeability (mD)	Derived Hydraulic Conductivity (m/d)*
Etingimbra	Osborne and Edwards (1990)	31–32		
Colson	Beach Petroleum (1979)	13–16		
Hale River No 1	Amerada Petroleum (1966)	15–22 (25)**	632 (Kv)# 2529 (Kh)##	0.53 2.44
McDills No 1	Amerada Petroleum (1965)	15–25 (19–22)**	135–187	0.11–0.16
Mokari	French Petroleum (1966)	3.7–10.4		
Macumba	Delhi International (1978)	13	2	0.002
Purni	French Petroleum (1964)	19 (16.2–22)**		
Dalmatia	New (1988)	>20		
CBM93-1	Central Petroleum (2008)	16.7	0.2–96^	$1.7x10^{-4}$-0.004
CBM107-001	Central Petroleum (2010)		36.7^	0.03

*Hydraulic conductivity values converted from permeability measurements assuming water temperature of 20°C

**Bracketed porosity values indicate laboratory measurements of core samples, other values derived from geophysical logging

^ Permeability measurements taken over coal measures

#Vertical hydraulic conductivity

Horizontal hydraulic conductivity

4.3.3.2. Crown Point Formation (CP-c)

The reservoir quality of the Crown Point Formation is generally considered poorer than that of the overlying Purni Formation (Questa 1990). Conglomerate and coarse sandstone are more common on depositional highs, while lower permeability mudstones are present in the depositional troughs (Munson and Ahmad, 2012). Greater porosity and permeability are expected in the Tirrawarra Sandstone equivalent, which lies conformably between the Crown Point Formation and Purni Formation. Higher porosity (13.5–24.5%) and permeability (1998 mD) were also reported in the lower Crown Point Formation at Mt Hammersley No. 1, located in the south-east of the basin. Artesian flows were encountered in the Crown Point Formation at Witcherrie 1 (906 Barrels per day or 1.77 L/s from 778–790 m) and McDills No. 1 (724 m). However, the permeability of the formation was too low to produce water in a drill stem test at Mokari (2155 m). There are suggestions of secondary porosity within the Crown Point Formation with Tucker (1997) noting that, in thin section, feldspar is uncommon; suggesting secondary porosity development via feldspar dissolution.

Similarly, Alexander and Jensen-Schmidt (1995) and Faridi (1986) note the development of minor secondary porosity via the dissolution of labile minerals, although they also mention potential reductions in porosity via compaction and pyrite formation. Reported Crown Point Formation porosity measurements derived from geophysical logs range from 3–30%, values from laboratory core analysis range from 11–32%. Permeability is reported to range between 91–1998 mD (equivalent hydraulic conductivity range of 0.08–1.66 m/d). The full range of porosity and permeability measurements for the Crown Point Formation are summarised in Table 4.5.

Table 4.5: Crown Point Formation porosity and permeability values extracted from well completion reports

Well Name	Reference	Porosity (%)	Permeability (mD)	Derived Hydraulic Conductivity (m/d)*
Mt Hammersley	New (1988)	13.5–24.5	91–1998	0.08–1.66
Colson	Beach Petroleum (1979)	9–13		
Hale River No 1	Amerada Petroleum (1966)	15–22 (11)**	582 (Kv)# 836 (Kh)##	0.49 0.70
McDills No 1	Amerada Petroleum (1965)	15–25		
Mokari	French Petroleum (1966)	2.9		
Macumba	Delhi International (1978)	11–12		
Etingimbra	Osborne and Edwards (1990)	28–30		
Witcherie	French Petroleum (1964b)	(9–21)** V (12–32)** H	557	0.46
Oolarinna	Delhi Petroleum (1985)	8.5–13.4		
Dalmatia	New (1988)	13–18		

*Hydraulic conductivity values converted from permeability measurements assuming water temperature of 20°C

**Bracketed porosity values indicate laboratory measurements of core samples, other values derived from geophysical logging

#Vertical hydraulic conductivity

##Horizontal hydraulic conductivity

4.3.4. GROUNDWATER FLOW

4.3.4.1. Data Analysis

Combined Crown Point Formation / Purni Formation groundwater level data has been used to construct a generalised potentiometric surface. Water levels have been taken from multiple sources including: water level estimates from wells at the time of drilling, measurements collected during field surveys/audits and formation pressure readings from drill stem tests in petroleum and coal exploration wells. There are no groundwater observation wells that regularly monitor the Crown Point Formation or Purni Formation and only a limited number of observation points; as a consequence it is not possible to produce a potentiometric surface specific to a single year or even decade. In order to maximise the number of data points the potentiometric surface is a time composite surface which includes water level readings and formation pressures from the 1960s onwards.

Each water level observation point has been assigned a land surface elevation from the SRTM 1 Second DEM-Sv1.0, which was used to convert the standing water level (SWL) (measured in metres below the ground level) to a reduced standing water level (RSWL) in metres relative to the Australian Height Datum (m AHD). In order to compare groundwater level and formation pressure data, the groundwater level observations were corrected to freshwater heads using the method proposed by Luscinsky (1961):

$$h_{fi} = \frac{\rho_i}{\rho_f} h_i - \frac{\rho_i - \rho_f}{\rho_f} z_i$$

Where: h_{fi} is the freshwater hydraulic head (m)

ρ_i is the water density at the measured point (kg/m^3)

ρ_f is the density of freshwater (kg/m^3)

h_i is the measured hydraulic head (m)

z_i is the elevation head (m).

This method accounts for changes in water density due to variations in temperature and salinity, however, it assumes the density of groundwater in the water column is constant. This assumption can lead to errors in the correction of the water levels in aquifer systems with density stratification (Post et al, 2007). However, the effects are considered negligible for the correction of Pedirka Basin data because all available water level measurements are on the basin margin, with relatively small water columns (<100 m) and minimal variation in groundwater temperature (24–30°C). The correction process resulted in an average change in groundwater levels of 0.02 m with an absolute range of -0.10/+0.13 m.

Eight drill stem tests (DST) targeting the Crown Point Formation and Purni Formation were identified from six separate exploration wells. A DST is a procedure for isolating and testing the pressure, permeability and productive capacity of formations during the drilling of a well. Discrete intervals in the well are isolated - generally using inflatable packers housed in a specialised DST tool - and exposed to atmospheric pressure via a valve within the tool. Pressure transducers record the resulting change in formation pressure which yields information on formation permeability. DST measurements of formation pressure have been used in a number of hydrogeological studies to construct regional potentiometric surfaces where there is a paucity of conventional groundwater infrastructure (Hitchon and Hays, 1971; McNeal, 1965) and to assess pressure gradients between overlying/underlying formations, particularly in deep basins (Orr, 1985; Toth, 1978; Hitchon, 1969).

The initial shut in pressure (ISP) and the final shut in pressure (FSP) can be used as estimates of formation pressure across the test interval. ISP/FSP measurements are typically lower than the true formation water pressure (Orr, 1985), so where both FSP and ISP data were available the higher pressure reading was selected. The selected ISP/FSP was cross referenced against test data (were available) to ensure the formation pressure had stabilised. At wells Mokari and CBM93-1, tests were conducted at multiple depths within the Permian sequence; for the purposes of constructing the potentiometric surface the shallowest DST was selected. Formation pressure readings (in PSI) were converted to a freshwater head using the following formula:

$$h_{fi} = RLNS - z + 0.703\rho$$

Where h_{fi} is the freshwater hydraulic head (m)

RLNS is the surface elevation (m AHD)

z is the depth to the formation pressure measurement (m)

ρ is formation pressure (PSI).

Formation pressure measurements and equivalent freshwater head values from the DST conducted in the Permian formations are summarised in Table 4.6

Table 4.6: Summary of Permian formation DST and converted freshwater head values

Well Name	Formation Tested	Elevation (m AHD)	Formation Pressure (PSI)	Pressure Measurement Depth (mbgs)	Standing Water Level (mbgs)	Freshwater Head (m AHD)
CBM93-01	Purni	169.0	1067	799	48.9	120.1
CBM93-01	Purni	169.0	1325	974	41.9	127.1
CBM107-001	Purni	164.0	1179	832	13.1	150.9
Mokari 1	Purni	67.7	2910	2025	-21.7	89.3
Mokari 1	Crown Point	67.7	3067	2155	-1.6	69.3
Witcherie	Crown Point	82.0	1200	784	-60.0	141.9
Macumba 1	Purni/Crown Point	36.6	3530	2496	13.5	23.0
Purni	Purni	72.9	Test failed and pressure readings deemed unreliable			

4.3.4.2. Groundwater Depth

Depth to groundwater ranges from 159 mbgs on the basins western edge through to 60 m artesian at Witcherie exploration well located in the south of the basin. Generally, depth to groundwater is significant (>100 m) where the aquifer is unconfined along the western margin, with the exception of the area adjacent to the Finke River where depths to groundwater of less than 10 m have been recorded. DST formation pressures suggest artesian conditions are present in the centre of the basin. This is supported by observations during the drilling of McDills No 1, when an artesian flow was intersected at the top of the Purni Formation. McDills No 1 was completed as a water well, with a shot hole screened interval over the Algebuckina Sandstone (GAB aquifer). There is some evidence that McDills No 1 sources water from both the Jurassic and Permian sequence and it has been categorised as a Permian well in previous studies (Lau and Jacobson, 1991). Observations from this well have not been included in the potentiometric surface as it is uncertain whether the pressure measurements reflect conditions in the Jurassic aquifer, the Permian aquifer or a combination of both.

4.3.4.3. Potentiometric Surface

Twenty-six freshwater heads, comprising 21 groundwater levels and five DST formation pressures have been used to construct a time-composite regional potentiometric surface for the Permian formations in the Pedirka Basin (Figure 4.3). The time period from which data was obtained ranges between the mid 1960's for a number of the DST formation pressure data points to the present day. Confidence levels in the surface can be considered reasonable in the north-west of the basin where there is a cluster of groundwater level data. However, outside this area there are only five additional data points and the reliability of the surface should be viewed as very low; that being said, given head data from this region is largely based on DST formation pressures from subsequently plugged exploration drilling and that there is no abstraction to interfere with formation pressure at these locations, it is not felt that aquifer pressures within this part of the basin will vary significantly over time.

The regional groundwater flow direction is to the south-east, with flow emanating from the north-west margin of the basin, an area that coincides with the surface expression of the Crown Point Formation. This flow pattern suggests that the Permian aquifer either receives active recharge or recharge has occurred along this margin under wetter climates in the past; under the second scenario the groundwater flow pattern would reflect a palaeo-head distribution. The highest groundwater elevations occur where the Finke River flows through a region of outcropping Crown Point Formation and suggests potential recharge interaction between the river and the Permian aquifer.

Data coverage is very poor along the south-west margin and in the centre of the basin. The Dalhousie-McDills Ridge is a major structural feature bisecting the centre of the basin, which may cause flow partitioning within the Permian aquifer. Unfortunately, the data density is too low to prove or disprove the influence of this feature. Likewise, data coverage is too poor to discern the groundwater flow pattern along the south-west margin around the Dalhousie Springs complex. DST data in the east of the basin infers a flow direction from the centre to the south-east extension of the basin. The basin is very deep in this area and is overlain by 2000 m of Cretaceous and Jurassic sediments. Due to the burial depth it would seem more likely that any terminal discharge from this area would take the form of cross-formational flow, rather than spring flow or other surface expression.

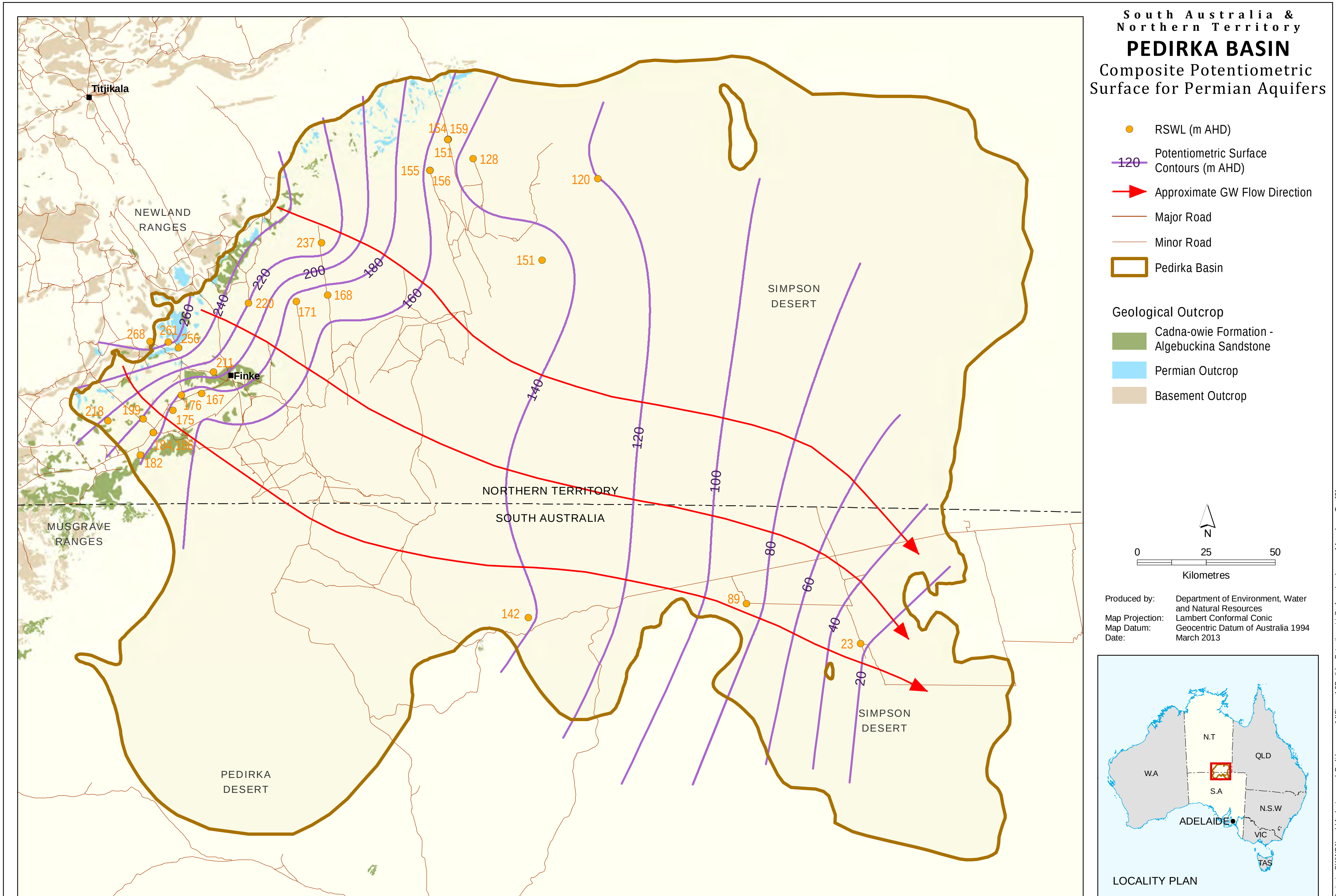

Figure 4.3: Time composite potentiometric surface of Permian units, Pedirka Basin

4.3.5. RECHARGE

4.3.5.1. Diffuse Recharge

There are no published studies investigating recharge rates or processes for the Permian aquifers in the Pedirka Basin. Wells et al. (1970) suggest that recharge is likely to occur where the Crown Point Formation outcrops on the north-west margin of the basin in the Northern Territory. The groundwater flow pattern presented in Figure 4.3 supports the operation of this area as a recharge zone however, it is not clear whether any recharge is currently occurring under today's arid climatic conditions.

A saturated chloride mass balance (CMB) approach has been used to provide a first order estimate of diffuse recharge to the Permian aquifer along the north-west margin of the basin. Methodology for this approach has previously been described in Section 3.3.3.4. Twenty-two wells were identified that both screen the Crown Point Formation and possess historical groundwater chloride measurements. Of these, eleven wells are located in close proximity to the Finke River and Goyder Creek, which are thought to provide a potential source of indirect recharge to the Permian aquifers. As the CMB technique is only valid for estimating diffuse recharge, these wells were not considered in the recharge analysis. The eleven wells used in the analysis have a groundwater chloride range of 580–3520 mg/L, with an average chloride concentration of 1600 mg/L. Point estimates of chloride deposition at each of the well sites were estimated using the Australian 0.05° gridded chloride deposition spatial coverage (Davies et al., 2011). Across the sites, chloride deposition ranged from 0.82–0.98 kg/ha/y, with a mean of 0.87 kg/ha/y.

Estimated CMB recharge rates range from 0.02–0.16 mm/y with an average rate of 0.07 mm/y (Figure 4.4). These results are an order of magnitude lower than CMB rates estimated by Love et al. (2013b), who investigated recharge to the GAB aquifer immediately to the east of the Crown Point outcrop. This study found diffuse recharge to the GAB ranged from <0.1 mm/y to 1.5 mm/y. The difference in rates is consistent with the relatively higher chloride concentrations found in the Permian aquifer away from water courses. As a first order estimate, the CMB results suggest that diffuse recharge is effectively zero at the sites considered in this analysis. However, this doesn't account for potential focused recharge through local low lying areas or from ephemeral rivers. There is also uncertainty associated with the chloride deposition rate as these values were obtained from a national interpolated surface with no data points in the study area and very limited data coverage in arid central Australia. Likewise, as previously stated in Section 3.3.3.4, given the generalisations and uncertainties characteristic of the data used to undertake this CMB-based assessment if diffuse recharge, it must be emphasised that the rates obtained are order of magnitude estimates only.

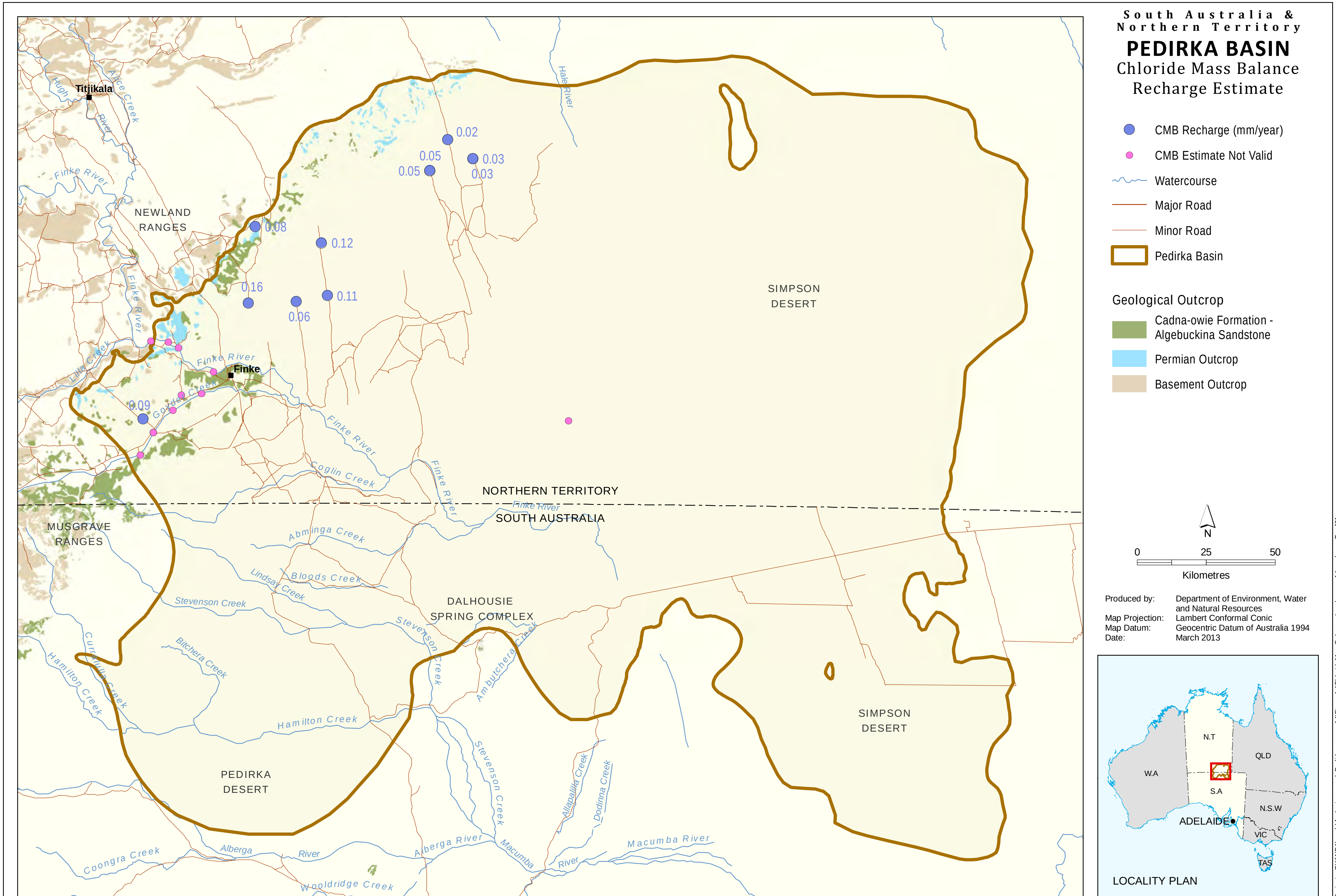

Figure 4.4: Chloride mass balance recharge estimate, Pedirka Basin

4.3.5.2. Ephemeral River Recharge

Ephemeral river recharge (ERR) describes the process of indirect recharge to aquifers resulting from episodic flow events in arid zone rivers. ERR relates to recharge occurring through the base of a river bed and does not include any localised recharge that results from overbank flooding. No published studies were identified that investigated ERR or estimated recharge rates through this mechanism to the Permian aquifer in the Pedirka Basin. However, Love et al. (2013b) studied ERR in the GAB aquifer along several rivers in the western Lake Eyre Basin. Rates of recharge for the Finke River (which also crosses the Pedirka Basin west of the GAB recharge zone) were estimated at between 380–850 mm/y using Carbon-14 derived groundwater velocities; while recharge from a single flow event in 2010 was estimated at 1275 mm based on hydraulic head measurements. The volumetric contribution of this recharge event across the recharge zone was estimated at 17000 ML (Love et al., 2013b).

Potential for ERR exists where drainage lines intersect outcropping Permian sediments or where the Permian aquifer sub-crops beneath permeable sediments. Figure 2.3 shows the surface water drainage system superimposed on the Pedirka Basin. Insufficient data exists to delineate the unconfined/confined boundary within the Permian aquifer, however as it is an overlying aquifer, the confining boundary for the GAB provides a guide highlighting regions of the Pedirka Basin where the ERR mechanism is unlikely to operate. This analysis suggests there is potential for ERR along the Finke River and lower Hale River as well as Goyder and Coglin Creeks in the Northern Territory, and Stevenson Creek and the Alberga River in South Australia.

There are no data available along the Alberga or Stevenson systems in South Australia with which to make an assessment of potential connection between the water courses and the Permian aquifer. In the Northern Territory, groundwater elevations are highest in the three wells adjacent to the Finke River. This is reflected in a mounding feature where the Finke River crosses the Crown Point Formation outcrop and suggests active recharge is occurring (Figure 4.5). This is supported by groundwater chloride data which shows distinctly lower chloride concentrations (79–109 mg/L) in wells adjacent to the Finke River compared with wells located away from the Finke River/Goyder Creek (580–3420 mg/L). The average chloride concentration from five flow events in the Finke River is 59 mg/L. The chloride distribution suggests recharge from Finke River flows are actively lowering chloride concentrations in the Permian aquifer.

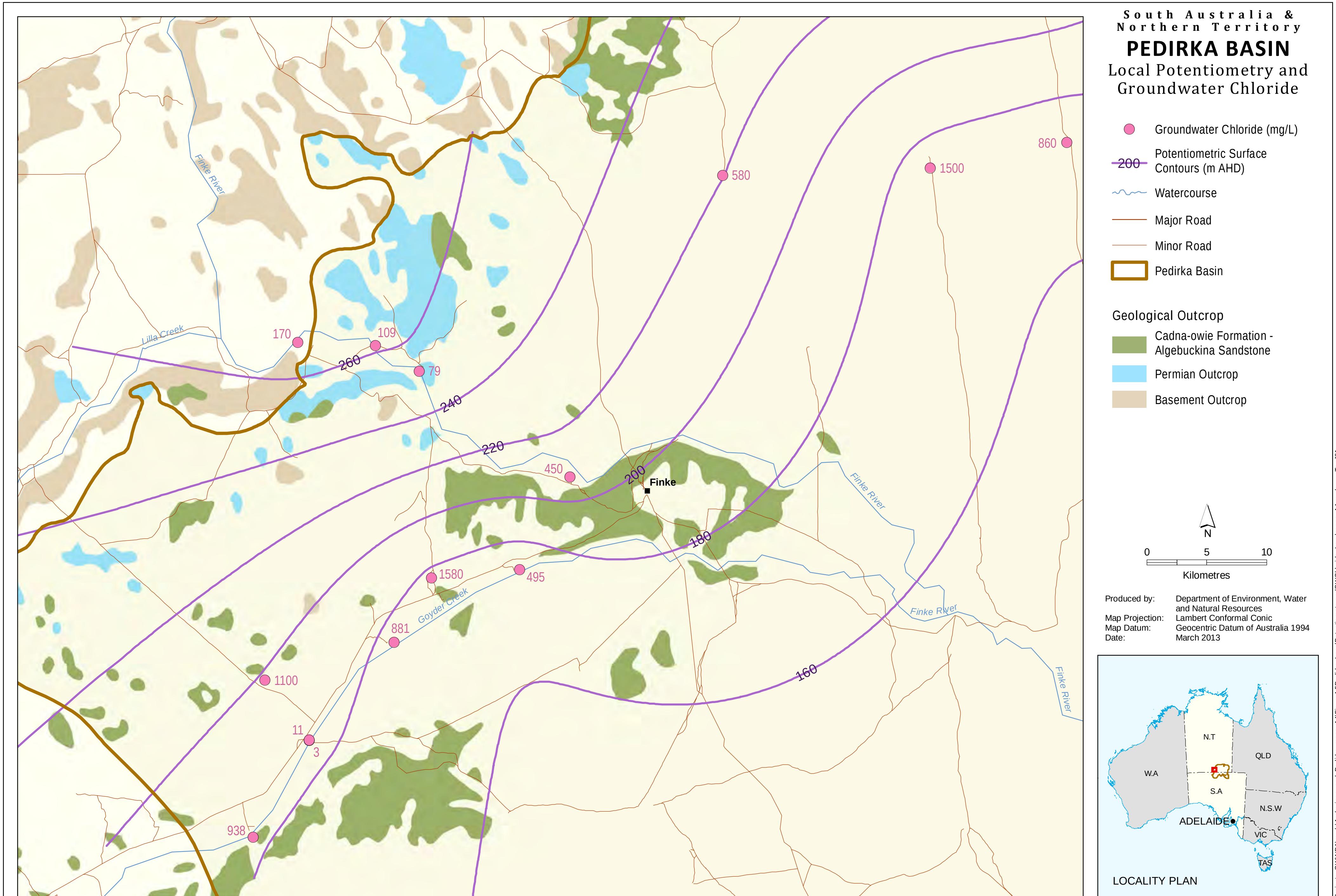

Figure 4.5: Potentiometric surface and groundwater chloride, north-west Pedirka Basin

4.3.6. DISCHARGE

There is limited information documenting groundwater discharge from the Permian aquifers in the Pedirka Basin. On a regional scale, Love et al. (2013a) suggests the Crown Point Formation may represent a potential source of discharge to the Dalhousie Springs complex. At a local scale, a series of waterholes identified in the bed of the Finke River on Lilla Creek Station may reflect a small scale flow system with local discharge from the Crown Point aquifer. Discharge is also likely to occur as cross-formational flow; however no studies were identified that characterised the direction or magnitude of this discharge component. The relative significance and knowledge gaps associated with inter-aquifer flow are discussed further in Section 4.5.

4.3.6.1. Regional Discharge – Dalhousie Springs

Of hydrogeological significance to the Pedirka Basin region is the Dalhousie Spring Complex. Dalhousie Springs is the largest spring complex within the western GAB, covering more than 200 km^2, (Habermehl, 1982). It is an important natural resource for the Lower Southern Arrente people and contains over 114 individual spring vents (Love et al., 2013a). The spring complex is located along the Dalhousie-McDills Ridge at the southern margin of the basin within South Australian; Krieg (1989) surmised that tensional fracturing and faulting associated with the development of the anticline that forms the ridge was the primary structural contributor to spring conduit formation. Dalhousie Springs is an important ecological and cultural asset that is entirely a dependant on spring discharge.

A recent investigation by Love et al. (2013a) summarised hydrochemical and water quality evidence obtained from Permian formation drill stem tests and spring samples, and hypothesised that groundwater from the Crown Point Formation contributes to discharge at the Dalhousie Spring Complex, in addition to the more widely recognised contributions from GAB groundwater sources. The fracture and fault system associated with the Dalhousie-McDills Ridge was postulated as providing subsurface connection between the Crown Point Formation and the spring complex. This study did not review the over-arching architecture of the Permian and basement formations in the Dalhousie region, and did not consider groundwater chemistry samples from the Crown Point aquifer on the edge of the basin. The findings from this study regarding the source aquifer for Dalhousie Springs are equivocal. Given the ecological and cultural significance of the spring complex, further investigation is warranted.

4.3.6.2. Local Discharge – Finke Waterholes

During a preliminary groundwater sampling trip undertaken in December 2012, several small waterholes were identified in the bed of the Finke River adjacent to outcropping Crown Point Formation. Discussion with the Lilla Creek Station manager suggested that these waterholes were transient and persisted for up to six months after significant rainfall or a flow event in the Finke River. One of these waterholes, approximately 200 m long and more than 50 m wide, has been identified on a Digital Globe image from 19 September 2006 (see Figure 4.6).

Figure 4.6: Digital Globe image taken on 19/09/2006. Length of water feature is approximately 200 m

A review of the rainfall records for 2006 from the Horseshoe Bend Homestead (Figure 4.7), located 30 km to the north, indicates that this image was captured in a period of extreme drought with only 70 mm of rainfall recorded for the calendar year with a maximum daily rainfall of 16 mm. The timing suggests that some of these waterholes may be permanent discharge features. Water quality attributes of the waterholes are not known but the closest stock bore (Paddy's Well) produces groundwater from the Crown Point Formation with a salinity of 463 mg/L and suggests that the water holes may contain potable water resources.

At present it is not clear whether these discharge features are associated with the Crown Point Formation or the Finke River alluvial system. In addition the number of waterholes, their size, permanence, water quality attributes, the nature of the connection with the groundwater system and their ecological significance remain unknown.

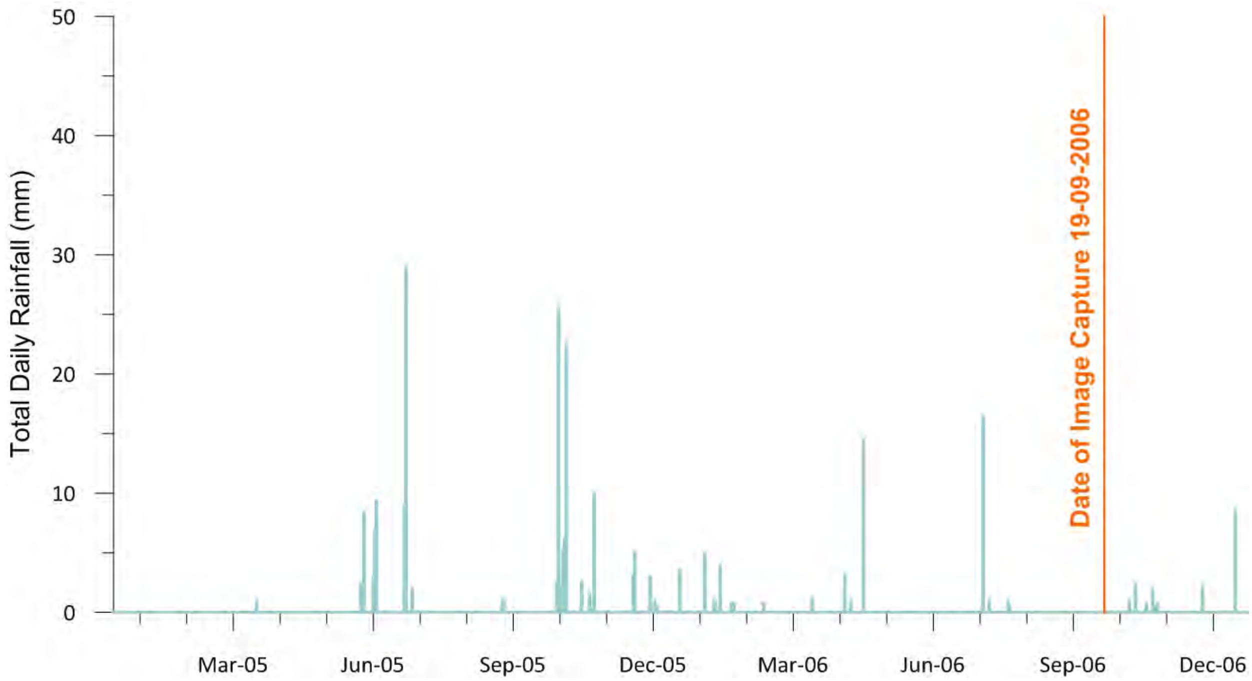

Figure 4.7: Rainfall record at Horseshoe Bend Station 2005–06

4.3.7. INTER-AQUIFER CONNECTION AND FLOW

Potential inter-aquifer connection, particularly between the Permian formations and the overlying GAB aquifer, represents a key unknown in the Pedirka Basin. Developing an enhanced understanding of this process will be critical in assessing the impact any potential development will have on the water resource and ecological assets of the region. Further investigation is needed to characterise the geological composition and hydraulic properties of the basal GAB aquifer and the upper sequence of the Purni and Crown Point Formations; particularly in areas of high development potential and/or high value water and ecological assets. Additional research is also required to understand baseline groundwater gradients between the Permian aquifer, the overlying GAB aquifer and the underlying Finke Group aquifer. At present the degree of interconnection between these formations is unknown, given the potential connection between the GAB aquifer and the Lake Eyre Basin this represents a key knowledge gap.

4.3.8. HYDROCHEMISTRY

Hydrochemistry data for the Crown Point Formation has been drawn from several sources, including: analyses of mandatory water samples taken from wells at the time of drilling; data from water quality benchmarking of pastoral wells, undertaken by the NT Water Resources Division intermittently over the last three decades; and published reports. Water quality data for the first two sources is available in the well statements which can be accessed online through the Northern Territory NRETAS maps data portal (http://www.nt.gov.au/nreta/nretasmaps/index.html).

Published investigations that present hydrochemistry data for wells intersecting the Crown Point Formation include: Mathews (1996), Radke (2000) and Love et al. (2013b). It should be noted that all of these studies focus on the GAB aquifer and do not necessarily distinguish the Crown Point Formation samples.

Twenty-one wells screening the Crown Point aquifer have data available on physical parameters and major ion chemistry. Salinities of Permian groundwater range from 93 to 7910 mg/L with an average water quality of 2470 mg/L. The lowest salinity groundwater is encountered in wells adjacent to the Finke River and Goyder Creek, where five wells contain high quality potable groundwater (salinity < 500 mg/L). The salinity is greatest in the northern most wells where it approaches 8000 mg/L and exceeds the guideline value for cattle watering of 5000 mg/L. There is very limited hydrochemistry data available for the Crown Point Formation outside the north-west margin of the basin. McDills No.1 is commonly categorised as producing water from the Permian sequence (Lau and Jacobson, 1991), however all samples taken after completion of the well as a water well, source water from the GAB aquifer rather than the Permian. The well completion report (Amerada Petroleum, 1965) does provide chemical analyses of a sample taken from an artesian flow at the top of the Permian sequence and reports a salinity of 2425 mg/L. An additional six chemical analyses have been undertaken on samples obtained during DST with a reported salinity range of 1084 to 14980 mg/L and an average salinity of 8900 mg/L. DST results have the potential to be contaminated by drilling fluids and are of much poorer quality than samples obtained from conventional groundwater wells. There are limited data available beyond major ion chemistry and physical parameters for the Crown Point Formation and no data available for the Purni Formation.

Crown Point Formation hydrochemistry data have been plotted on a tri-linear Piper diagram (Figure 4.8) which displays the relative concentrations of major and minor ions in groundwater samples. The data clusters in two distinct groupings: Group 1 with a HCO_3-Ca dominant water type and Group 2 with a Cl-Na dominant water type. The HCO_3-Ca end member (Group 1) is commonly associated with recharging groundwater, with all samples in this group sourced from wells located directly adjacent to the Finke River and Goyder Creek suggesting that these water courses are operating as recharge sinks. In contrast samples from Group 2 show a Cl-Na dominant water type which is associated with more evolved groundwater that has had longer residence time within the aquifer system.

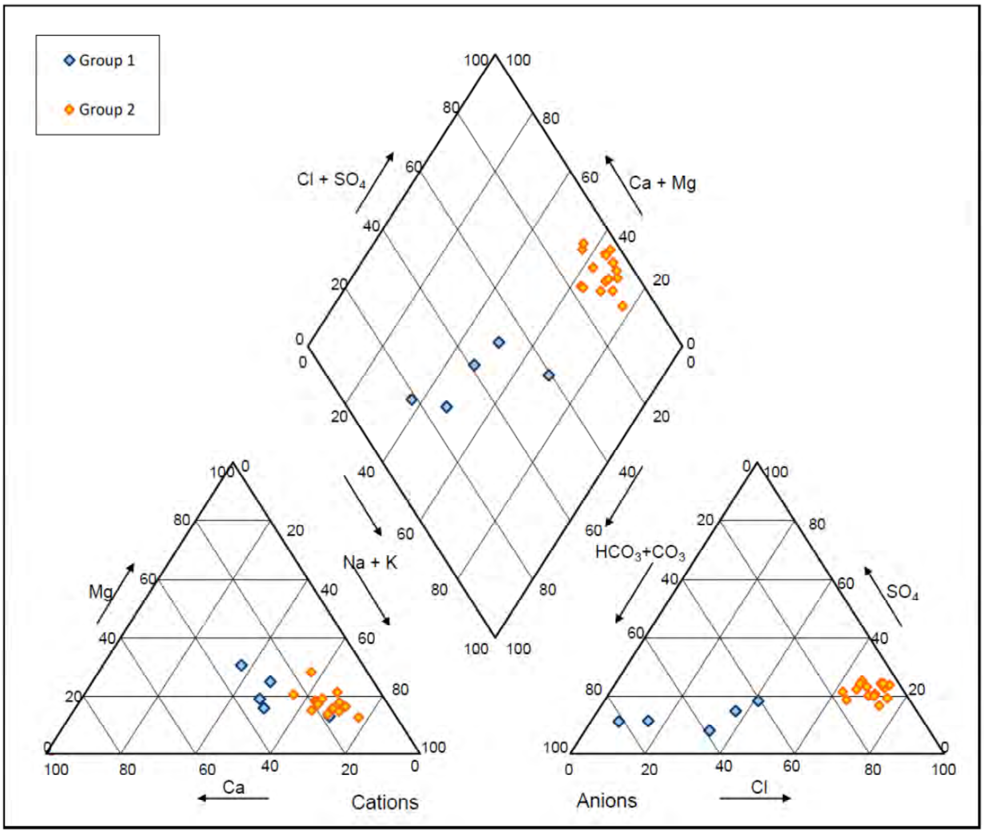

Figure 4.8: Tri-linear piper diagram, Permian groundwater

4.4. NEW KNOWLEDGE

4.4.1. BASIN ARCHITECTURE

4.4.1.1. Seismic and Log Interpretation

This section provides a regional, stratigraphic framework of Permian strata in the Pedirka Basin. The stratigraphic interpretation builds on previous work (e.g. Alexander and Jensen-Schmidt, 1995) to provide an improved understanding of basin development and architecture, with three-dimensional subsurface datasets highlighting areas of coal potential and connectivity to associated groundwater resources.

The inferred basin architecture is based on a process of interpreting several thousand line kilometres of seismic data, which are then integrated with stratigraphic control points (formation tops from 345 water, petroleum and mineral wells and a spatial coverage of surface geology [1:100000 scale]) using a process of gridding, contouring and review. The base Permian and top Permian seismic picks were clearly discernible. The seismic picks were then integrated with stratigraphic control–point data to provide surface structures for the base Permian and top Permian, and allowed for the creation of the Permian isopach. The interpreted Crown Point Formation and Purni Formation extents and structure surfaces were delineated using stratigraphic control data as the seismic picks used to distinguish these formations were inadequate. Individual isopachs of the Crown Point Formation and Purni Formation were regularly aggregated to ensure interpretation errors were minimised.

To summarise, three structure surfaces have been developed:

- Base Permian
- Top Crown Point Formation
- Top Purni Formation

For each structure surface, the formation extent has been determined with the base Permian extent providing the absolute extent of the Pedirka Basin. Additionally, three isopachs have been created:

- Permian (Crown Point Formation plus Purni Formation)
- Crown Point Formation
- Purni Formation

Seismic interpretation examples

The following seismic interpretation examples (Figure 4.9) provide an indication of the top GAB pick (green), top Permian pick (red) and top pre-Permian (blue). In these examples, the Crown Point Formation and Purni Formation have not been distinguished. These sections show that syn and post depositional folding and faults are prevalent within the Pedirka Basin succession. This deformation has important implications with respect to displacement and partitioning of Permian sequences and may provide evidence for flow partitioning within the Permian formations, or at least the existence of very complex flow paths within Permian aquifers. Such deformation may also provide evidence for vertical connectivity with overlying and underlying aquifer units.

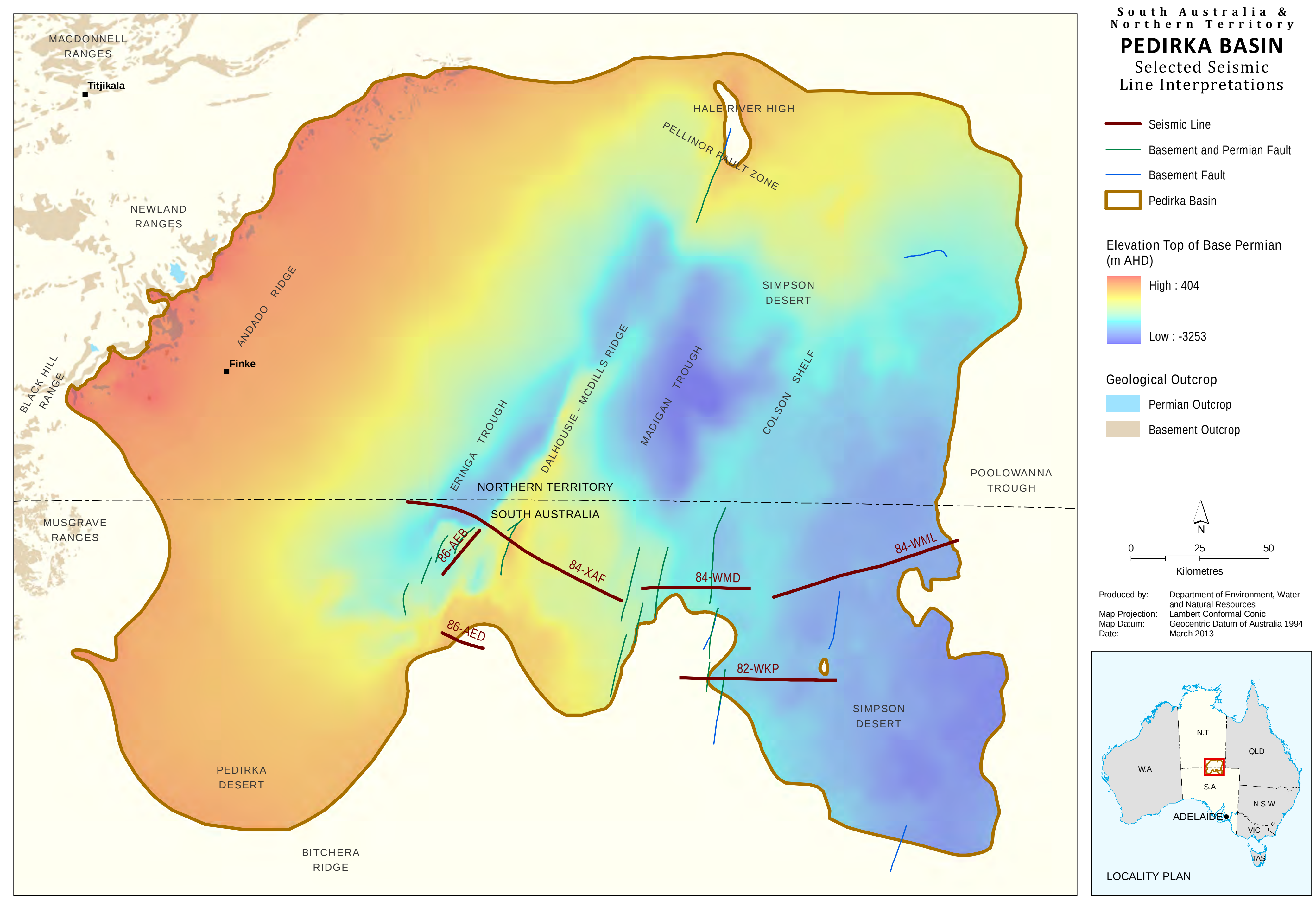

Figure 4.9: Location of seismic line interpretation examples, Pedirka Basin

Figure 4.10 (Line 86-AED) highlights the variable thickness of the Permian succession, which thins and pinches out on the western side of the Dalhousie-McDills Ridge. On the east side the Permian formation is absent. At this location the Dalhousie-McDills Ridge appears to form a bounding feature for the Permian formation.

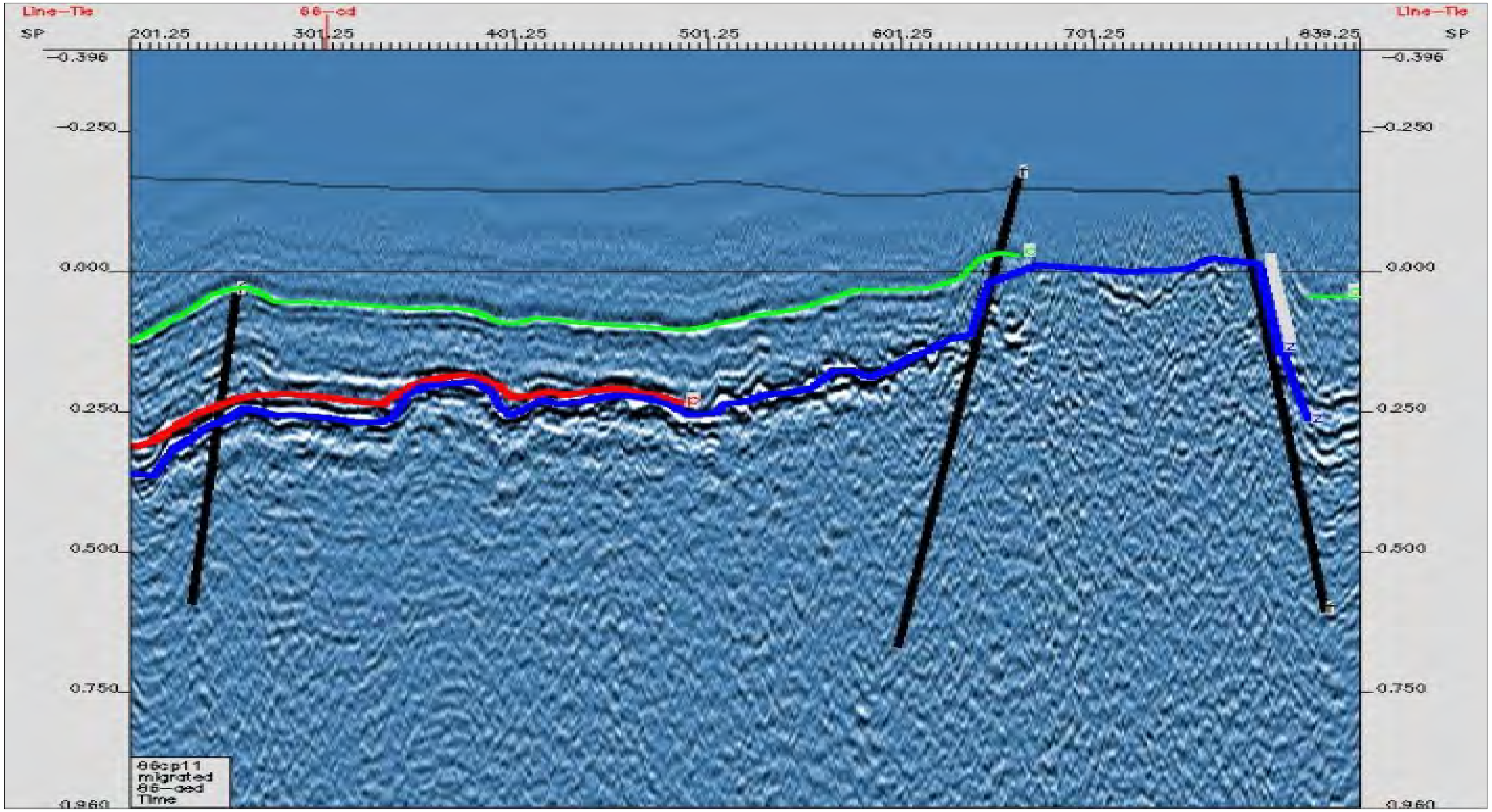

Figure 4.10: Line 86-AED

Figure 4.11 (Line 84-WMD) displays an example of fault deformation within the Pedirka Basin succession. Although the displacement along the fault within the western half (left hand side) is not sufficient to completely disrupt connectivity between formation strata, the displacement along the fault within the eastern half of the section is great enough to cause significant disconnection within the Permian sequence. The significance of faulting with respect to the hydrogeology of Pedirka Basin aquifers is highlighted in two ways: a) faulting may cause partitioning and therefore the formation of sub-basins and b) faulting may enable vertical connectivity between overlying or underlying aquifers.

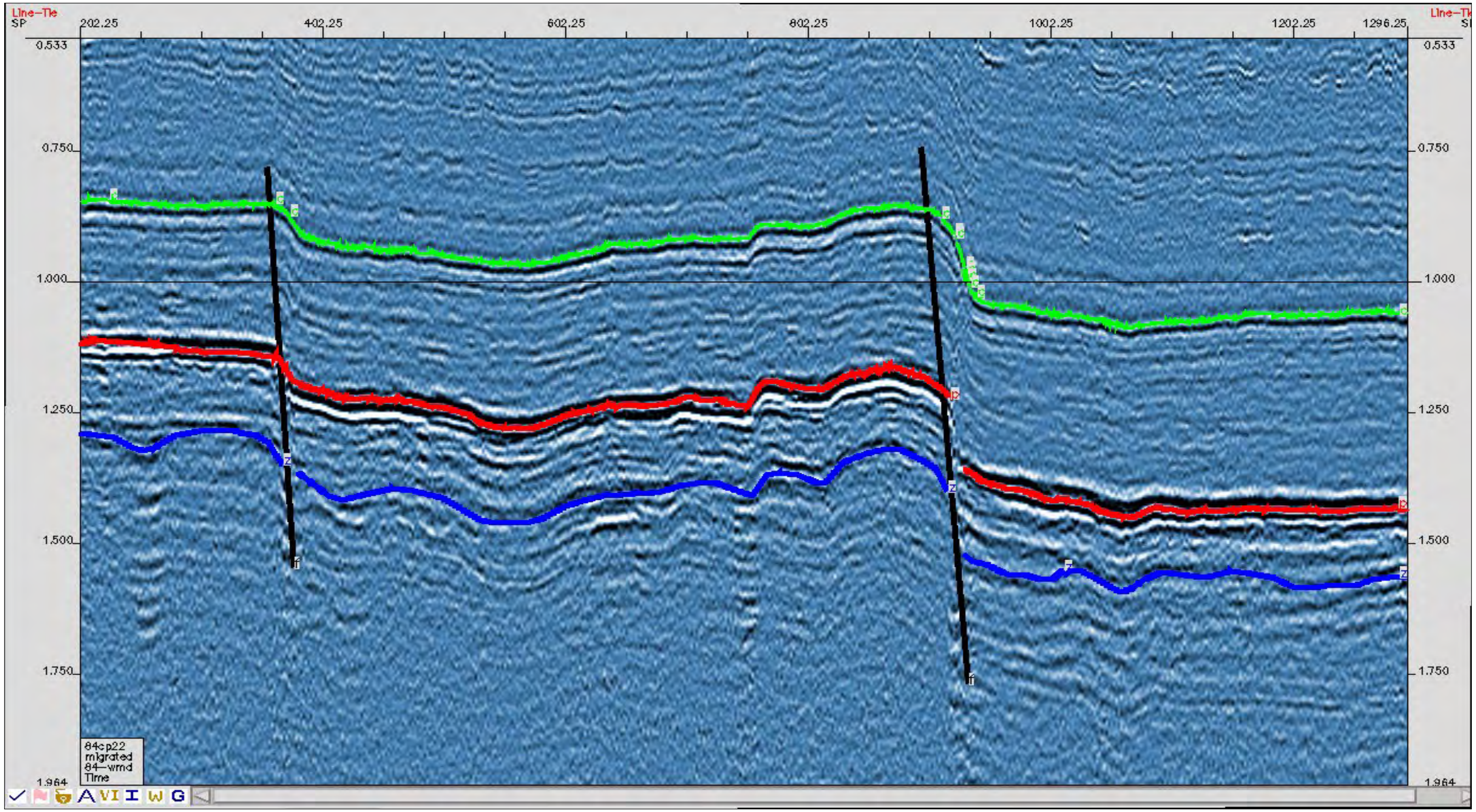

Figure 4.11: Line 84-WMD

Figure 4.12 (Line 82-WKP) Displays the influence of faulting pre, syn and post deposition. Firstly, displacement appears greater within basement units than overlying Permian and Mesozoic sediments. Secondly Permian sediments appear to be truncated to the west of faulting, suggesting a shallowing of the basin and/or erosion prior to the deposition of the Mesozoic sediments.

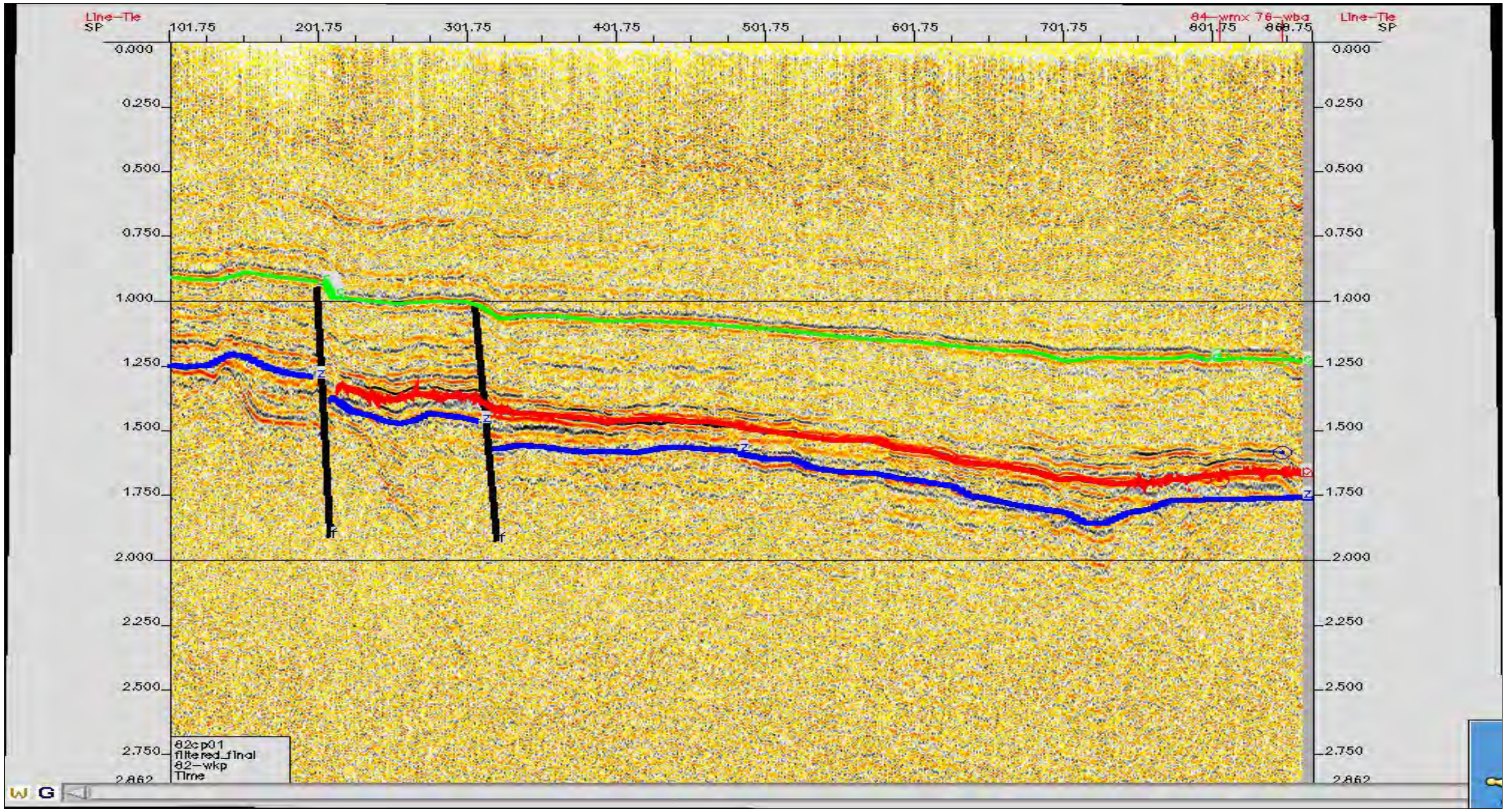

Figure 4.12: Line 82-WKP

Figure 4.13 (Line 84 XAF) shows the pinching and truncation of the Permian formations by significant folding and faulting associated with the Dalhousie McDills Ridge. These faults may provide pathways for groundwater movement between the Permian aquifers and the overlying GAB aquifers, as well as the potential demarcation of sub-basins within the Pedirka Basin. Also note the significant difference in formation thickness when comparing the left (western) and right (eastern) sides of the fault block.

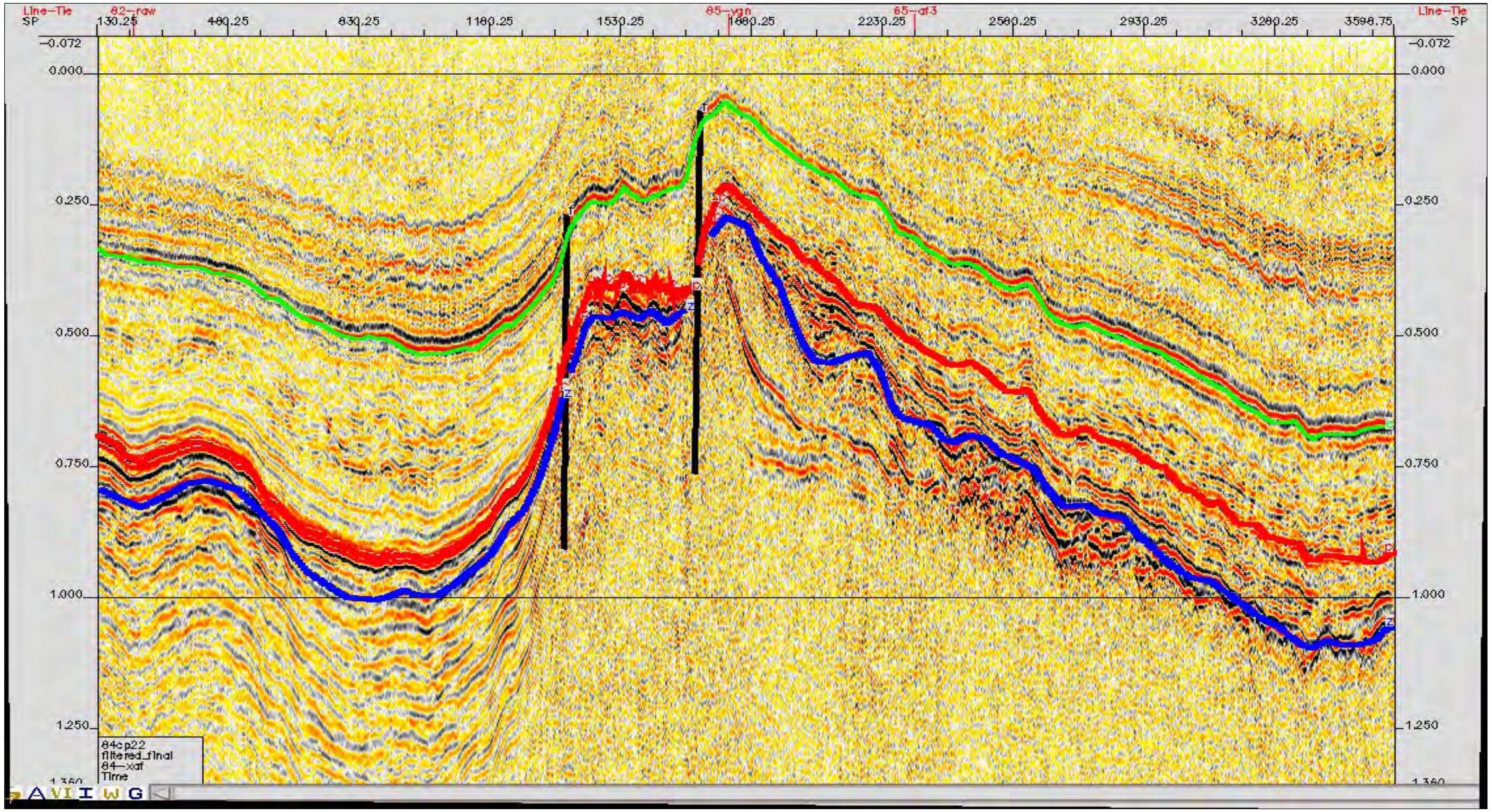

Figure 4.13: Line 84-XAF

Figure 4.14 (Line 84-WML) displays a seismic section trough the south–eastern portion of the Pedirka Basin. Faulting is interpreted to define the eastern boundary of the basin. Faulting does not appear to have displaced the Mesozoic sediments as much as underlying units, although these sediments appear draped over the resultant footwall.

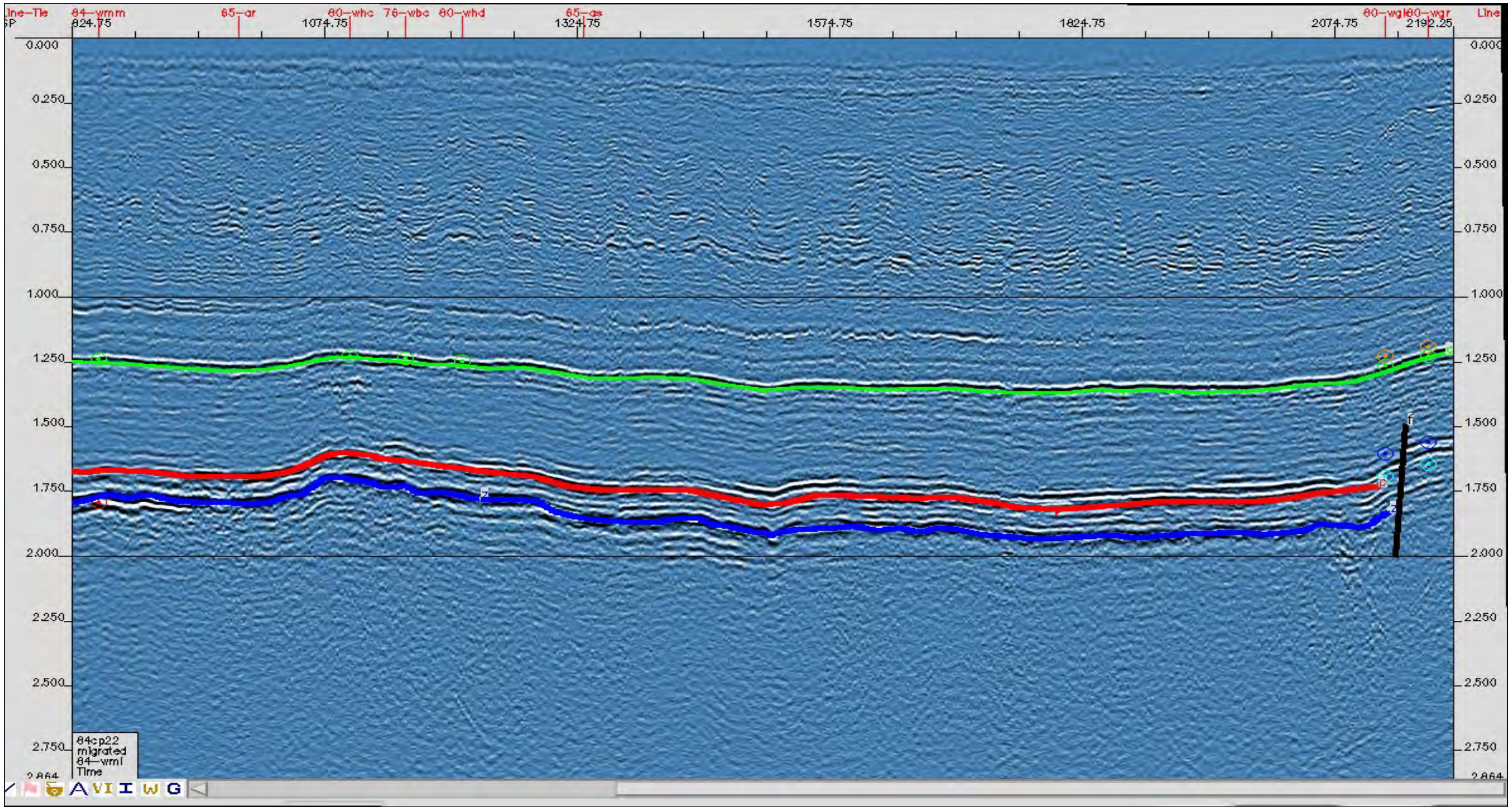

Figure 4.14: Line 84-WML

Figure 4.15 (Line 86-AEB) Displays a section located parallel to the strike of and near the southern end of the Eringa Trough. The trough structure to the left (south) of the section may have formed through erosion via glacial scouring and/or alluvial activity. The position of the channel may have been dictated by pre and syn depositional faulting, which appears to have upthrust strata located to the right (north). Greater thicknesses of Permian sediments occur within these troughs.

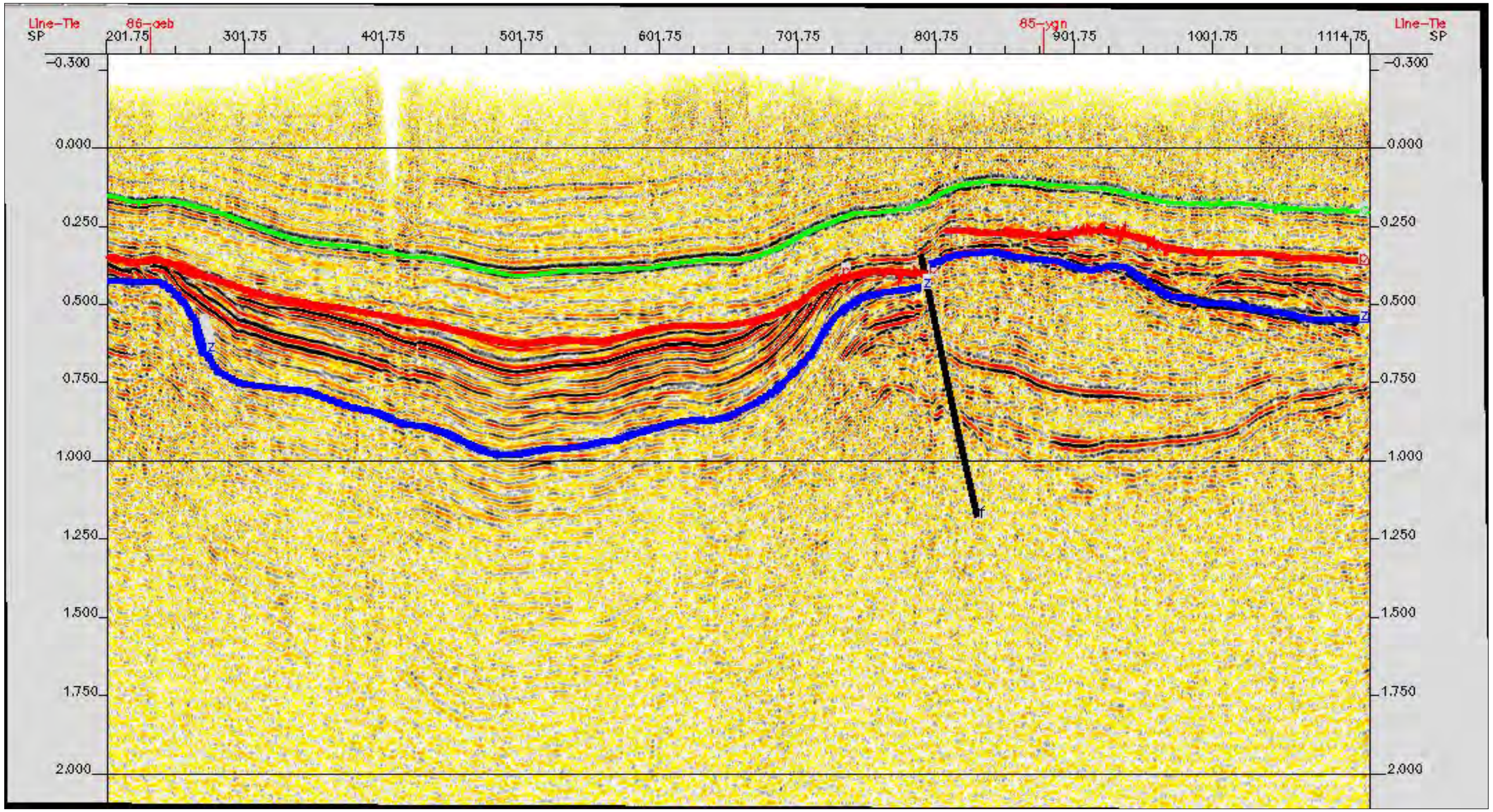

Figure 4.15: Line 86-AEB

4.4.1.2. Basin cross-sections

Basin-wide cross-sections (Figure 4.16) developed using the structural surfaces show a number of important architectural characteristics in the Pedirka Basin, these include:

- Permian sediments appear to be significantly faulted, with a number of normal and reverse faults identified; resulting in vertical displacement or the removal of sediments by erosion. In some instances, the displacement appears to have caused at least localised discontinuity within the Permian sequence; this being particularly evident in the vicinity of the Dalhousie-McDills Ridge. This feature may have led to the formation of partially disconnected hydrogeological sub-basins within the Permian sediments. Faulting is also important in identifying areas of potential secondary porosity development or the interconnectivity between the Permian aquifers with overlying and/or underlying formations.
- Similarly to the Arckaringa Basin, the base of the Permian strata forms a complex, glacially-scoured surface with significant erosional relief.
- The reinterpretation of seismic and logging data suggests that Permian sediments do not directly underlie the Dalhousie Springs Complex. Wolaver et al. (in press) suggested a deeper source of groundwater contributing to discharge at the Dalhousie Spring Complex based on temperature and related this to Permian formations. As a consequence, further analysis of structural features and water temperature and chemistry is required to ascertain whether or not Permian formation groundwater is contributing to spring discharge at Dalhousie Springs via fault and unconformity-related preferential flow pathways to surface.
- The cross-sections have helped redefine the thickness and extent of the Purni Formation, which extends further west than previously thought.

4.4.1.3. Confidence

As with the Arckaringa basin, the integration of seismic and logging data and subsequent mapping provides a consistent regional three-dimensional chronostratigraphic framework for the Pedirka Basin. This framework provides the basis for further studies investigating the stratigraphic, hydrostratigraphic and structural relationships between the Permian coals and shales, and the overlying Mesozoic units that contain significant groundwater resources.

As for the Arckaringa Basin, effort was made within the timeframe given to not only verify seismic interpretation against existing geological and hydrogeological data sets, but to also check the veracity of data and to re-interpret logging information appropriately when discrepancies between seismic and logging data became apparent. The coverage of seismic and stratigraphic logging data used to compile this interpretation of basin architecture and regional scale cross sections is provided with the inset map of Figure 4.16.

It is important to note that the seismic project and interpretations may need to be revised and refined by the inclusion of additional data. Likewise, drilling logs used to tie and verify seismic interpretation may need additional review, or where possible with the existence of archive material, re-logging and re-interpretation. This is particularly pertinent for drilling completed prior to the official classification of the Purni Formation separate to the Crown Point Formation.

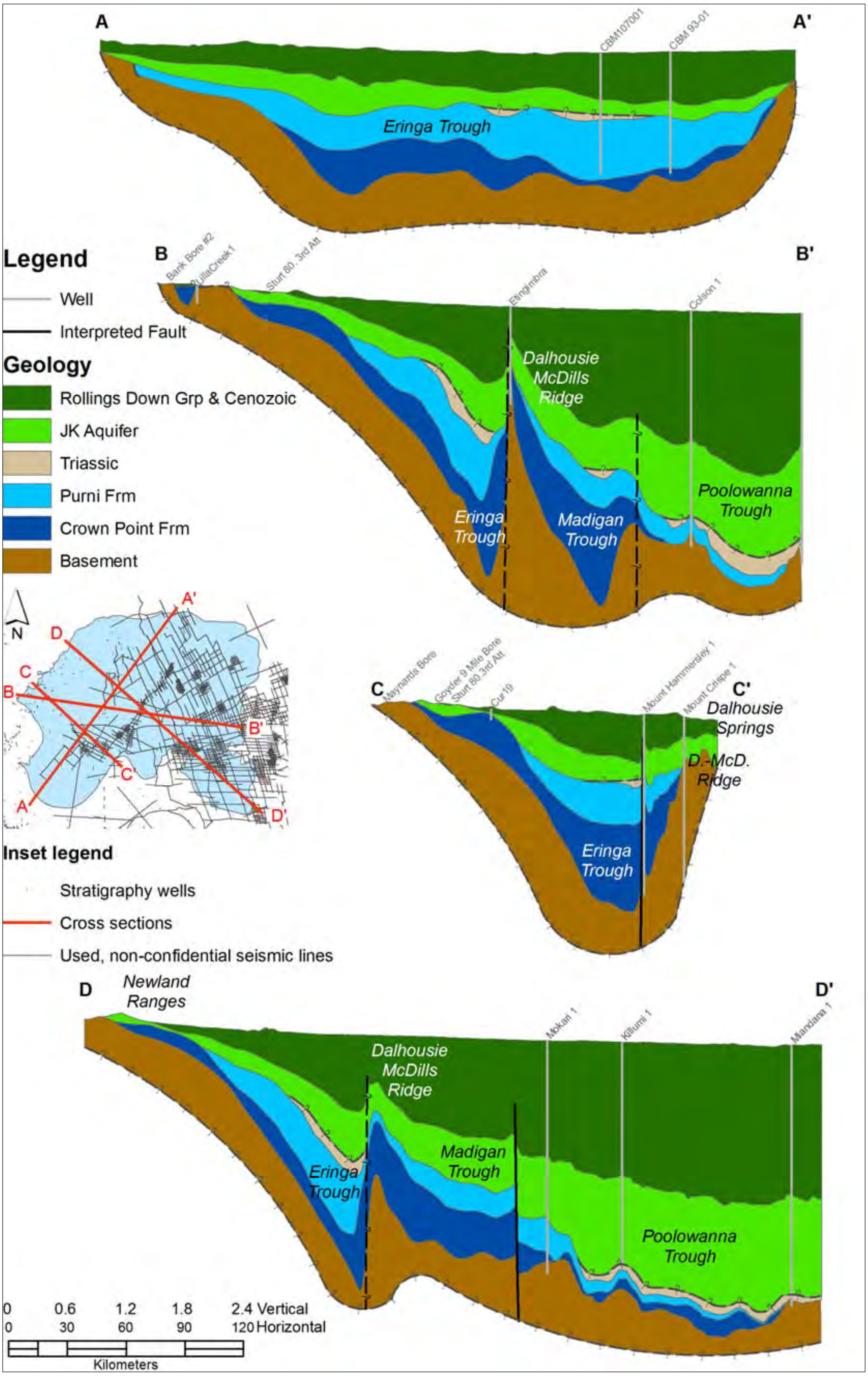

Figure 4.16: Interpreted cross-sections based on surfaces from seismic and well data

4.4.2. FIELD AUDIT

The South Australian portion of the Pedirka Basin, according to SA Geodata records and the basin extent described in Section 1.3.2.1, contains approximately 114 drill holes classified as water wells. An additional 17 wells have been indicated as backfilled. These 114 water wells form the basis of the field audit commenced under this project (Stage 1).

The objective for the field audit team was to produce a field survey report (Appendix B) for each water well, whether located or not. During the initial field surveys, a number of water wells were found to be:

- New – for which a new record was generated in SA Geodata and referral to the State Drilling Inspector provided
- Not located – for which the status on SA Geodata has been updated
- Backfilled – for which the status on SA Geodata has been updated

As part of the initial Stage 1 field surveying, 108 water wells have been audited within the Pedirka Basin (SA). Of these, 24 were confirmed as new wells not previously recorded in SA Geodata, 41 were able to be measured for water level (i.e. not equipped with a pump or windmill) and 21 were not located.

Salinity samples were collected from equipped water wells where possible.

Figure 4.17 shows the general spatial coverage of the initial Stage 1 Bore Audit Program (to March 2013), and represents approximately 95% of the total wells originally identified within the Pedirka Basin (SA). The Northern Territory Government's Department of Land Resource Management plans to undertake the Bore Audit Program within the Northern Territory portion of the Pedirka Basin beginning April 2013.

Table 4.7 provides a summary of the available water well data collected for the Pedirka Basin. These results are preliminary and subject to update upon the completion of the overall program

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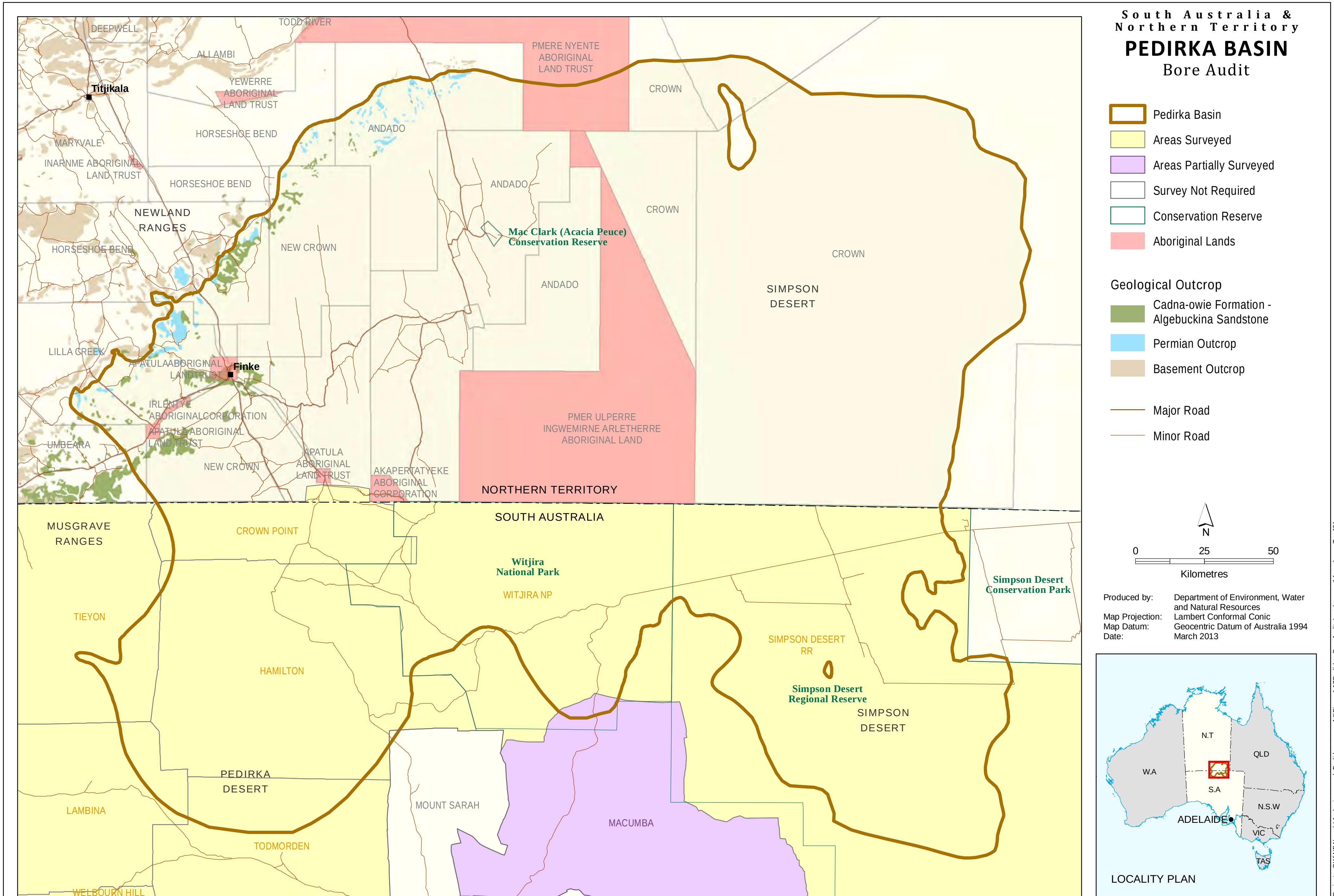

Figure 4.17: Initial Bore Audit Program, Pedirka Basin (areas surveyed prior to March 2013)

Table 4.7: Summary of surveyed wells, Pedirka Basin

Trip No.	Date of Trip	Pastoral Stations	Water Wells per Station	Water Wells Surveyed per Station	New Water Wells Found	Water Wells Not Located	Water Wells where WL Obtained	Comments
3	Oct 12	Crown Point	8	8	3	0	5 (1 dry)	
3	Oct 12	Hamilton	44	43	15	8	21 (1 dry)	1 well not visited
3	Oct 12	Lambina	12	12	1	1	5 (2 dry)	
3	Oct 12	Tieyon	8	7	0	4	0	1 well not visited
4	Sep 12	Macumba	7	3*	0	0	0	* Covered by GAB field survey Survey to be completed
4	Nov 12	Simpson Desert RR	9	9	0	1 (6*)	0	* Wells not located due to access issues
4	Nov 12	Witjira NP	26	26	5	7	10 (4 dry)	
Total		7	114	108	24	21	41	

4.4.3. HYDROGEOLOGICAL MAP

The accompanying Pedirka Basin hydrogeological map (part 1 and part 2) is a first edition for the Pedirka Basin. Information displayed in these maps include:

- A locality plan depicting administration boundaries, transport infrastructure and surface water hydrology.
- A plan of geological provinces showing the location of key geological and groundwater sub-basins, these include the underlying Amadeus and Warburton Basins, the overlying Eromanga Basin (GAB) and Lake Eyre Basin, and the pre-Cambrian basement (Musgrave and Arunta Blocks).
- Post plots of groundwater salinity for the Permian aquifer (excluding data from drill stem testing). The coverage of these data are restricted to the north-west of the Pedirka Basin, and highlights fresher groundwater around the Finke River and Goyder Creek relating to ephemeral river recharge. Little is known about water quality attributes of the aquifer outside this area.
- A density corrected potentiometric surface for the Permian aquifer (combined Crown Point and Purni Formations) which depicts the generalised direction of regional groundwater flow.
- As requested by the Office of Water Science, a phreatic watertable surface which depicts the first groundwater intersection at each well location. When compiling data for the production of this map, care was taken to remove any data points that were obviously artesian or sub artesian. This surface provides an estimate of the watertable depth across the Pedirka Basin but does not necessarily imply continuous groundwater movement across aquifers in different formations.
- The distribution of groundwater investigation and observation wells, and the location of any operational monitoring networks.
- Structural surfaces, isopachs (unit thickness) and extents for the Purni Formation, Crown Point Formation and the combined Permian sequence.
- Surface geology data sources, including, 1:1000000 surface geology and faults which were used for the interpretation of the seismic data and in the generation of the structure and isopach coverage's.
- A series of cross-sections showing the basin wide relationship between the Permian sequence, overlying and underlying units as well as the influence of structural elements (faulting and folding) on basin geometry.

4.5. CONCEPTUAL MODEL

Recharge is postulated to occur along the north-west margin of the basin where the Crown Point Formation outcrops in the Northern Territory. Groundwater level and chemistry data suggest that surface water flows in the Finke River and potentially the Goyder Creek are contributing indirect recharge to the Crown Point Formation; though at present a detailed understanding of the mechanism and recharge rates is not available. Several other watercourses intersect the western margin in South Australia and the Northern Territory; however, groundwater infrastructure is not available to assess the potential for recharge in these areas. The regional potentiometric surface suggests that diffuse recharge is occurring - or has occurred under a wetter palaeo-climate - where the Crown Point Formation outcrops in the north-west of the basin. A first order estimate of diffuse recharge using a groundwater CMB approach gave a range of 0.02–0.16 mm/y. The zone across which diffuse recharge could potentially occur is not currently defined.

There are no estimates of aquifer parameters (transmissivity, storage coefficients) available for either the Crown Point Formation or the Purni Formation; consequently there is no estimate of groundwater flow rates. The hydrogeological characteristics of the two formations are not well understood – the Crown Point Formation is an developed aquifer on the north-west margin of the basin and drill stem tests suggest sandstone intervals within both formations have reasonable permeability. However, it is not clear whether the Crown Point Formation and Purni Formation operate as a single aquifer, two separate aquifers or a series of discrete hydraulic units separated by less permeable layers of coal and mudstone. Due to paucity of data available for this review, the Permian formations have been treated as a single aquifer. Groundwater elevations are highest along the north-west margin of the basin with a regional groundwater flow direction to the south-east. The basin is conceptualised as a single continuous flow system; however, a review of the Permian structure reveals significant faulting and folding which may imply compartmentalised flow. Cross-formational flow between the Permian formations, the overlying GAB sequence and the underlying Finke Group aquifers is likely to be a significant process. However, little is currently known as groundwater data is too limited to establish vertical gradients and no studies have investigated hydraulic connectivity between these units.

Groundwater salinity in the Crown Point Formation ranges from 93–7910 mg/L with an average salinity of 2470 mg/L. The lowest salinity groundwater is found adjacent to the Finke River where the aquifer contains a potable water supply (<500 mg/L). Groundwater from wells in this area has a Ca-HCO_3 ionic signature and is distinct from other groundwater in the Crown Point Formation, which has a Na-Cl signature; this is viewed as further evidence of the active recharge from the Finke River.

Love et al. (2013a) suggests regional flow from the Crown Point Formation may provide a source of discharge at Dalhousie Springs – a significant regional spring complex which has previously been exclusively attributed as a discharge feature of the GAB aquifer system. Groundwater discharge has also been identified on the north-west margin in the form of a series of waterholes located in the Finke River. These discharge features are coincident with the zone of outcropping Crown Point Formation and are potentially fed by a local flow system within the Permian formations. No other groundwater discharge was identified.

Table 4.8 presents a summary of the conceptual groundwater model for the Pedirka Basin. Because published information and data from groundwater infrastructure is extremely limited, Table 4.7 also details knowledge gaps and information required to develop a more rigorous characterisation of the system.

Table 4.8: Conceptual groundwater model, Pedirka Basin

	COMPONENT	SUMMARY OF CURRENT INFORMATION	KNOWLEDGE GAPS
Recharge	Recharge Zones	Recharge postulated to occur on the north-west margin of the basin where the Crown Point Formation outcrops in the NT (Wells et al., 1970), however, recharge zone is not defined nor is the river reach contributing to ERR	Spatial extent of the potential zone for diffuse recharge is not defined. Recharge reaches of Finke River/Goyder Creek are not defined
	Recharge Mechanisms	Diffuse recharge presumed to occur where Crown Point Formation outcrops (Wells et al., 1970). Groundwater flow pattern supports diffuse recharge in this area. Potential for indirect recharge exists where the Finke River intersects the edge of the Pedirka Basin north-west of Finke Community (Love et al., 2013b). Hydraulic head, groundwater chloride and distribution of chemical water types support active recharge from the Finke River and potentially Goyder Creek.	It is unclear if diffuse recharge is still occurring under today's climate or if the head distribution reflects palaeo-recharge from a wetter climate Groundwater data are too limited to comment on the operation of focused recharge in systems other than the Finke River/Goyder Creek. No information available on focused recharge by overland flow
	Recharge Rates	Diffuse recharge rates estimated at between 0.02–0.16 mm/y using groundwater CMB method. The rate of ERR unknown.	High uncertainty surrounding CMB estimates of diffuse recharge The rate of ERR is not known
Aquifer Parameters	Transmissivity	No information available	No estimates of transmissivity or aquifer storage coefficients. Permeability measurements are primarily based on core analysis of small formation intervals and cannot reasonably be up-scaled to estimate formation hydraulic conductivity/transmissivity.
	Storage	No information available	
	Permeability and Hydraulic Conductivity	Purni Formation—Permeability estimates for sandstone intervals range from 135–2529 mD with a hydraulic conductivity range of 0.11–2.44 m/d. Permeability of the coal measures ranges from 0.2–66.7 mD with a hydraulic conductivity range of 1.7×10^{-3}–0.03 m/d.	
		Crown Point Formation—Permeability is reported at between 91–1998 mD with a hydraulic conductivity range of 0.08–1.66 m/d	
	Porosity	Purni Formation —Porosity ranges from 4–32% (16–25% for core analysis)	
		Crown Point Formation—Porosity ranges from 3–30% (11–32% for core analysis)	

Hydrodynamics	Aquifer Composition and Extent	The Crown Point Formation is a groundwater resource in the north-west of the basin. However, outside this area it is not clear whether the formation behaves as a single hydraulically connected aquifer or a series of discrete aquifers and aquitards. No groundwater wells are constructed in the Purni Formation. The nature of flow, connection and storage within the Purni Formation is not known. The western extent of the Purni Formation is unclear.	Outside the western margin the behaviour of the Crown Point Formation and Purni Formation as hydrogeological units is unknown. It is not clear whether they operate as independent or joint hydraulic units, or as a series of discrete aquifers and aquitards.
	Groundwater Flow	Regional groundwater flow direction is to the south-east. Local groundwater gradients along the western margin support active recharge from the Finke River.	Flow direction in the central portion of the basin and in South Australia is unknown. Flow direction is based on a composite Permian aquifer, individual flow directions within the Crown Point/Purni Formations are unknown
	Flow Scale	Not known at present. It is assumed that groundwater flow is regional; however, basin architecture suggests possible partitioning by faulting associated with the Dalhousie-McDills Ridge and around other major fault zones. The identification of waterholes along the Finke River suggests a local flow system in this area.	It is not known if the basin structure has resulted in partitioned flow systems within the Permian aquifer. Local flow components appear to drive discharge in the Finke River waterholes but the extent and dynamic of this system is not known
	Potentiometric Surface	A time composite, density corrected potentiometric surface was constructed for the Permian formations. The surface is based on very limited data and outside the north-west of the basin is only valid to infer very general flow direction. There are uncertainties associated with the reference elevation; the varying dates when water level measurements were collected; and the use of head estimates generated from formation pressures recorded in old drill stem tests, which may have an associated error of +/-30% (Hackbarth, 1970)	No groundwater level data outside the north-west region of the basin, with the exception of less reliable DST formation pressure estimates. The presented potentiometric map is a time composite surface; no data exist for the compilation of a single time or even decadal estimate. No data exist to distinguish individual surfaces for the Crown Point and Purni Formations.
	Cross-formational Flow	Potential inter-aquifer connections, particularly between the Permian formations and the overlying GAB aquifer, are unknown in the Pedirka Basin. Basin architecture and seismic sections identify areas where the Permian aquifer is displaced by faults and abuts the GAB sequence. At this point data is too limited to establish gradients and no studies have investigated hydraulic connectivity between these units.	The geological composition and hydraulic properties of the basal GAB aquifer and the upper Purni/ Crown Point Formations require characterisation. Vertical gradients need to be determined between the Permian aquifer, the overlying GAB and the underlying Finke Group.
	Basin Dynamics	Basin dynamics refers to whether the flow system is in a transient or steady state (i.e. whether recharge is equivalent to discharge). No information is available.	No information is available about the relative magnitude of recharge and discharge or the basin dynamic

	Hydrochemistry	Groundwater salinity ranges from 93–7910 mg/L. Low chloride, Ca-HCO_3 groundwater around the Finke River suggests active recharge. Little is known about groundwater chemistry outside the western margin	No reliable information on hydrochemistry outside the western margin. No isotope data to assess aquifer recharge processes or groundwater residence time.
DISCHARGE	Discharge Zones	Love et al. (2013a) suggests groundwater from the Crown Point Formation potentially contributes to discharge at Dalhousie Springs. The extent of this discharge zone is well characterised; however, the Permian formation flow component is not known. Several waterholes were identified in the Finke River adjacent to outcrop of the Crown Point Formation. It is not clear if these discharge features are associated with the Crown Point or the Finke River alluvial system. The number and permanence of these features is also yet to be determined.	The number, size and permanence of waterholes along the Finke River are unknown.
	Discharge Mechanisms	Regional discharge from Dalhousie Springs – discharge mechanism is believed to be driven by faulting/fracturing associated with the Dalhousie-McDills Ridge structure. The Finke River waterholes potentially relate to discharge from a local flow system within the Crown Point Formation; however, they could alternatively be sourcing water from the Finke River alluvial deposits. There is no information on water quality or discharge mechanisms.	The potential connection between the Permian formations and Dalhousie Springs requires verification. The discharge mechanism and the source aquifer for the waterholes is unknown, as are their water quality attributes and ecological significance
	Discharge Rates	No information available on discharge rates from the Permian Formations.	The component of Permian groundwater (if any) contributing to discharge at Dalhousie is not known. The rate of groundwater discharge to Finke water holes is unknown

5. CONCLUSIONS

5.1. SUMMARY OF DATA AND KNOWLEDGE GAPS

The process of reviewing and compiling data for the Stage 1 report revealed significant knowledge gaps in our understanding of groundwater recharge and discharge processes, flow dynamics and inter-aquifer connection within the Arckaringa Basin and Pedirka Basin. This data and knowledge paucity limits the accuracy and reach of assessments investigating potential risks to groundwater resources from coal seam gas and large coal mining developments.

The Stage 1 investigation begins to address some of the data deficiencies by collating all existing information associated with the hydrostratigraphy, basin architecture and hydrogeological characteristics of the Arckaringa Basin and Pedirka Basin. This review provides an initial conceptual model of groundwater flow and hydrodynamics within each basin. It is hoped this preliminary conceptualisation will provide a platform for future work aimed at addressing critical knowledge gaps.

5.1.1. ARCKARINGA BASIN

5.1.1.1. Summary of data

The Arckaringa Basin is an inter-cratonic, sedimentary basin composed of Carboniferous to Permian-aged rocks, the majority of which is sub-cropping. The Permian formations are largely overlain by a Mesozoic sequence associated with the Great Artesian Basin, and Palaeocene and Holocene sediments associated with the current day Lake Eyre Basin.

There are three major hydrostratigraphic units within the Arckaringa Basin: Mount Toondina Formation, Stuart Range Formation and Boorthanna Formation. Aquifers are known to occur in the terrestrial and transitional sediments and coal sequences found within the Mount Toondina Formation; as well as the glaciogenic and palaeochannel sediments of the Boorthanna Formation. In particular, coarse grained sandstones associated with the basal units of the Boorthanna Formation have been identified in palaeochannels, and are interpreted to occur in the main basin depocentres. In contrast, the largely quiescent-marine sediments of the Stuart Range Formation are finer grained and largely regarded as a confining layer. Aquifers reported within the Mount Toondina and Boorthanna Formations include intra-formational units that are laterally discrete, only partially connected and dependent on the formation of secondary porosity. Sediments can be divided into two sequences; the first sequence includes the Boorthanna Formation and some Stuart Range Formation, and represents a period of glaciation and marine transgression. The second sequence comprises the remaining Stuart Range Formation and the Mount Toondina Formation, and represents a period of marine regression.

The structural architecture of the Arckaringa Basin is complex. The initial formation, as well as syn- and post- depositional deformation was controlled by tectonic activity associated with the activation of deep-seated fault systems that first originated in the Pre-Cambrian. This faulting has formed a basin in which the formation thickness is highly variable. Seismic interpretation indicates that the base of the Permian succession is glacially-scoured with significant relief. The existence of semi-discrete sub-basins is demonstrated through previous work undertaken in the south-eastern portion of the basin (the Billa Kalina sub-basin) and is supported through seismic interpretation and cross-section development presented in this report. There is a notable distinction between the western and eastern Arckaringa Basin; the western half of the basin is characterised by a thin sediment package, relatively simple hydrostratigraphy and moderate faulting, while the eastern Arckaringa is characterised by highly variable but comparatively thick sediment package, a more complex hydrostratigraphy and a comparatively high degree of fault-related deformation.

Groundwater from Arckaringa Basin aquifers has generally been described as brackish to ultra-saline, with hyper-saline groundwater (>100000 mg/L) observed in the coal seam aquifers of the Mount Toondina Formation. Better quality groundwater, including potentially potable groundwater, occurs near the south-eastern and eastern margins of the basin, in the vicinity of the Gawler Ranges, southern Stuart Ranges, and Peake and Denison Inlier. An increase in salinity occurs between these two areas, east of the Mount Woods Inlier and the Stuart Range and also in the vicinity of the Phillipson Trough. Yields from wells completed in Arckaringa Basin aquifers typically vary from <0.1 to 5 L/s.

5.1.1.2. Knowledge Gaps

Existing groundwater data and knowledge in the Arckaringa Basin come from discrete areas associated with mining or energy exploration, with the largest and most notable of these being the Billa Kalina sub-basin area. Information regarding the hydraulic characteristics of basinal sediments is also available from coal and petroleum exploration and mining feasibility studies. The concentration of existing work in a few spatially constrained areas limits the use of these studies in describing the behaviour of the groundwater system on a regional scale.

Recharge zones and recharge mechanisms are not well understood for the Permian formation aquifers. A range of possible recharge areas and mechanisms have been suggested in the literature, however there is limited supporting data. Reported recharge processes include: diffuse recharge in areas where the overlying GAB sequence is unsaturated; indirect recharge from swamp and marsh areas located near the margins of the basin; and upward flow from underlying aquifers, particularly those associated with limestone sediments. In most studies, supporting evidence has come from data obtained from pre-existing wells or is based on an extrapolation of data from a small study area. Direct evidence of recharge zones and mechanisms is very limited.

Discharge zones and mechanisms are similarly poorly characterised in the Arckaringa Basin. Potential processes include:

- discharge into fractured rock and karstic aquifers associated with the underlying Stuart Shelf in the south-east of the basin
- diffuse discharge along ephemeral stream lines
- discharge through salt-pan and playa environments located in the south-west margin
- spring discharge.

With respect to discharge to karstic aquifers and discharge along stream lines, supporting evidence has come from data obtained from pre-existing wells or is based on an extrapolation of data from a small study area. A detailed argument against spring discharge has been made for the Billa Kalina sub-basin, but this cannot be used to exclude other areas in the wider Arckaringa Basin, where little to no work has been undertaken. As with recharge processes, there have been no focused studies to identify and characterise discharge in the Arckaringa Basin.

The spatially and temporally limited scope of existing studies reduces their regional application. In several studies the limited spatial extent of the investigation is insufficient to explain contradictions between groundwater hydraulics and hydrochemistry (e.g. Howe et al., 2008; Lyons et al., 2010). Similarly, the Stuart Range Formation has been described as both an effective barrier to downward leakage (SKM, 2009: Lyons et al., 2010) but has also been speculated to provide sufficient leakage to allow drawdown stabilisation during pumping tests (SKM, 2009; Aquaterra, 2009). This may suggest that the porosity and permeability of the Stuart Range Formation is heterogeneous at a regional scale and is perhaps subject to secondary porosity development.

With respect to hydrostratigraphic interpretation, a comparison of drilling logs with collated seismic data has revealed inconsistencies with: a) the identification of the Stuart Range Formation; and b) the differentiation between Mesozoic and Permian sands particularly near the margins of the basin. These inconsistencies have arisen because much of the drilling data were not collected for the purpose of hydrogeological studies. In both instances reliance on these data for the interpretation of groundwater flow and estimations of hydraulic properties will involve greater uncertainty.

Finally, the restriction of hydrogeological studies to small and discrete areas means a significant proportion of the Arckaringa Basin has little to no well coverage. In such areas, conceptualisation of the regional hydrogeological characteristics of the basin is conjecture at best. A number of these areas include regions where coal seam gas and large coal mining developments are proposed, most notably the northern parts of the Boorthanna Trough, the Wallira, West, Penrhyn and Phillipson troughs located near the southern margin and the Karkaro and Mt Furner Troughs that occupy the northern half of the basin.

5.1.2. PEDIRKA BASIN

5.1.2.1. Summary of data

The Pedirka Basin is an intracratonic sedimentary basin comprising largely early to late Permian sediments and coal sequences. The basin is located in the north of South Australia and straddles the South Australian / Northern Territory border. Much of the Pedirka Basin occurs at depths greater than 400 m, although outcrop of Pedirka Basin sequences occurs along the north-west margin of the basin in the Northern Territory (Munson and Ahmad, 2012).

Currently, there are two recognised hydrostratigraphic units within the Pedirka Basin: the Purni Formation and underlying Crown Point Formation. It is noted that logging of core and cutting material completed before Jaques (1966) may not utilise formal names for Permian sequences or may refer to all Permian strata as Crown Point Formation. Additionally, more recent work suggests a review of formal stratigraphic nomenclature is required including: the subdivision into units on the basis of stratigraphy, palynology and unconformities (e.g. Sub-units A1, A, B and C of the Purni Formation).

With respect to the hydrogeological characteristic of each formation, the Crown Point Formation is reported as an aquifer along the western margin of the basin where it is developed as a stock and domestic water supply. Data from drill stem testing further towards the centre of the basin confirms the presence of permeable sequences within the Crown Point Formation. There is no information on the hydrogeological status of the Purni Formation. On the basis of stratigraphic descriptions and geophysics it is likely that both the Crown Point and Purni Formations behave as a series of aquifer and aquitards rather than single, homogeneous hydraulic unit. There are no transmissivity or storage coefficient estimates available for either the Crown Point Formation or the Purni Formation. Petroleum and coal investigations provide a range of porosity estimates for both formations. Associated laboratory analysis of formation core and drill stem tests offer an estimate of formation permeability, which have been converted to hydraulic conductivity values for this report. Hydraulic conductivity estimates for sandstone intervals range from 0.08–1.66 m/d for the Crown Point Formation and 0.11–2.44 m/d for the Purni Formation.

Depth to groundwater is greatest on the north-west margin of the basin, approaching 150 mbgs. The direction of regional groundwater flow is to the south-east and artesian groundwater conditions are expected to occur in the centre and eastern regions of the basin. Groundwater quality is generally suitable for stock (cattle) watering but improves around the Finke River where it forms a quality potable water resource; salinity ranges from 93 to 7910 mg/L with an average water quality of 2470 mg/L.

Recharge is believed to occur along the north-west margin of the basin where the Crown Point Formation outcrops. Groundwater chloride and major ion chemistry distribution support the operation of indirect recharge from the Finke River and potentially Goyder Creek. Less clear is the contribution of diffuse recharge, which is estimated using groundwater CMB methods at between 0.02–0.16 mm/y. Love et al. (2013b) suggests Dalhousie Springs may form a regional discharge point for the Crown Point Formation. Several water holes have been identified in the Finke River adjacent to outcropping Crown Point Formation, existing information is insufficient to determine whether these discharge features are associated with the Permian aquifer or the Finke River alluvial system. Cross-formational flow is considered to represent a significant groundwater inflow/outflow process, but could not be assessed due to insufficient data.

5.1.2.1. Knowledge Gaps

The existing level of hydrogeological information on the Pedirka Basin is extremely limited. Existing published reports invariably discuss Permian aquifers as a contextual adjunct to the main focus of the study, generally groundwater resources within the Great Artesian Basin or Amadeus Basin. The vast majority of groundwater information concerning the Pedirka Basin comes from wells installed for groundwater extraction. These are located exclusively along the western margin of the basin within the Northern Territory, where the Crown Point Formation is used as a source of stock water for pastoral enterprises and provides a water supply for several Aboriginal outstations west of Finke (Apatula) Community. Additionally, some information regarding the hydraulic characteristics and formation pressures within Permian sediments has been sourced from petroleum exploration studies.

As a consequence of the paucity of groundwater-related infrastructure, little is known about the groundwater characteristics of the Permian sequence across much of the Pedirka Basin. Key knowledge gaps are associated with: recharge mechanisms; zones and rates; absence of aquifer parameters (hydraulic conductivity, transmissivity and storage coefficients); the groundwater flow pattern outside the north-west margin; the hydraulic characterisation and interconnection between the Crown Point and Purni Formations; groundwater flow rates and basin dynamics; cross-formational flow – particularly connections with the GAB; and characterisation of the driving mechanisms, extent and flow rates associated with local and regional discharge features. Further detail on these data gaps is documented in Table 4.8.

6. RECOMMENDATIONS

6.1. *PROPOSED STAGE 2 ACTIVITIES*

6.1.1. HYDROGEOLOGICAL INVESTIGATION – GROUNDWATER RESOURCE CHARACTERISATION AND CAPACITY TESTING

- Finalise field audit of existing water wells
- Characterise recharge processes, mechanisms and rates
    - Initial characterisation of recharge zones
        - Assessment of regional potentiometric surfaces, where data are sufficient
        - Constrain areal extent of diffuse recharge
        - Constrain the locations of focused recharge
    - Initial investigation of diffuse recharge
        - Constrain regional chloride mass balance
        - Determine point diffuse recharge estimates
            - Drilling and assessment of continuous core to determine palaeorecharge
            - Assessment of environmental tracers
    - Initial investigation of focused recharge
        - Initial assessment of ephemeral river recharge
            - Drill cross-section of observation bores
            - Assessment of water level mounding (reliant on river flow)
            - Assessment of geochemical tracers – isotopes and chemistry
            - Comparison against regional observations
        - Initial assessment of recharge via ephemeral swamps
            - Drill cross-section of observation bores
            - Assessment of water level mounding (reliant on inflow)
            - Assessment of geochemical tracers – isotopes and chemistry
            - Comparison against regional observations
    - Initial assessment of timescales
- Characterise discharge processes, mechanisms and rates
    - Initial investigation of diffuse and point discharge
        - Initial investigation of Permian contribution to Dalhousie Springs
        - Initial investigation of Permian discharge at other spring complexes
            - Initial investigation of fault controls on groundwater discharge e.g. Weedina Fault area
        - Initial assessment of water holes along the Finke River
            - Assessment of geochemical tracers – isotopes and chemistry
            - Areal extent mapping
            - Determination of simple water balance
        - Up scaling discharge estimates
- Characterise groundwater flow
    - Initial assessment of potentiometric surfaces, where data are sufficient
    - Initial assessment of intra- and inter-basin connectivity

- Assessment of existing monitoring data from compliance wells located within the Billa Kalina sub-basin for evidence of interconnection between the Boorthanna Formation Aquifer and aquifers within the GAB.
- Partnership with industry drilling and seismic investment
  - Initial investigation of through flow to the Stuart Shelf
    - Regional geochemical tracer analysis
    - Regional hydraulic head analysis
    - Seismic acquisition to improve basin characterisation and influence of faulting
  - Initial assessment of vertical flow - continuous core drilling
    - Pore-fluid chemistry and geochemical tracers
    - Physical parameters
    - Wire-line pressure loggers
- Constrain conceptual hydrogeological models of the Arckaringa Basin and Pedirka Basin
- Development of initial elementary numerical groundwater models of the Arckaringa Basin and Pedirka Basin
- Summary reporting on activities and outcomes

6.1.2. REPORTING OF NEW KNOWLEDGE AND THE PROVISION OF KEY INFORMATION PRODUCTS FOR STAKEHOLDER GROUPS

- 2nd Edition Hydrogeological Map(s) of the Pedirka Basin
- 2nd Edition Hydrogeological Map(s) of the Arckaringa Basin
- Provision of recommendations for regional monitoring network(s)
- Reporting – summary reporting for activities and outcomes

6.2. RECOMMENDED ACTIVITIES BEYOND STAGE 2

6.2.1. DATA EVALUATION, GEOPHYSICAL INTERPRETATION, FIELD MAPPING AND FIELD PROGRAM PLANNING

- Design and planning of follow up drilling and water analysis programs

6.2.2. HYDROGEOLOGICAL INVESTIGATION – GROUNDWATER RESOURCE CHARACTERISATION AND CAPACITY TESTING

- Enhanced stratigraphic determination – tie into existing data sets and enhance geological understanding
  - Engage with industry to incorporate new seismic data
  - Acquisition of complimentary seismic data
  - Targeted wireline logging
  - Targeted stratigraphic drilling
  - Consider the influence of secondary and primary porosity
  - Improved field geological mapping of outcropping material (e.g. Pedirka Basin – Crown Point)
  - Improved stratigraphic interpretation using palynological techniques (e.g. Pedirka Basin – distinguish between Crown Point and Purni Formations)
- Final basin architecture

    - Incorporate new data into existing framework
- Characterise recharge processes, mechanisms and rates
    - Final investigation of diffuse recharge
        - Finalise regional chloride mass balance
        - Finalise assessment of point diffuse recharge
            - Multiple continuous core investigation sites
    - Detailed investigations into focused recharge
        - Consolidated assessment of ephemeral river recharge
        - Consolidated assessment of water holes along the Finke River
        - Consolidated assessment of recharge via ephemeral swamps
        - Consolidated assessment of mountain system recharge
    - Finalise assessment of timescales related to recharge
- Characterise discharge processes, mechanisms and rates
    - Detailed investigation of diffuse and point discharge
        - Consolidated investigation of Permian contribution to Dalhousie Springs
        - Consolidated investigation of Permian discharge other spring complexes
            - Detailed investigation of fault controls on groundwater discharge
        - Consolidated investigation of up scaling discharge estimates
- Characterise groundwater flow
    - Final assessment of intra- and inter-basin connectivity
        - Horizontal versus vertical flow investigation
            - Pressure – elevation assessment
        - Down-hole logging using Magnetic Resonance Sounding technology to inform aquifer porosity
        - Extended drilling investigation program
            - Continuous core drilling, plus hydraulic and hydrogeologic analysis
            - Multiple nested sites for long term aquifer testing to determine hydraulic properties
            - Installation of wire-line pressure logging technology to determine vertical fluxes
    - Determine hydrodynamic state - relate to modelling
        - $R = D$ or $R < D$
        - Boundary conditions
        - Transient versus steady-state
- Revisited water sampling program to address key information and knowledge gaps as identified in development of the initial conceptual model
- Integration of hydrogeological knowledge with hydro-ecological assets
- Consolidated reporting on activities and outcomes

6.2.3. REPORTING OF NEW KNOWLEDGE AND THE PROVISION OF KEY INFORMATION PRODUCTS FOR STAKEHOLDER GROUPS

- Data collaboration road map – ensuring partnership with data custodians, e.g. compatible formats for incorporation into national data and information records systems
- Reporting of consolidated regional hydrostratigraphic assessment of existing lithological and stratigraphic information
- Consolidated and revised hydrogeological conceptual understanding to inform the bioregional assessment
- Establishment of the regional monitoring networks(s)

- Assessment and reporting of all related ecological data
    - Development of an ecological risk assessment in consideration of hydrogeological investigation outcomes
- Development and reporting of recommendations for groundwater resources management guidelines
- Development of numerical model
    - Report detailing modelling guidelines
    - Provide basis for assessment of development scenarios with respect to groundwater resource management guidelines
- Reporting - summary report for activities and outcomes
- Risk map (data density vs. development activity)

APPENDICES

A. SUMMARY OF CRITICAL INFORMATION SOURCES

Reference	Subject	Location	Scope of Works	Comments/ outcomes
Wells et al (1970)	Geology of the Amadeus Basin, Central Australia	Amadeus Basin including western margin of the Pedirka Basin	Review of the geology of the Amadeus Basin, including the hydrogeology	Identified 22 wells constructed in the Crown Point Formation with a salinity range of 397 to 3854 mg/L and an average depth of 135 m. Suggests diffuse recharge to Crown Point Formation occurs in outcropping areas in the vicinity of the northwest margin of the basin
Australian Groundwater Consultants (AGC) (1975)	Dewatering investigations Lake Phillipson Area, S.A.	Lake Phillipson area (Phillipson Trough)	Drilling and testing program for hydraulic analysis and first order estimates of dewatering requirements and yields for coal mining development	Four separate aquifers delineated: the GAB aquifer, two Permian coal aquifers and one Permian sand aquifer. Water quality determined not suitable for either potable or processing purposes. Hydraulic properties and yield estimates developed for area.
Coffey and Partners (1983)	Wintinna Coalfield Hydrogeological Study	Wintinna Coalfield (Boorthanna Trough)	Hydrogeological study of the Wintinna Coalfield proposed mine site area to determine aquifer properties and groundwater behaviour. Study included the acquisition of pump test data	Hydrogeological properties and hydrochemistry data of the Permian coal seam aquifer obtained.
Read (1984)	Stuart Highway – Gosses to Mirikata section, drilling for construction water	Stuart Highway between Kingoonya and Coober Pedy	Production well report for road construction and maintenance works	Groundwater generally found in GAB aquifers. Information regarding groundwater in Stuart Range Formation provided.
Dames and Moore (1986)	Geotechnical and hydrogeological feasibility studies 1985, Boorthanna Project, proposed coal development Arckaringa, South Australia. For Getty Coal Australian company	Weedina Coalfield (Boorthanna Trough)	Presentation of geotechnical and hydrogeological investigations assessing the engineering properties of site materials for the purposes of a feasibility study	Report primarily focussed on the GAB, however, coal seams within the Mount Toondina Formation thought to be in hydraulic continuity with the GAB proper at the southern end of the Peake and Denison Inlier.
Dodds (1996)	Report on a transient electromagnetic survey around Garford Palaeochannel, SA.	Garford Palaeochannel	Report on an transient electromagnetic survey conducted over the Garford Palaeochannel to improve knowledge on basement topography	Permian units (notably the Stuart Range Formation) could be interpreted on the basis of transient electromagnetic survey data

Lau and Jacobson (1991)	Aquifer characteristics and groundwater resources of the Amadeus Basin	Amadeus Basin including western margin of the Pedirka Basin	Review of groundwater chemistry and evidence for palaeorecharge to aquifers within the Amadeus Basin, inclusive of pertinent review of hydrogeology in neighbouring basins	12 wells in the vicinity of outcrop areas along the margin of the Pedirka Basin were determined to be accessing groundwater from the Crown Point Formation; average aquifer depth of 89 m, a mean standing water level of 71 m and an average yield of between 0.1 and 2.0 L/s was reported. Groundwater salinity was considered brackish. Also details evidence to suggest the former petroleum exploration bore McDills 1 sources water from both the Jurassic and Permian sequence and notes that it has been categorised as a Permian well in previous studies
Mathews (1996)	Great Artesian Basin water resource investigation	Northern Territory portion of the GAB	Investigation to characterise groundwater resources in the GAB. Work included a program of groundwater sampling for carbon-14, stable isotopes and major chemistry	Focused on GAB aquifer, however, sampling also picked up some bores in the Permian and underlying sequences.
Kellett et al. (1999)	Hydrogeological Assessment of a Region In Central Northern South Australia	South eastern Arckaringa Basin (Billa Kalina sub-basin)	Details a reconnaissance survey of the hydrogeology within central-north South Australia.	Aquifers in the GAB were determined to be the most important. Other dominant aquifers include the Boorthanna Formation and Andamooka Limestone; both these aquifers are interpreted to receive discharge from the GAB and transmit water to Lake Torrens and Olympic Dam. Groundwater was found to be fresh to brackish.
Radke (2000)	Hydrochemistry and implied hydrodynamics of the Cadna-owie - Hooray Aquifer, Great Artesian Basin	Basin wide GAB study	Extensive investigation looking at the hydrochemistry and flow dynamics within the GAB. Involved a large groundwater sampling program to characterise major chemistry and isotope hydrology.	Focused on GAB system and specifically the Cadna-owie - Hooray Aquifer, however, sampling also picked up some bores in the Permian and underlying sequences.
Aquaterra REM (2005)	Water supply option assessment for the Prominent Hill Mine Project	Prominent Hill area (Billa Kalina sub-basin)	Desktop review of available information concerning Project water	
Aquaterra REM (2005)	Prominent Hill Numerical Groundwater Model	Prominent Hill area (Billa Kalina sub-basin)	Describes the development of two numerical models for the Billa Kalina sub-basin area, the difference between the two related to sources of groundwater flow and connectivity to springs located near the eastern margin of the study area.	Both models give similar results in terms of regional and local scale effects. Maximum predicted drawdown from mine related abstraction was <5m and that this had no effect at the eastern boundary. Sensitivity analysis did not alter the general conclusions obtained from modelling.
Belperio (2005)	Water in Permian palaeochannels draining the Mount Woods Block	Prominent Hill area (Billa Kalina sub-basin)	Exploratory drilling works for groundwater supply for the development of mineral resources at Prominent Hill	Presence of water-bearing sands at the base of Permian sequences at shallow depths. Groundwater was found to be brackish but in good supply.
Enesar (2006)	Prominent Hill Copper-Gold Project, Mining Lease 6228, Mining and Rehabilitation Program	Prominent Hill area (Billa Kalina sub-basin)	Details the proposed environmental monitoring and rehabilitation program for the Prominent Hill mining development	Provides a summary of regional and localised groundwater systems as understood, as well as a conceptual model for the hydrogeology of the region surrounding the Prominent Hill mine site.

REM (2006)	Prominent Hill Mine Project Construction Water Supply assessment of Effects	Prominent Hill area (Billa Kalina sub-basin)	Discusses the commissioning and operation of a water supply for mine construction works over an 18-month period, from August 2006 through to early 2008, at the Virgo borefield.	Drilling and aquifer testing investigations identified the Boorthanna Formation aquifer as a viable groundwater supply for the Prominent Hill Mine Project construction. The large separation distance between the borefield and GAB springs is suggested to make any measurable impact on GAB springs unlikely. Likewise impacts on shallow aquifers in the vicinity is suggested to be minimal
REM (2006)	Monitoring Program – Construction Water Supply borefield (Virgo and Taurus) 2006)	Prominent Hill area (Billa Kalina sub-basin)	Describes the proposed environmental monitoring activities undertaken for the Prominent Hill Mine Project Construction Water Supply borefields.	
Aquaterra (2007)	Prominent Hill Mine regional groundwater model	Prominent Hill area (Billa Kalina sub-basin)	Refinement of regional groundwater model developed in Aquaterra REM (2005b). Employed refined hydrogeological conceptual model and calibration from abstraction and monitoring data	Predicted impacts from the PH2 model of groundwater abstraction were found to be similar to those from the previous model. Continued prediction of adequate supply of groundwater for operation with minimal impact on overlying GAB or GAB related springs.
REM (2007)	Prominent Hill region conceptual model	Prominent Hill area (Billa Kalina sub-basin)	Refinement of the hydrogeological conceptual model first described in Aquaterra REM (2005a)	Reiterate previous concepts such as the variability of the non-artesian GAB and underlying Boorthanna aquifer, the influence of structure on transmissivity, a general west to east flow path, but with evidence for groundwater mixing from multiple recharge sources and the demarcation of three distinct groundwater systems in the broader area.
Howe et al. (2008)	Hydrogeology of the South-east portion of the Arckaringa Basin and South-west portion of the Eromanga Basin, South Australia	Prominent Hill area (Billa Kalina sub-basin)	Paper presenting important aspects of the Arckaringa Basin groundwater system in the vicinity of the Prominent Hill Mining operation, focussing on geology, hydrostratigraphy, groundwater dynamics and regional scale recharge and discharge mechanisms.	Groundwater in non-artesian GAB aquifer flows west to east and discharges at salinas and salt pans to east of study area. Groundwater within the Boorthanna Aquifer flows from the west and north, converging in the study area where the majority discharges into the Stuart Shelf, although some diffuse discharge to the previously mentioned salt pans and salinas considered possible. GAB springs are supplied by water from the eastern artesian GAB aquifer and are not connected with groundwater within the Billa Kalina sub-basin. Another groundwater system associated with artesian GAB water north of the Boorthanna Fault is also discussed.
Aquaterra (2009)	Prominent Hill Mine regional groundwater model	Prominent Hill area (Billa Kalina sub-basin)	Refinement of regional groundwater model developed by Aquaterra (2007). The new PH4 model employed a wider area of study, employed new monitoring and abstraction data, used updated Kh and Kv values based on pump testing and used a longer calibration period.	Generalised predicted impacts from the PH4 model of groundwater abstraction were found to be similar to those from the previous models. Continued prediction of adequate supply of groundwater for operation with minimal impact on overlying GAB or GAB related springs.

Humphreys and Kunde (2008)	Rehabilitation of Flowing Bores in the Northern Territory Portion of the Great Artesian Basin	South east corner of the NT	Details rehabilitation program targeting flowing bores within the NT portion of the GAB	Suggests that away from the western margin, the only registered well intersecting Permian aquifers is McDills No.1
Sinclair Knight Merz (SKM) (2009)	Prominent Hill Regional Conceptual Hydrogeological Model	Prominent Hill area (Billa Kalina sub-basin)	Refinement of the hydrogeological conceptual model first described in Aquaterra REM (2005a)	Reiterate previous concepts such as a general north and west to east flow path, with evidence for discharge in salt pans and salinas east of the project area, the demarcation of three distinct groundwater systems in the broader area and the distinct separation between the Boorthanna aquifer and the GAB, the latter primarily supportive of pastoral and spring activity in the region. Also presents a finding from REM (2007) concerning the limited lateral extent of aquifers within the Boorthanna Formation
Lyons and Hulme (2010)	Hydrogeology of the south-eastern Arckaringa Basin and overlying south-western Eromanga Basin, and the implications for sustainable water supply development in central South Australia	Prominent Hill area (Billa Kalina sub-basin)	Presentation reviewing the hydrogeology of the Billa Kalina sub-basin, including a review of the technical and social challenges with respect to studying this resource.	A previously unknown industrial-quality groundwater resource in the Arckaringa Basin was successfully developed for use at the Prominent Hill Mining operation. The new groundwater resource was demonstrated to be separate from other important groundwater resources that supply community, pastoral and environmental users on the basis of hydrochemistry and hydraulic data sets.
Fulton (2012)	Great Artesian Basin Water Allocation Planning Process Resource Assessment and Technical Review	South east corner of the NT	Review of groundwater resources in the GAB Water Control District, an area which encompasses the north-west of the Pedirka Basin	Seventeen wells that screen the Crown Point Formation were identified. Reported groundwater quality for the Permian formation ranged between 100–8000 mg/L with an average salinity of 3100 mg/L.
Wolaver et al (2013)	Chapter 6: Hydrogeology of Dalhousie Springs.	Western margin of the Pedirka	Review of the hydrogeological and hydrochemical evidence	Some hydrochemical evidence to suggest that springwater at Dalhousie springs may be at least partly supplied by aquifers

B. FIELD AUDIT SHEET

Arckaringa & Pedirka Basin NPA
Bore Survey Report

Government of South Australia
Department of Environment, Water and Natural Resources

UNIT NO: ....

PERMIT NO: ....

WELL NAME: ....

PASTORAL LEASE /STATION: ....

DATE: .... **TIME:** .... (AM/PM)

INSPECTED BY: ....

WELL COORDINATES

Easting: ....

Northing: ....

Zone: 52☐ 53☐ 54☐

Datum: GDA94 / WGS84 / AGD 66 / AGD84 / other ....

Survey Method: Average Position ....☐
Differential ....☐
Standalone navigation ....☐
Other....☐

Duration of Averaging: .... minutes

Est. Positional Error: .... metres

Existing Coordinates OK: ☐

AQUIFER CONDITION:

Artesian ....☐ Non-artesian....☐

BORE STATUS

Controlled flowing ....☐ Equipped ....☐
Uncontrolled flowing....☐ Unequipped ....☐
Not in use ....☐ Backfilled ....☐
Operational ....☐ Abandoned....☐
Not located ....☐ Blocked....☐
Other ....

BORE PURPOSE:

Observation....☐ Industrial ....☐
Irrigation ....☐ Stock....☐
Domestic....☐ TWS....☐
Unknown ....☐
Other ....

FIELD WATER QUALITY:

Temperature (max): .... °C

Conductivity: .... µS/cm @ 25 °C

pH: ....

Water Sample Collected: .... Yes ☐ No ☐

MONITORING POTENITAL

Bore suitable for monitoring? .... Yes ☐ No ☐

Comments ....

....

GENERAL COMMENTS: (incl. drains, swamps, wastage, water distribution systems): ....

....
....
....
....

....
....
....
....
....

Water distribution system:.............. Yes ☐ No ☐

Photo(s) taken: .... Yes ☐ No ☐

NON-ARTESIAN BORE

Bore depth: .... (m)

Water level (DTW): .... (m)

Depth from:

Ground level....☐ Top of casing....☐

TOC (or reference point) above ground: .... (m)

RP description: ....

Casing size: .... (m)

Casing material: .... (m)

Casing condition: .... (m)

Pump type:

Centrifugal....☐ Turbine....☐
Windmill....☐ Mono....☐
Submersible....☐
Other ....

Pump diameter: .... (mm)

Pump depth: .... (m)

Comments (restrictions for monitoring e.g. centralisers)

....
....
....
....
....

ARTESIAN BORE

MAIN VALVE

Exists .... Yes ☐ No ☐

Operating .... Yes ☐ No ☐

Type (size, material) ....

Leakage: None....☐ Gland ....☐ Flange....☐

Time to shut in: .... minutes

Headworks

Are the headworks protected? .... Yes ☐ No ☐

How: ....

....

Condition Good....☐ Fair ....☐
Poor....☐ None ....☐

Leakage:.................... Yes ☐ No ☐

Comments: ....

....
....
....

arckaringa_pedirka_npa_bore_survey_data_sheet_check_box active

Arckaringa & Pedirka Basin NPA
Bore Survey Report

Headworks Description (incl: Control Valves (size, type, operating))

....

....

....

....

....

....

....

Facility To Measure Shut-In Pressure: .... Yes ☐ No ☐

3/8" Ball Valve:... Yes ☐ No ☐

Other (details, diam): ....

Comments: ....

....

ANTECEDENT CONDITIONS

Status Shut In ....☐ Flowing........................☐

Pressure on Arrival: .... (kPa, psi, m)

Flow Rate on Arrival: .... L/sec

How measured:

Bucket/Drum ....☐ V notch .... ☐

Estimated ....☐ Calculated.......... ☐

Flow Meter ....☐ Ultrasonic .... ☐

Other ....

Water Temperature: .... °C

Comments ....

....

....

SURVEY MEASUREMENTS

Shut In Pressure Test

Duration of Flow Period: .... minutes

Flow Rate: .... L/sec

Max water temperature: .... °C

Shut In time: .... minutes

Dist to Ref Point: .... metres

(Vertical distance from the gauge to the Reference Point)

(-ve if above, +ve if below reference point)

Shut In Pressure (max): .... (kPa, psi, m)

Flow Rate

Flow Rate (max): .... L/sec

How Measured:

Bucket/Drum ....☐ V notch ....☐

Estimated ....☐ Calculated....................☐

Flow Meter ....☐ Ultrasonic ....☐

Other ....

Pressure at max flow: .... (kPa, psi, m)

Time (min)	Pressure (kPa / psi / m)	Comments
0		

Additional Comments:

arckaringa_pedirka_npa_bore_survey_data_sheet_check_box_active

UNITS OF MEASUREMENT

Units of measurement commonly used (SI and non-SI Australian legal)

Name of unit	Symbol	Definition in terms of other metric units	Quantity
day	d	24 h	time interval
gigalitre	GL	10^{6} m^{3}	volume
gram	g	10^{-3} kg	mass
hectare	ha	10^{4} m^{2}	area
hour	h	60 min	time interval
kilogram	kg	base unit	mass
kilolitre	kL	1 m^{3}	volume
kilometre	km	10^{3} m	length
litre	L	10^{-3} m^{3}	volume
megalitre	ML	10^{3} m^{3}	volume
metre	m	base unit	length
microgram	µg	10^{-6} g	mass
microlitre	µL	10^{-9} m^{3}	volume
milligram	mg	10^{-3} g	mass
millilitre	mL	10^{-6} m^{3}	volume
millimetre	mm	10^{-3} m	length
minute	min	60 s	time interval
second	s	base unit	time interval
tonne	t	1000 kg	mass
year	y	365 or 366 days	time interval

Shortened forms

~ approximately equal to

bgs below ground surface

EC electrical conductivity (µS/cm)

K hydraulic conductivity (m/d)

Ma Million years Before Present

mD millidarcies

pH acidity

pMC percent of modern carbon

ppb parts per billion

ppm parts per million

ppt parts per trillion

w/v weight in volume

w/w weight in weight

GLOSSARY

Aquifer — An underground layer of rock or sediment that holds water and allows water to percolate through

Aquifer, confined — Aquifer in which the upper surface is impervious (see 'confining layer') and the water is held at greater than atmospheric pressure; water in a penetrating well will rise above the surface of the aquifer

Aquifer test — A hydrological test performed on a well, aimed to increase the understanding of the aquifer properties, including any interference between wells, and to more accurately estimate the sustainable use of the water resources available for development from the well

Aquifer, unconfined — Aquifer in which the upper surface has free connection to the ground surface and the water surface is at atmospheric pressure

Aquitard — A layer in the geological profile that separates two aquifers and restricts the flow between them

Arid lands — In South Australia, arid lands are usually considered to be areas with an average annual rainfall of less than 250 mm and support pastoral activities instead of broadacre cropping

Artesian — An aquifer in which the water surface is bounded by an impervious rock formation; the water surface is at greater than atmospheric pressure, and hence rises in any well which penetrates the overlying confining aquifer

Basin — The area drained by a major river and its tributaries

BoM — Bureau of Meteorology, Australia

Bore — See 'well'

^{14}C — Carbon-14 isotope (percent modern Carbon; pmC)

CFC — Chlorofluorocarbon; measured in parts per trillion (ppt)

CMB — Chloride mass balance

Confining layer — A rock unit impervious to water, which forms the upper bound of a confined aquifer; a body of impermeable material adjacent to an aquifer; see also 'aquifer, confined'

δD — Hydrogen isotope composition, measured in parts per thousand ($^{o}/_{oo}$)

DEWNR — Department of Environment, Water and Natural Resources (Government of South Australia)

DMITRE — Department for Manufacturing, Innovation, Trade, Resources and Energy (Government of South Australia)

EC — Electrical conductivity; 1 EC unit = 1 micro-Siemen per centimetre (µS/cm) measured at 25°C; commonly used as a measure of water salinity as it is quicker and easier than measurement by TDS

Ephemeral streams or wetlands — Those streams or wetlands that usually contain water only on an occasional basis after rainfall events. Many arid zone streams and wetlands are ephemeral.

Evapotranspiration — The total loss of water as a result of transpiration from plants and evaporation from land, and surface water bodies

Floodout — An area where channelised flow ceases and floodwaters spill across adjacent alluvial plains

Floodplain — Of a watercourse means: (1) floodplain (if any) of the watercourse identified in a catchment water management plan or a local water management plan; adopted under the Act; or (2) where (1) does not apply — the floodplain (if any) of the watercourse identified in a development plan under the *Development (SA) Act 1993*; or (3) where neither (1) nor (2) applies — the land adjoining the watercourse that is periodically subject to flooding from the watercourse

Flow regime — The character of the timing and amount of flow in a stream

Fresh — A short duration, small volume pulse of streamflow generated by a rainfall event that temporarily, but noticeably, increases stream discharge above ambient levels

GAB — Great Artesian Basin

Geological features — Include geological monuments, landscape amenity and the substrate of land systems and ecosystems

GIS — Geographic Information System; computer software linking geographic data (for example land parcels) to textual data (soil type, land value, ownership). It allows for a range of features, from simple map production to complex data analysis

Groundwater — Water occurring naturally below ground level or water pumped, diverted and released into a well for storage underground; see also 'underground water'

Hydraulic conductivity (K) — A measure of the ease of flow through aquifer material: high K indicates low resistance, or high flow conditions; measured in metres per day

Hydrogeology — The study of groundwater, which includes its occurrence, recharge and discharge processes and the properties of aquifers; see also 'hydrology'

Lake — A natural lake, pond, lagoon, wetland or spring (whether modified or not) that includes part of a lake and a body of water declared by regulation to be a lake. A reference to a lake is a reference to either the bed, banks and shores of the lake or the water for the time being held by the bed, banks and shores of the lake, or both, depending on the context.

Land — Whether under water or not, and includes an interest in land and any building or structure fixed to the land

LMWL — Local meteoric water line

m AHD — Defines elevation in metres (m) according to the Australian Height Datum (AHD)

Model — A conceptual or mathematical means of understanding elements of the real world that allows for predictions of outcomes given certain conditions. Examples include estimating storm run-off, assessing the impacts of dams or predicting ecological response to environmental change

Monitoring — (1) The repeated measurement of parameters to assess the current status and changes over time of the parameters measured (2) Periodic or continuous surveillance or testing to determine the level of compliance with statutory requirements and/or pollutant levels in various media or in humans, animals and other living things

Natural recharge — The infiltration of water into an aquifer from the surface (rainfall, streamflow, irrigation etc). See also recharge area, artificial recharge

$\delta^{18}O$ — Oxygen isotope composition, measured in parts per thousand (‰)

Observation well — A narrow well or piezometer whose sole function is to permit water level measurements

Palaeochannels — Ancient buried river channels in arid areas of the state. Aquifers in palaeochannels can yield useful quantities of groundwater or be suitable for ASR

Pasture — Grassland used for the production of grazing animals such as sheep and cattle

Permeability — A measure of the ease with which water flows through an aquifer or aquitard, measured in m^2/d or millidarcies

PIRSA — Primary Industries and Regions South Australia (Government of South Australia)

Population — (1) For the purposes of natural resources planning, the set of individuals of the same species that occurs within the natural resource of interest. (2) An aggregate of interbreeding individuals of a biological species within a specified location

Potable water — Water suitable for human consumption such as drinking or cooking water

Potentiometric head — The potentiometric head or surface is the level to which water rises in a well due to water pressure in the aquifer, measured in metres (m); also known as piezometric surface

Production well — The pumped well in an aquifer test, as opposed to observation wells; a wide-hole well, fully developed and screened for water supply, drilled on the basis of previous exploration wells

Recharge area — The area of land from which water from the surface (rainfall, streamflow, irrigation, etc.) infiltrates into an aquifer. See also artificial recharge, natural recharge

SA Geodata — A collection of linked databases storing geological and hydrogeological data, which the public can access through the offices of PIRSA. Custodianship of data related to minerals and petroleum, and groundwater, is vested in PIRSA and DEWNR, respectively. DEWNR should be contacted for database extracts related to groundwater

Specific storage (S_s) — Specific storativity; the amount of stored water realised from a unit volume of aquifer per unit decline in head; it is dimensionless

Specific yield (S_y) — The volume ratio of water that drains by gravity, to that of total volume of the porous medium. It is dimensionless

Stock use — The taking of water to provide drinking water for stock other than stock subject to intensive farming (as defined by the Act)

S — Storativity; storage coefficient; the volume of groundwater released or taken into storage per unit plan area of aquifer per unit change of head; it is dimensionless

Sub-catchment — The area of land determined by topographical features within which rainfall will contribute to run-off at a particular point

Surface water — (a) water flowing over land (except in a watercourse), (i) after having fallen as rain or hail or having precipitated in any another manner, (ii) or after rising to the surface naturally from underground; (b) water of the kind referred to in paragraph (a) that has been collected in a dam or reservoir

Sustainability — The ability of an ecosystem to maintain ecological processes and functions, biological diversity, and productivity over time

T — Transmissivity; a parameter indicating the ease of groundwater flow through a metre width of aquifer section (taken perpendicular to the direction of flow), measured in m^2/d

TDS — Total dissolved solids, measured in milligrams per litre (mg/L); a measure of water salinity

Tertiary aquifer — A term used to describe a water-bearing rock formation deposited in the Tertiary geological period (1–70 million years ago)

Transmissivity (T) — A parameter indicating the ease of groundwater flow through a metre width of aquifer section

Underground water (groundwater) — Water occurring naturally below ground level or water pumped, diverted or released into a well for storage underground

Watercourse — A river, creek or other natural watercourse (whether modified or not) and includes: a dam or reservoir that collects water flowing in a watercourse; a lake through which water flows; a channel (but not a channel declared by regulation to be excluded from the this definition) into which the water of a watercourse has been diverted; and part of a watercourse

Water quality data — Chemical, biological, and physical measurements or observations of the characteristics of surface and groundwaters, atmospheric deposition, potable water, treated effluents, and wastewater, and of the immediate environment in which the water exists

Water quality information — Derived through analysis, interpretation, and presentation of water quality and ancillary data

Water quality monitoring — An integrated activity for evaluating the physical, chemical, and biological character of water in relation to human health, ecological conditions, and designated water uses

Water quality standard — A law or regulation that consists of the beneficial designated use or uses of a water body, the numerical and narrative water quality criteria that are necessary to protect the use or uses of that particular water body, and an anti-degradation statement

Water resource monitoring — An integrated activity for evaluating the physical, chemical, and biological character of water resources, including (1) surface waters, groundwaters, estuaries, and near-coastal waters; and (2) associated aquatic communities and physical habitats, which include wetlands

Water resource quality — (1) The condition of water or some water-related resource as measured by biological surveys, habitat-quality assessments, chemical-specific analyses of pollutants in water bodies, and toxicity tests. (2) The condition of water or some water-related resource as measured by habitat quality, energy dynamics, chemical quality, hydrological regime, and biotic factors

Well — (1) An opening in the ground excavated for the purpose of obtaining access to underground water. (2) An opening in the ground excavated for some other purpose but that gives access to underground water. (3) A natural opening in the ground that gives access to underground water

Wetlands — Defined by the Act as a swamp or marsh and includes any land that is seasonally inundated with water. This definition encompasses a number of concepts that are more specifically described in the definition used in the Ramsar Convention on Wetlands of International Importance. This describes wetlands as areas of permanent or periodic to intermittent inundation, whether natural or artificial, permanent or temporary, with water that is static or flowing, fresh, brackish or salt, including areas of marine water, the depth of which at low tides does not exceed six metres.

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