Lake Eyre Basin Springs Assessment

A hydrogeological-based conceptualisation of springs in the Neales River catchment and Lake Cadibarrawirracanna regions, Lake Eyre Basin, South Australia

DEWNR Technical report 2015/13

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

Funding for these projects has been provided by the Australian Government through the Bioregional Assessment Programme.

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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.

Sandy Pitcher
CHIEF EXECUTIVE
DEPARTMENT OF ENVIRONMENT, WATER AND NATURAL RESOURCES

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Funding for these projects has been provided by the Australian Government through the Department of the Environment. For more information on bioregional assessments, visit <http://www.bioregionalassessments.gov.au>

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Summary

The Australian Government established an Independent Expert Scientific Committee (IESC) on Coal Seam Gas (CSG) and Large Coal Mining Developments to provide independent expert scientific advice concerning the impacts such developments may have on water resources. As part of this initiative, the South Australian Department of Environment, Water and Natural Resources (DEWNR), were provided funding to collate and ground-truth groundwater, surface water and ecology information in regions with the potential for CSG and large coal mining development and conduct vulnerability assessments. Key to any vulnerability impact assessments are the Environment Protection and Biodiversity Conservation Act (EPBC)-listed Threatened Ecological Communities. Threatened Ecological Communities are dependent on discharge springs fed by groundwater from Great Artesian Basin (GAB) aquifers underlying the Lake Eyre Basin (LEB). Many of these spring complexes are located in close proximity or down-gradient of coal resources.

This report presents the hydrogeological component of a wider characterisation of a number of spring complexes located within the Neales River catchment and Lake Cadibarrawirracanna regions. These spring complexes were identified as those most at risk to either diminish or hydrochemically altered flow as a consequence of any potential CSG or coal resource developments within the Arckaringa Basin. The level of risk primarily centres on their close location to known coal resources within the Arckaringa Basin. Included in this report is a description of the structural setting and primary controls on the spring's formation using recently developed basinal architecture interpretations, geophysical data and a description of the primary groundwater source based on hydrochemistry data.

A number of conceptual models describing the variations of structural architecture primarily responsible for spring formation within the investigation area were developed. These models are:

- 1a – Basin margin, structure (fracture zone)
- 1b – Basin margin, structure (fault zone)
- 2 – Basin margin, sediment thinning
- 3 – Basin margin structure/ sediment thinning combination
- 4 – Astrobleme.

At face value, springs that have a clear spatial relationship with either the margin or a structure affecting the Arckaringa Basin are interpreted as being at higher risk to impacts associated with coal resource developments. The reason for this concerns the potential increased number of groundwater-connectivity pathways between coal resources and springs afforded by structure or basin architecture. With respect to identifying structures potentially related to spring formation, it was found to be possible to map differences associated with structure-based conceptual models using geophysical techniques. Primarily, time-domain electromagnetic (TEM) and surface self-potential (SP) techniques proved useful with respect to mapping the nature of the confining layer and the conduit structures responsible for springs.

Finally, three broad hydrochemical classifications for groundwater were developed: Peake Creek East, Peake Creek West and Mount Dutton (mixing zone). There is currently insufficient information to identify either temporal or multiple-aquifer influences on spring hydrochemistry. It is likely that springs that are supplied with groundwater with a Group 2 (Peake Creek West) hydrochemistry profile are at more risk from any groundwater-impacting developments associated with CSG and coal mining developments within the Arckaringa Basin, as a consequence of the closer locality to coal resources in the Arckaringa Basin. However this must be prefaced with the fact that very little is known about the hydrochemistry and aquifer connectivity to the Arckaringa Basin in the immediate vicinity of these springs. Further work characterising the hydrochemistry and determining the extent of any connectivity between the GAB and Arckaringa Basin within the region is required before a definitive assessment can be made.

1 Introduction

1.1 Bioregional Assessment Programme and IESC

The Bioregional Assessment Programme (BAP) is a transparent and accessible programme of baseline assessments that increase the available science for decision making associated to potential water-related impacts of coal seam gas and large coal mining developments. A bioregional assessment is a scientific analysis of the ecology, hydrology, geology and hydrogeology of a bioregion with explicit assessment of the potential direct, indirect and cumulative impacts of coal seam gas and large coal mining development on water resources. This Programme draws on the best available scientific information and knowledge from many sources, including government, industry and regional communities, to produce bioregional assessments that are independent, scientifically robust, and relevant and meaningful at a regional scale. For more information on bioregional assessments, visit http://www.bioregionalassessments.gov.au.

The Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (the IESC) is a statutory body under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) which provides scientific advice to Australian governments on the water-related impacts of coal seam gas and large coal mining development proposals.

Under the EPBC Act, the IESC has several legislative functions to:

- Provide scientific advice to the Commonwealth Environment Minister and relevant state ministers on the water-related impacts of proposed coal seam gas or large coal mining developments.
- Provide scientific advice to the Commonwealth Environment Minister on:
  - bioregional assessments being undertaken by the Australian Government;
  - research priorities and projects commissioned by the Commonwealth Environment Minister, and
- Publish and disseminate scientific information about the impacts of coal seam gas and large coal mining activities on water resources.

1.2 Background

In 2012, the Australian Government established the IESC to provide independent expert scientific advice concerning the impacts such developments may have on water resources. As part of this initiative, the South Australian Department of Environment, Water and Natural Resources (DEWNR), was funded to collate and ground-truth groundwater, surface water and ecology information in regions with the potential for CSG and large coal mining development and conduct vulnerability assessments. A key focus of any assessment of impact and vulnerability is the EPBC-listed Threatened Ecological Community: 'The community of native species dependent on natural discharge of groundwater from the Great Artesian Basin (GAB) (Harrison et al., 2013). This Threatened Ecological Community is dependent on discharge springs fed by groundwater from aquifers underlying the Lake Eyre Basin (LEB) (Figure 1-1).

Knowledge of the location, ecology beyond that listed under the EPBC Act, and hydrology of GAB springs in general is limited. There is a particularly poor understanding of the responses and impacts to spring flows from water extraction from potential coal mining and coal seam gas development. These information gaps place significant constraints on the capacity of regulatory authorities to manage environmental risks associated with CSG and coal mining developments, both individually and cumulatively. A primary step in addressing these information gaps is the establishment of survey data and structural interpretation for these spring complexes. Such studies may enable earlier and better informed decision making in advance of cumulative development pressures. This report represents the hydrogeological component of a wider characterisation of a number of spring complexes located within the Neales River catchment and Lake Cadibarrawirracanna regions.

These springs were identified by DEWNR as those potentially most at risk to either diminished or hydrochemically altered groundwater flow, as a consequence of any potential CSG or coal resource developments within the Arckaringa Basin. The level of risk primarily centres on their close location to known coal resources within the Arckaringa Basin.

1.3 Objectives

The primary objective of this report is to provide hydrogeological information and an initial conceptualisation of spring environments within the Neales River Catchment and Lake Cadibarrawirracanna regions that are supporting the Threatened Ecological Community (Harrison et al., 2013), and are most at risk from potential coal seam gas and coal mining developments in the Arckaringa subregion. Hydrogeological information and conceptualisation includes an initial description of the structural setting and primary controls on spring formation using recently developed basinal architecture interpretations (Keppel et al. 2015), an interpretation of near surface conditions using acquired geophysical data and a description of the primary groundwater source based on hydrochemistry data. This information will help inform the development of targeted monitoring and mitigation strategies required as part of Australian and state governments' development approval processes (Harrison et al., 2013). In addition, a further object is to develop conceptual models for springs and spring groups where appropriate that synthesis and summarise the structural and hydrogeological information compiled during this study. A final objective is to provide a brief initial assessment of risk to flow and water quality to various springs posed by potential development of CSG and coal resources within the area of investigation.

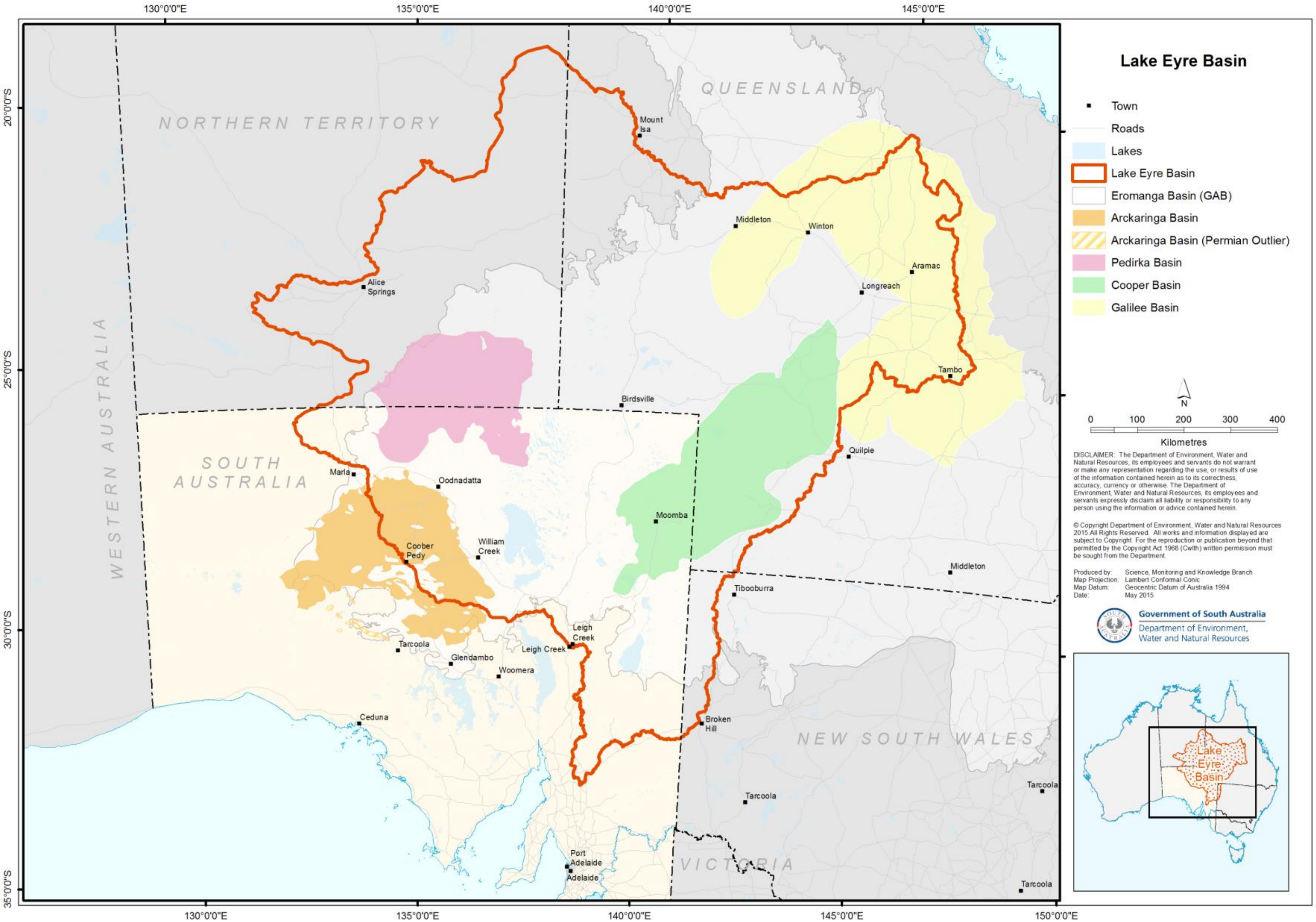


Figure 1-1: Lake Eyre Basin, the Great Artesian Basin and coal-bearing Permo-carboniferous basins that occur within the vicinity

2 Background information

2.1 Regional setting

A detailed description of background information covering the current investigation area is provided by previous reports written as part of this initiative, Wohling et al. (2013b) and Miles et al (2015). The following is a summary of information first compiled for these reports.

2.1.1 Location and physiology

The investigation area covers approximately 15 000 km^2 and extends from Lake Cadibarrawirracanna at the southern end to Mount Dutton in the north (Figure 2-1). In total, five spring complexes, namely Mount Toondina, Mount Dutton, Peake Creek East, Peake Creek West and Lake Cadibarrawirracanna are covered by this area. The investigation area includes the eastern margin of the Arckaringa Basin, as well as an important region of the western GAB where the margin of artesian groundwater is influenced by the Peake and Denison Inlier.

The area is located in northern South Australia, approximately 650 km north–north-west of Adelaide. The climate of the region is generally arid, with weather patterns dominated by persistent high pressure systems. Rainfall predominantly comes from weak winter cold fronts originating from the Southern Indian Ocean or sporadic summer monsoon rainfall that originate in north-west Australia; rainfall for the region averages 150 mm/y, although this can vary significantly from year to year.

Given the arid climate, aeolian-driven erosion as described by Mabbutt (1977) is an important process in shaping the physiology of the region. Although the landscape is predominantly largely flat-lying, desert-dominated, consisting of sand dunes and gibber plains, there are important landscape variations within the investigation area. Of particular significance are the Peake and Denison Inlier (Denison and Davenport Range) to the east, which consists of a low-lying mountain range consisting of outcropping basement rocks and the silt and clay pans of Lake Cadibarrawirracanna. Additionally, the Boorthanna Trough, a depocentre within which a number of significant coal deposits occurs, is located within the investigation area and abuts the western margin of the Peake and Denison Inlier (Figure 2-2).

The largest town within the investigation area is Oodnadatta, with a population of approximately 300 (Figure 2-1). Parts of the Maralinga Tjarutja and the Pitjantjatjara, Yankunytjatjara and Ngaanyatjarra (or Anangu) Aboriginal freehold lands are situated within the Arckaringa Basin, but not all within the investigation area.

The pastoral industry represents the predominant land use across the region, while mining and tourism are increasingly becoming important industries. The majority of water supplies for domestic, pastoral, commercial and industrial purposes in the region are derived from groundwater, as surface water resources are small and unreliable. Most groundwater is sourced from the GAB J-K aquifer, with some supplies derived from the underlying aquifers within the Arckaringa Basin.

2.2 Geology and hydrostratigraphy

2.2.1 Crystalline basement

A number of localised fractured rock aquifers occur within crystalline, largely Precambrian, but also some early Cambrian, basement rocks within the investigation area and can be discussed as a number of geological provinces. These rocks are lateral equivalents and are referred to as Adelaidean (Preiss, 1987). They represent largely marine deposition within a pelagic and continental shelf environment respectively, and include limestone, sandstone, shale, quartzite, dolomite, tillite, conglomerate and volcanic rocks. These units outcrop within the Peake and Denison Inlier, in the vicinity of the Mount Woods Inlier and to the south and south-east of Coober Pedy (Figure 2-3).

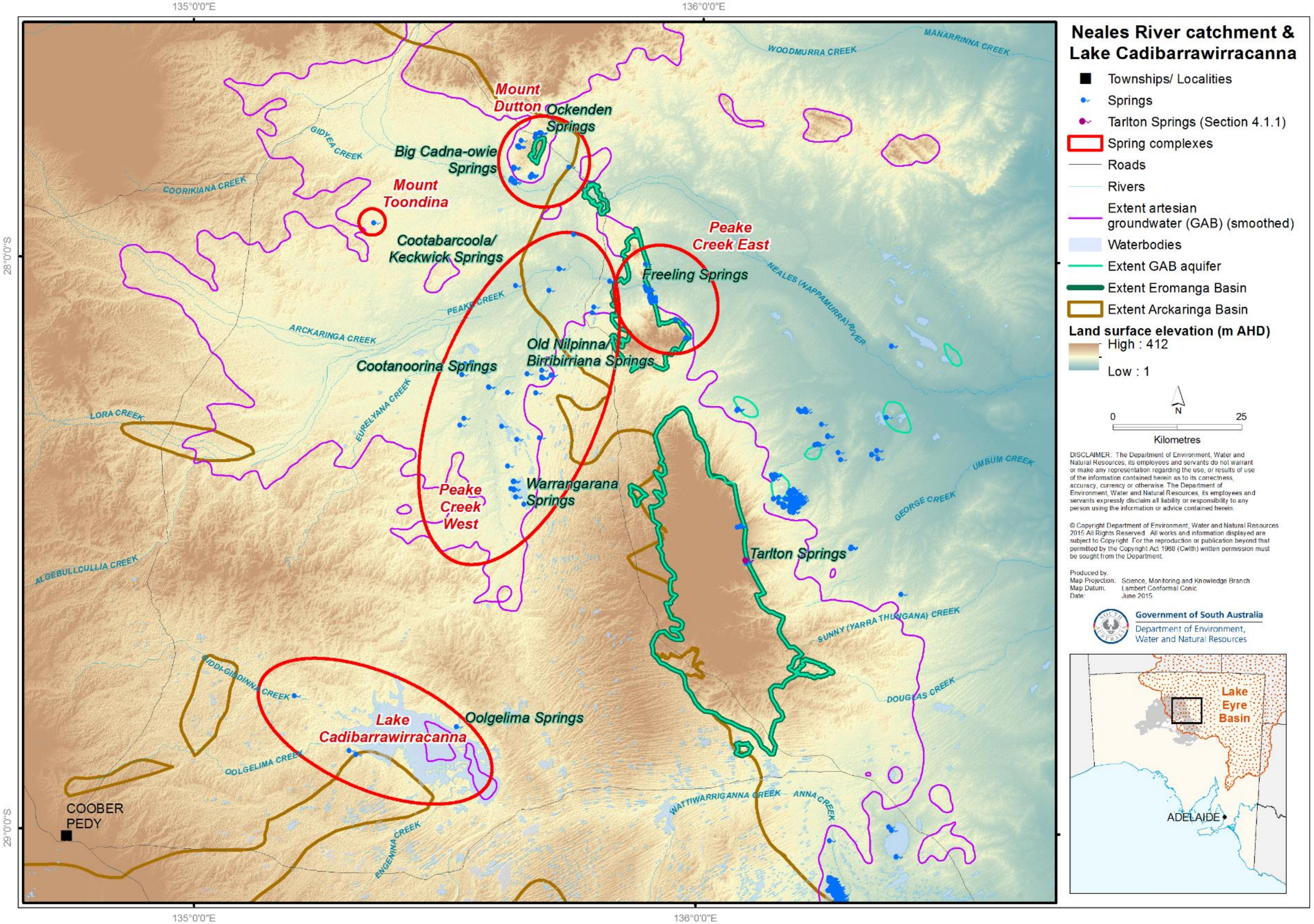


Figure 2-1: Physical geography of the investigation area

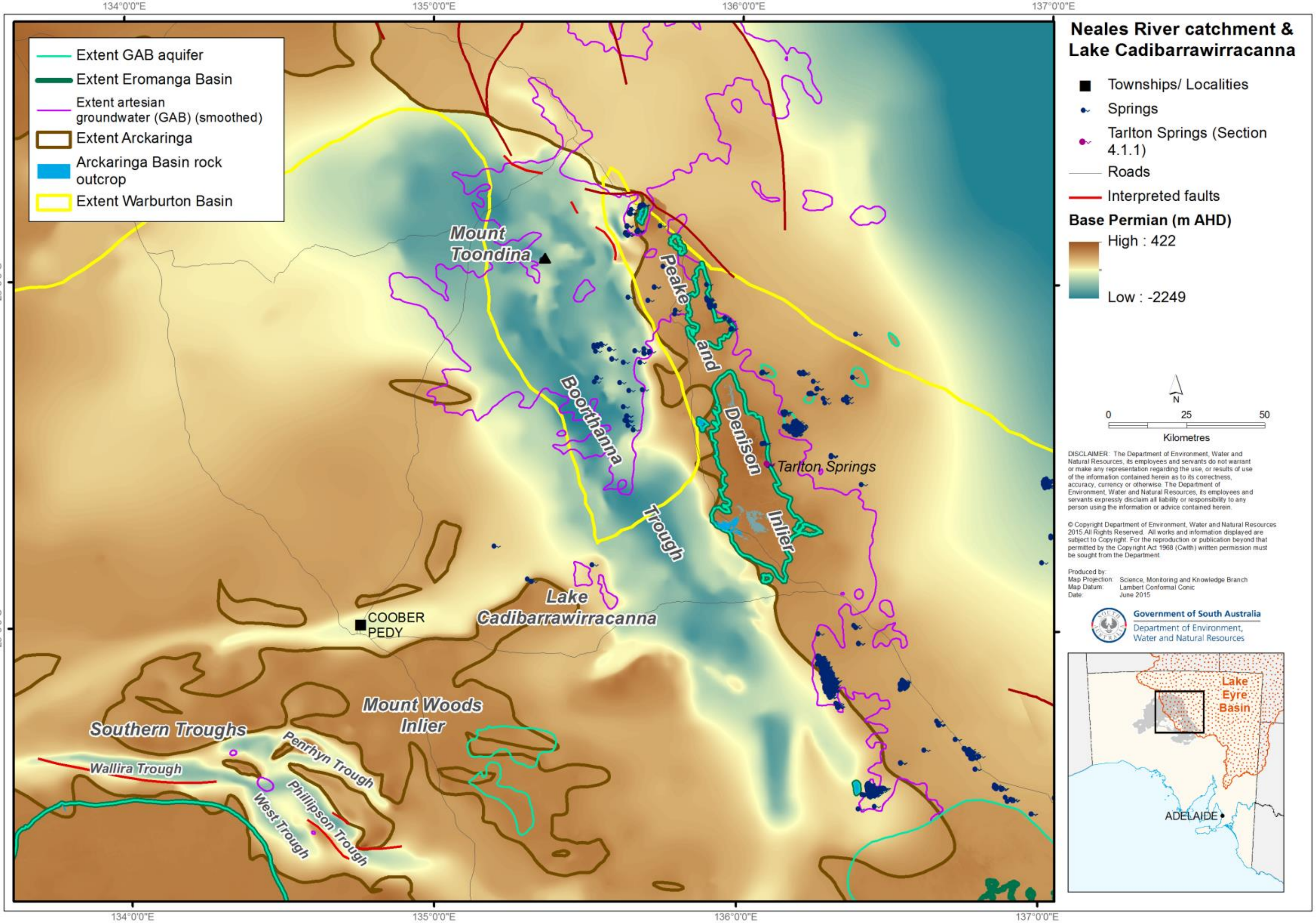


Figure 2-2: Structural geology of the investigation area

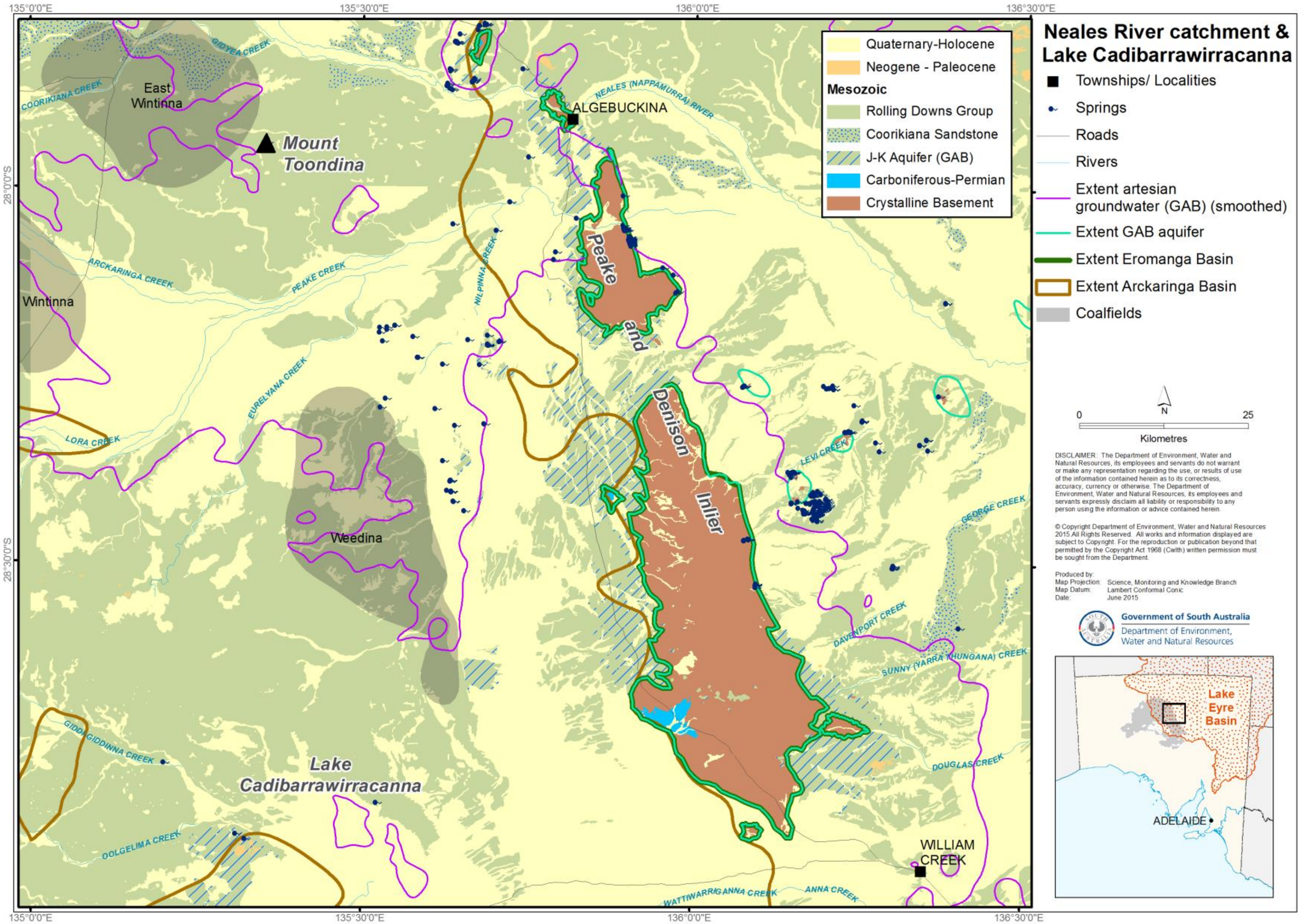


Figure 2-3: Surface geology of the investigation area

2.2.2 Warburton Basin

Within the area of investigation, Warburton Basin sediments are interpreted to occur within the northern and central portion of the Boorthanna Trough (Figure 2-2). Sedimentary rocks of the Warburton Basin are primarily Cambrian to Ordovician, with Devonian strata (Mintabie beds) occurring near the northern margin of the investigation area (Gravestock et al., 1995). Gravestock et al. (1995) presented evidence for five separate depositional sequences in the Warburton Basin—simplistically, these sequences include a basal suite of shallow marine sedimentary rocks, followed by a marine prograding sequence through to deep marine organic-rich lime mud and shale. A marine regression sequence then followed into a shallow marine sequence. Additionally, there are also minor volcanolithic units (Gravestock et al., 1995; Radke, 2009).

2.2.3 Arckaringa Basin

The Arckaringa Basin largely occurs within the western and central portions of the study area and unconformably overlies crystalline basement and older rocks (Preiss et al 2010). There are three main geological formations that comprise the Arckaringa Basin: Mount Toondina, Stuart Range and Boorthanna formations. The upper Mount Toondina Formation contains extensive Permian coal measures comprising a number of discrete deposits and is an important target for coal and CSG exploration (Figure 2-3). Arckaringa Basin strata outcrop in the study area is restricted to isolated occurrences on the western flank of the Peake and Denison Inlier, and at Mount Toondina (Figure 2-2 and Figure 2-3). A summary of the major units within the Arckaringa Basin is provided in Table 2-1.

Table 2-1: Summary of hydrostratigraphy of the Arckaringa Basin

Period	Formation name	Lithology description	Depositional environment	Hydrogeological characteristics
Permian	Mount Toondina Formation	Upper unit: inter-bedded marine clastic rocks, with grain sizes ranging from silt to boulders. Coal seams. Lower unit: shale, siltstone and sandstone	Fluvial, alluvial and glaciogene. Evidence for density-driven deposition in a marine environment in deeper parts of the basin	Groundwater from sandstone and conglomerate units are good aquifers with high yield
	Stuart Range Formation	Grey mudstone, siltstone and shale	Low energy marine	Main confining bed in the Permian sequence
Carboniferous-Permian	Boorthanna Formation	Upper unit: inter-bedded marine clastic rock, with grain sizes ranging from silt to boulders. Lower unit: glaciogene sandy to bouldery claystone diamictite, intercalated with shale and carbonate layers	Fluvial, alluvial and glaciogene. Evidence for density-driven deposition in a marine environment in deeper parts of the basin	Groundwater from sandstone and conglomerate units are good aquifers with high yield

2.2.4 Great Artesian Basin

Directly overlying most of the Arckaringa Basin and covering all of the area of investigation is the Great Artesian Basin. In South Australia, the Eromanga Basin and the GAB are synonymous. The GAB has been referred to as both a geological basin and hydrogeological basin: geologically, the GAB describes a terrestrial to marine Cretaceous–Jurassic super basin that covers much of eastern and central Australia (Keppel et al., 2013). Variations in either basin subsidence or up-warp and global sea level changes during the Mesozoic led to the development of a series of transgressional alluvial, fluvial and marine sequences (Krieg et al., 1995; Ollier, 1995; Toupin et al., 1997). Consequently, a number of stratigraphic units relating to various aquifers and confining layers exist within the study area; a summary of the major units is provided in Table 2-2. GAB aquifer outcrop occurs on the margins of the Peake and Denison Inlier and in isolated parts of the Neales River catchment (Figure 2-3).

2.2.5 Cenozoic sediments

The most recent phases of sedimentation are predominantly composed of braided fluvial and lacustrine sediments. Cenozoic sedimentation may be divided into two depositional episodes; sedimentation that occurred during the Paleogene and Neogene prior to upwarping at 15 to 5 Ma and those associated with the current hydrological system. Both phases outcrop extensively within the area of investigation (Figure 2-3) and may provide discrete aquifers.

Table 2-2: Summary of hydrostratigraphy of the Eromanga Basin (GAB)

Period	Formation name	Lithology description	Depositional environment	Hydrogeological characteristics
Cretaceous	Oodnadatta Formation (Rolling Downs Group)	Laminated, claystone and siltstone, with inter-beds of fine-grained sandstone and limestone	Low energy, shallow marine	Confining layer with minor aquifers
	Coorikiana Sandstone (Rolling Downs Group)	Predominately carbonaceous, clayey, fine-grained sandstone and siltstone	High energy, marine, shore face and gravel bars	Confined minor aquifer
	Bulldog Shale (Rolling Downs Group)	Grey marine shaly mudstone, micaceous silt and pyrite are also present, with very minor silty sands. Occasional lodestones	Low energy, marine, cool climate	Main confining bed for the Jurassic-Cretaceous aquifers
	Cadna-owie Formation	Heterogeneous, mainly fine-grained sandstone and pale grey siltstone. Coarser sandstone lenses occur in the upper part of the formation	Transitional from terrestrial freshwater to marine	Upper part is a good aquifer, high yields and good water quality
Jurassic	Algebuckina Sandstone	Fine to coarse-grained sandstone, with granule and pebble conglomerates	Low gradient fluvial including rivers, floodplain. Both arid and wet climates	Major GAB aquifer, high yielding bores

2.2.6 Coal and hydrocarbon deposits

The Arckaringa Basin contains thick, extensive Permian coal measures comprising a number of discrete deposits within the upper Mount Toondina Formation. In total, seven major deposits of largely lignite A/sub-bituminous C rank coal have been measured, indicated or inferred within the Arckaringa Basin. Of particular interest to this study are the Weedina, Wintinna and East Wintinna coal deposits, which are located nearest to the spring environments subject to this study (Figure 2-3). These deposits are multi-seam, with individual seams up to 10 m thick, with cumulative thickness of up to 35 m. SAPEX (2007) provided an initial estimate of between 0.207 to 1.1 trillion cubic feet (cf) of coal seam gas contained within the East Wintinna coal deposit. With respect to other hydrocarbon plays, the Arckaringa Basin is also subject to conventional hydrocarbon and shale oil exploration. Trace hydrocarbons have been found within sandstone units of the Mount Toondina and Boorthanna formations with analysis of oil samples suggesting a pre-Permian source. Additionally, organic-rich marine shale within the Stuart Range Formation, particularly within the Boorthanna and southern troughs, inclusive of the Wallira, West, Penrhyn, and Phillipson Troughs (Figure 2-2), as well as pre-Permian strata within the Warburton Basin have been identified as potential unconventional shale oil plays (DMITRE, 2011).

2.2.7 Regolith geology and soils

Soil across the investigation area changes with variations in topography and predominant regolith processes. Abundant outcropping and sub-cropping Mesozoic sedimentary formations, the most notable being the Bulldog Shale, have a significant role in determining the composition of the regolith in the region. Erosional landforms associated with Bulldog Shale and crystalline basement occur around the margins of the investigation area (Krapf et al., 2012), whereas aeolian, alluvial and colluvial depositional environments occur either side of the Peake and Denison Inlier and in the vicinity of rivers and creeks (Figure 2-4). Lacustrine and spring-related landforms are restricted in extent, but are primarily at Lake Cadibarrawirracanna and in the vicinity of Weedina Creek (Krapf et al., 2012) (Figure 2-4).

Much of the region either side of the Peake and Denison Inlier is generally composed of undulating plains, sand sheet areas and plateaus of silcrete lag and quartz gibbers, with numerous, well developed gilgais (hollows developed in expanding clay soils). This region also contains an extensive drainage system with large braided watercourses prevalent. Soils are saline and composed of either red clays or clay loams of notable depth. Most vegetation occurs within the watercourses or the gilgai areas, with the stony plains in between often bare (MOSCB, 2002).

Variations to this include soils between the Neales River, Arckaringa Creek and Peake Creek and along the northern shore of Lake Cadibarrawirracanna that are composed predominantly of silt, sand and heavy brown saline or grey clay, covered with silcrete lag and quartz gibbers (Figure 2-4). A variation on this soil type surrounds the rest of Lake Cadibarrawirracanna; here, soft lighter grey gypseous clay soils without any substantial cover of any type predominate. Soils in this latter environment are poorly drained, becoming boggy after rain. In contrast, soils found in eroding watercourses contain shale fragments and gypsum (MOSCB, 2002).

The Peake and Denison Inlier consists of rough and rocky hill slopes and deep gorges. The stripping of residual soil is advanced, although some areas of residual soil remain. An undulating gibber plain is present on top of the ranges, beneath which clay soils have been silcreted near surface. The lower slopes of the land system contain well developed gilgais (MOSCB, 2002).

An area of predominantly sand dune coverage occurs in the vicinity of Weedina Creek west of the Peake and Denison Inlier (Figure 2-4). These sand dunes overlie an older gibber plain, with gibber pavement present in the swales between dunes. Occasionally swales may contain low rises composed of either sand or calcareous clay. Sand dunes are up to 10 m high and between 100 and 500 m apart. Dune material is generally composed of deep red sandy soils, with sandy to clayey loam soils present in the swales (MOSCB, 2002).

Soils around mound springs, swamps, claypans and watercourses are present within the investigation area. Soils that occur in such zones are generally brown or grey clay which crack to a varying degree, or yellow to red sandy loam soils. Mound spring environments support dense grasslands and watercourses are commonly bordered with trees (MOSCB, 2002).

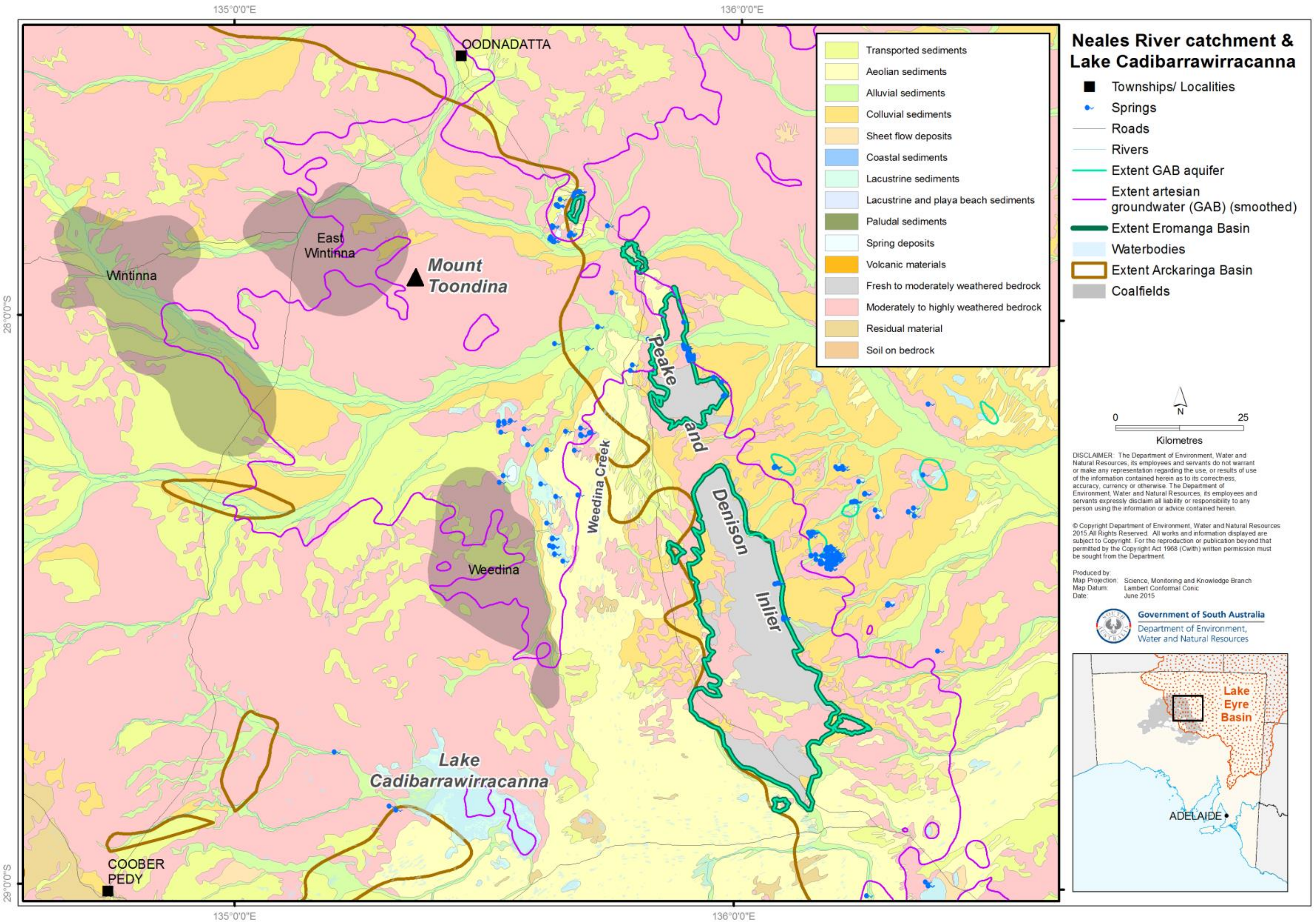


Figure 2-4: Regolith geology mapped within the investigation area (Krapf et al. 2012)

2.3 Hydrogeology

2.3.1 Fractured rock

Crystalline metasediment and igneous units of the Proterozoic and Archean basement sequences primarily outcrop within the Peake and Denison Inlier and in the vicinity of the Mount Woods Inlier. A fractured rock aquifer occurs 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 typically greatest near faults or fracture zones, 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. In the vicinity of the Mount Woods Inlier (Figure 2-2), groundwater extracted for mining has salinities ranging between 5000 and 10 000 mg/L and yields ranging between 400 and 4000 gph (~0.5–5 L/s) (Belperio, 2005). In contrast, Keppel et. al. (2015) noted that total salinities in Proterozoic fractured rock aquifer groundwater samples could be in excess of 40 000 mg/L. Wohling et al. (2013a) and Dailey (2011) discussed the potential for mountain system recharge to the GAB and Permian formations and groundwater from fractured rock aquifers in contact with the GAB in the vicinity of the Peake and Denison Inlier.

2.3.2 Arckaringa Basin

A paucity of data through the majority of the Arckaringa Basin renders the determination of the Arckaringa Basin groundwater system difficult beyond a very general and basic understanding. In the vicinity of coal resources and in the south-east of the basin, intra-formational aquifer units within the Mount Toondina and Boorthanna formations exist, whereas the Stuart Range Formation is a major confining layer (Keppel et al, 2015). SKM (2009), suggest that productive aquifer units may be present as relatively isolated semi-discontinuous ‘pods’ related to sporadic turbidite flows within an otherwise quiescent glacio-marine environment. Additionally, secondary porosity development, either by mineral dissolution or structural deformation, is seen as an important variable with respect to aquifer quality.

Salinities within the Arckaringa Basin typically range between 6000 and 25 000 mg/L, although higher salinities (>100 000 mg/L) do occur near the southern margin of the basin. pH ranges between 9.7 and 6.3. With respect to gross hydrochemistry, major ion hydrochemistry from Arckaringa Basin aquifers in the south and south-east of the basin is similar to that found within the overlying GAB, being predominantly Cl^- and $Na^+ + K^+$ dominant, with relatively high Mg^{2+} and SO_4^{2-} (e.g. AGC, 1975; Howe et al., 2008).

There have been a number of hydrochemistry-based studies designed to investigate groundwater flow systems of the Arckaringa Basin and determine their relationship with the GAB. The vast majority of these studies have concentrated on the south-east corner of the Arckaringa Basin. The most recent by Keppel et al. (2015) suggests that it is difficult to discriminate between aquifers on the basis of major ion data only, although the relative age and paleo-flow directions of groundwater from the GAB and Boorthanna Formation aquifer based on radiocarbon results displayed discernable differences. Additionally, Kleinig et al. (2015) was able to use environmental isotope and noble gas analysis to distinguish locations where the Boorthanna Formation and GAB aquifers were potentially connected.

2.3.3 Great Artesian Basin

A number of studies 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).

The Great Artesian Basin 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). Except for the far north and far eastern parts of Queensland and the Northern Territory, 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).

In the vicinity of the investigation area, the aquifer units of primary importance are the Algebuckina Sandstone, Cadna-owie Formation, and lateral equivalents (collectively referred to as the J-K aquifer in South Australia) as these form the major aquifer within this part of the basin. Whereas the most important confining layers include the Bulldog 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 at Olympic Dam in Well field B within the artesian component.

Groundwater flow within the J-K aquifer within the investigation area is interpreted to occur from areas of recharge in the vicinity of the western, northern and eastern margins of the basin, whilst flow from the western and northern regions dominate flow towards spring environments located in the vicinity of the Peake and Denison Inlier (Figure 2-5). A zone where the J-K aquifer is unsaturated extends southwest from the western margin of the Peake and Denison Inlier and coincides with a region of aquifer outcrop; this zone may act as an area of localised recharge to underlying aquifers inclusive of those within the Arckaringa Basin. Additionally Wohling et al. (2013a) investigated and found evidence for mountain system recharge (MSR) via fractured rock aquifers outcropping in the Peake and Denison Inlier to Permian formations on the western side and to the GAB on the eastern side. Groundwater gradients in the investigation area are between 0.0006 and 0.001.

2.3.4 Cenozoic

The most recent phases of sedimentation may provide discrete aquifers in areas covered by the Lake Eyre Basin. The Cenozoic aquifers represent a known resource of stock and domestic water in the wider Lake Eyre hydrological basin in South Australia. Shepherd (1978) reported salinities vary from 1000 mg/L to greater than 100 000 mg/L, while inferred transmissivities to be less than 100 m^2/d. In the Simpson Desert region, C. Bleys & Associates (1977) reported a Cenozoic aquifer consisting of clean quartz sands and salinities at several wells were approximately 8000 mg/L with yields from 5 L/s to 12.6 L/s. Cenozoic aquifers may be of importance to spring and other groundwater dependent ecosystems (GDEs) located within drainage channels, or where thick sequences occur, however this requires further investigation.

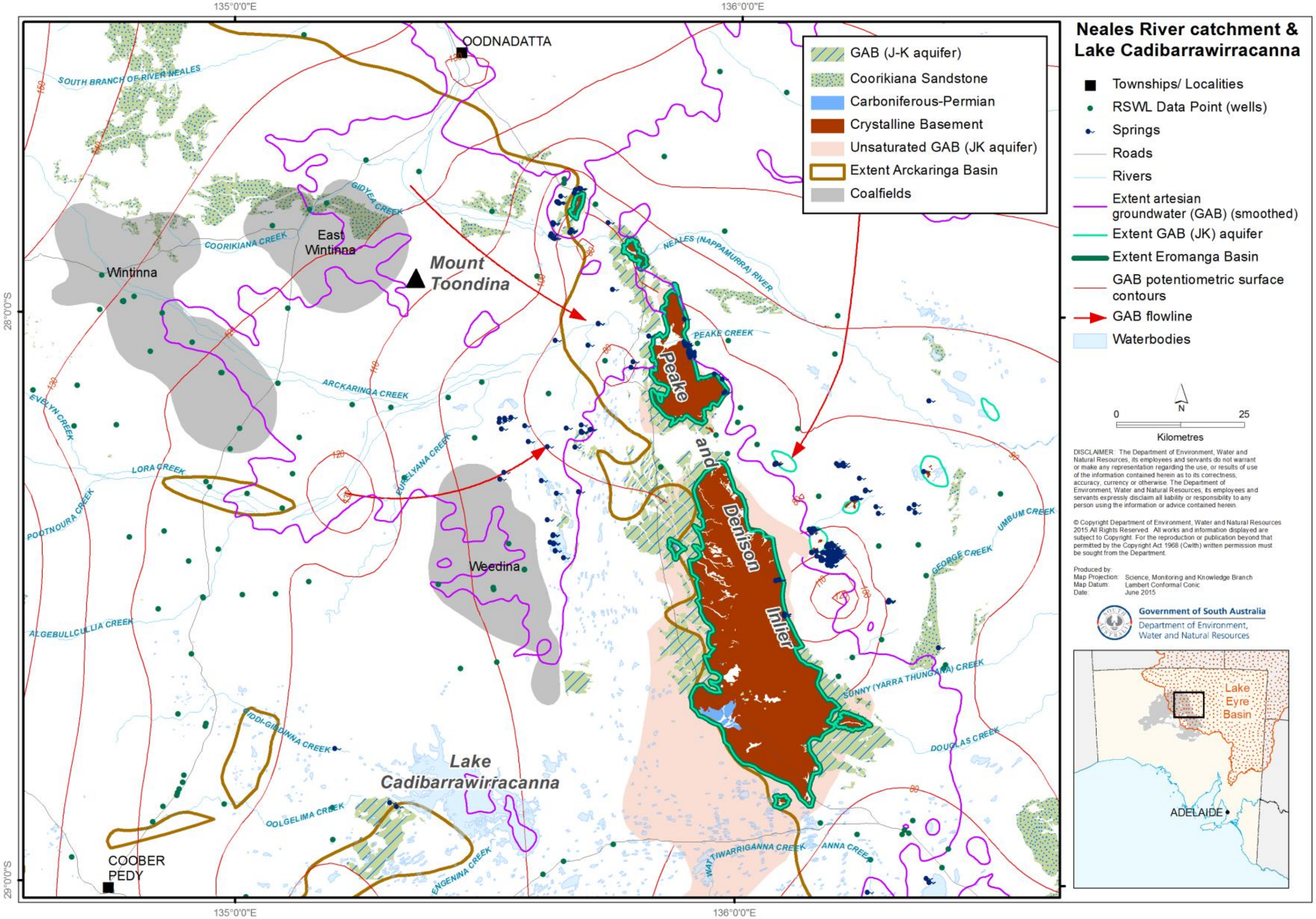


Figure 2-5: Potentiometric contours for the GAB (J-K) aquifer for the investigation area

3 Methods

3.1 Structural review

The location of springs were considered with respect to structural surface layers and isopachs developed for major stratigraphic horizons for basin sedimentary rocks in the region (Keppel et al. 2012; Keppel et al. 2015; Sampson et al. 2013).

The interpreted basin architecture was based on the development of isopachs for the GAB aquifer units (J-K aquifer), Mount Toondina, Stuart Range and Boorthanna formations using archival seismic and borehole data, and spatial coverage of 1:100 000 mapped surface geology. Development took place using the geoscientific mapping, modelling and data management software Petrosys dbMap®. Data were obtained from publically available reports and data files accessed via the SARIG online database, as well as data stored on the SA Geodata database. Three-dimensional subsurface datasets were developed describing the top and extent of each formation, as well as the base of the Permian sequence. Basement for the purposes of this study are all rocks older than the Permo-carboniferous units of the Arckaringa Basin.

Spring positions were compared to these structure surface layers via the development of cross-sections. An interpretation of primary and possible secondary controls was then developed.

3.2 Geophysics

Two spring vent sites were chosen for ground-based geophysical surveys. These were Cootanoorina spring vent PCN001 and Old Nilpinna springs vent POS007 (Figure 3-1). These sites were chosen because they provided good variation in the near-surface geology, were sites that did not have any existing geophysics information and were reasonably accessible.

3.2.1 Cootanoorina spring vent PCN001

Time-domain electromagnetic (TEM) data were collected along a 360 m profile that ran from south-west to north-east over the spring mound, with data collected directly over the main vent (Figure 3-2). The survey used a central in-loop configuration, with a 20 m square transmitter loop (single turn) and a 5 m square receiver loop (also single turn) located in the centre. A Zonge GDP-32ii geophysical receiver with integrated transmitter was used to acquire the data. The voltage decay data were recorded at each station and then the loops were moved along by 20 m, resulting in a continuous set of data along the line. Data from each station were inverted for a 1D resistivity model (resistivity variation with depth) using Zonge Engineering's STEMINV routine.

In addition, a surface self-potential (SP) survey was conducted along the same line, extending further to the north-east over a nearby drainage depression channel (total profile length 1250 m) (Figure 3-2). An absolute potential measurement was made at spacings of 20 m along the line between a roving electrode and a fixed reference electrode at the north-eastern end. Sealed Pb-PbCl porous pot electrodes were used and temperature variations were avoided by keeping electrodes in the shade.

3.2.2 Old Nilpinna spring group, vent POS007 ("New" Old Nilpinna Spring")

TEM data were collected along a kinked profile which ran approximately from west–south-west to east–north-east over spring vent POS007 (Figure 3-2). The total profile length was 560 m. The survey used a central in-loop configuration, with a 20 m square transmitter loop (single turn) and a 5 m square receiver loop (also single turn) located in the centre. Instrumentation and logging of data was the same as for the Cootanoorina survey.

A surface self-potential (SP) survey was also conducted along two lines at Old Nilpinna spring vent site POS007. The first, line ONS1, was coincident with the TEM profile line. The second, line ONS2, began at the POS007 spring vent (station 2000 on the TEM profile) and ran southeast past the nearby POS001 spring vent (Figure 3-2). An absolute potential measurement was made at spacings of 20 m along these lines between a roving electrode and a fixed reference electrode, located about 100 m north-east of the POS007 spring vent. Sealed Pb-PbCl porous pot electrodes were used and temperature variations were avoided by keeping electrodes in the shade.

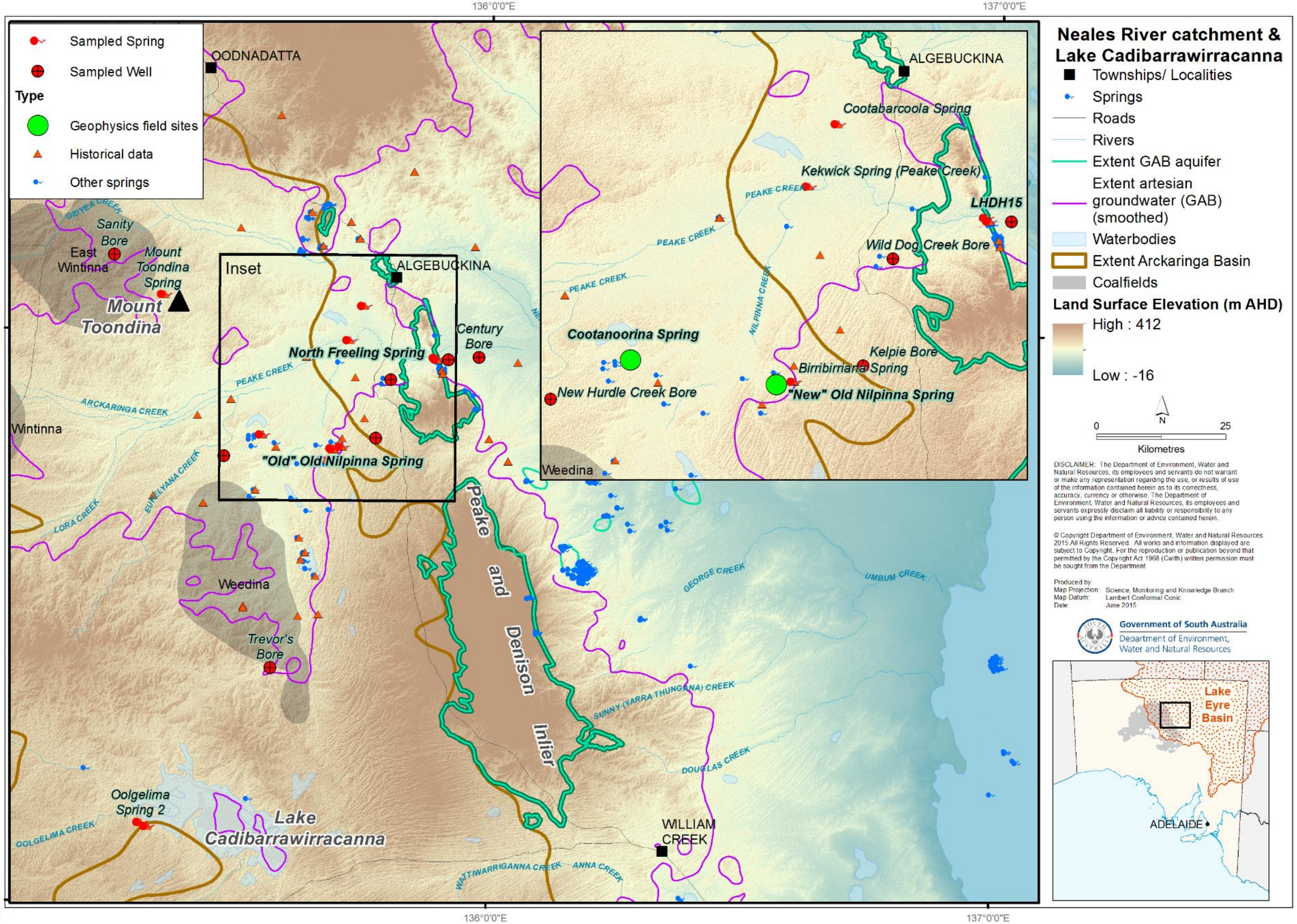


Figure 3-1: Location of hydrochemistry sampling and geophysics sites within the investigation area

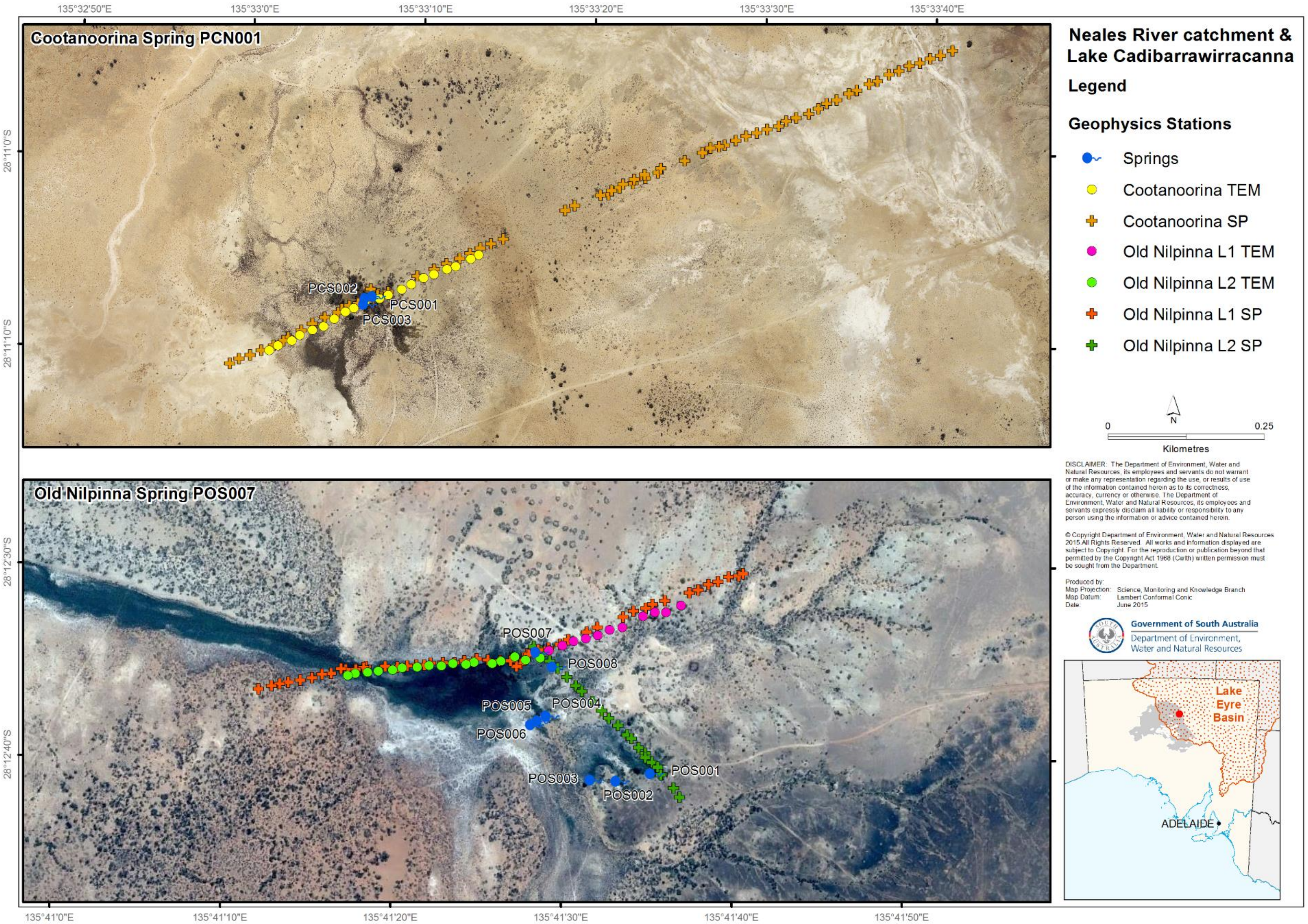


Figure 3-2: Location of geophysical survey stations at the Cootanoorina and Old Nilpinna Spring investigation sites

3.3 Hydrochemistry and environmental isotopes

Hydrochemistry data from 11 springs and 7 wells were collected between 5 and 11 November 2014. A table describing the sampled springs and wells is provided in Appendix A and locations are presented in Figure 3-1: Location of hydrochemistry sampling and geophysics sites within the results from laboratory analysis are provided in Appendices B and C.

Regular water quality measurements were taken using a YSI multi-parameter meter to ensure stabilisation of water quality prior to sampling, with results provided in Appendix B. At the time of sampling, a final water quality measurement for pH, electrical conductivity (EC), dissolved oxygen, (DO), redox potential (Eh) and temperature were recorded and a field alkalinity (as $CaCO_3$, using a Hach© titration kit) taken. A number of water samples were collected—the details of sampling, field preparation and laboratory techniques for each chemical and isotopic species are summarised in Table 3-1.

The hydrochemistry sampling program was designed to fill gaps in the coverage of the region to enable a more complete hydrochemical characterisation of groundwater discharging from springs. Scatter plots and Piper diagrams were used to determine broad hydrochemical characteristics of the groundwater.

3.3.1 Data analysis

3.3.1.1 Previously published major ion data

Major ion data previously collected from wells in the region were collated and assessed in parallel with major ion results obtained during this investigation. Locations of wells included in the results compilation are provided in Figure 3-1. Results were rejected if charge balances for major ions were ±5%.

Wells currently installed within the Wintinna coal resource were not sampled during this investigation because of concerns regarding construction. There are no known hydrochemistry data for these wells.

Table 3-1: Summary of collection and analysis technique

Analyte	Storage	Volume (mL)	Field preparation	Laboratory	Analytical technique
Cations and trace elements	HDPE bottle	125	Filtered -45µm. Addition of HNO_3 (pH<2)	CSIRO Land and Water, Adelaide	Inductively Coupled Plasma Optical Emission Spectrometry (ICP-OES) and Mass Spectrometry (ICP-MS)
Anions, water quality, and total carbon	HDPE bottle	125	Filtered -45µm	CSIRO Land and Water, Adelaide	Dionex ICS–2500 Ion Chromatograph
Stable isotopes	McCartney vial	28	Unfiltered	University of California, Davis Campus, USA	Laser Water Isotope Analyser
Strontium 87/86	HDPE bottle	1000	Filtered -45µm	Adelaide Research and Innovation, The University of Adelaide	Finnegan Mat 262 thermal ionisation mass spectrometer
Archive	HDPE bottle	1000	Filtered -45µm		

3.3.1.2 Stable isotopes of water

The stable isotopes deuterium (δD) and Oxygen-18 ($\delta^{18}O$) are compared to the Local Mean Water Line (LMWL) for Alice Springs (Crosbie et al., 2012; IAEA, 2013) to determine the effects of evaporation or mixing on groundwater samples. For comparison purposes, Alice Springs was favoured over Woomera (the closest town to the investigation area with stable isotopes in precipitation recorded) because of a limited stable isotope record at Woomera (Liu et al., 2010). The LMWL is derived from precipitation collected from a single site or set of "local" sites (USGS, 2004). Groundwater that has evaporated or has mixed with evaporated water typically plots below the LMWL along lines that intersect the LMWL at the location of the original un-evaporated composition of the water (USGS, 2004).

3.3.1.3 Stronium isotopes ($^{87}Sr/^{86}Sr$)

$^{87}Sr/^{86}Sr$ data was plotted against the reciprocal of Sr^{2+} concentrations as the primary means of assessment. Such treatment provides a useful means of discriminating between different processes such as mixing of groundwater with multiple $^{87}Sr/^{86}Sr$ signatures, evaporation, dilution, exchange or mineral precipitation (Shand et al., 2009). Additionally, plotting of $^{87}Sr/^{86}Sr$ against Ca^{2+} can provide a useful means of determining water–rock interactions within particular aquifer units. A full description of interpretation methodology can be found in Shand et al. (2009).

4 Results

4.1 Structural setting of spring formation

4.1.1 Common features to all spring conceptual-structure models

Although springs within the investigation area may display elements of a number of different conceptual models (Section 4.1.2), some models may better represent the primary reasoning for spring formation than others in particular examples. That being said, there are common themes to many spring localities when examined with respect to hydrogeological and topographic features, as well as to new interpreted regional structure and basement architecture of the study area as presented in Keppel et al. (2015).

Firstly, spring formation occurs in regions of artesian groundwater pressure. Although non-GAB, water table-fed springs such as Tarlton Springs in the vicinity of the eastern Peake and Denison Inlier exist (Figure 3-1), the vast majority of springs are understood to be primarily fed by artesian groundwater from the GAB. In most instances, these areas are on the margins of GAB artesian groundwater. Consequently all the springs described in this report can be primarily interpreted as discharge springs.

It should be noted that the majority of springs within the study area occur in areas where Quaternary and stream erosion and alluvium deposition has occurred (Figure 2-3 and Figure 2-4). Consequently, there may be some similarities evident between these springs, where watercourse development may have partly contributed to spring formation and 'riverine' wetlands (OGIA, 2015). Watercourse springs are sections where groundwater enters a stream from an aquifer through the streambed. That being said, the primary reliance on artesian groundwater conditions and requirement for localised structure-related spring conduits either through confining layers or cemented outcropping aquifer units leads to a preliminary description of discharge spring for all springs.

Secondly, removal of overburden by erosion, inclusive of stream erosion, is thought to be favorable for spring formation because this lessens the thickness of confining overburden for groundwater pressure to overcome.

With respect to structure and regional basement architecture, in the majority of instances springs are located near the margin of the Arckaringa Basin, where either large changes in architecture occur or where hydrostratigraphic units thin and ultimately pinch out, suggesting that the underlying architecture is the major control on spring formation. Structural deformation may also influence relative erosion and deposition rates by resulting in variations in topography. As an example, the eastern margin of the Arckaringa Basin in many instances is coincident with the margin of GAB artesian groundwater.

For the purposes of this report, basinal areas surrounding the Peake and Denison and Mount Woods inliers are being discussed as basin 'margins' despite their location within the GAB boundary. With respect to the underlying Arckaringa Basin, the Peake and Denison and Mount Woods inliers represent important structural features; the Peake and Denison Inlier represents the eastern margin of the Arckaringa Basin, whereas both inliers represent important structures over which overlying sediments are either thin or disrupted. In both cases, the hydrogeology of overlying sediments is greatly influenced by their presence, particularly with respect to the location of confining units and the extent of artesian groundwater. For this reason they act similarly to basin margins and are thus described accordingly.

4.1.2 Structural models

There are a number of conceptual models for spring formation near the margins of basins, within the south-western portion of the GAB presented here. The models are (Figure 4-1):

- 1a – Basin margin, structure (fracture zone)
- 1b – Basin margin, structure (fault zone)
- 2 – Basin margin, sediment thinning
- 3 – Basin margin structure/ sediment thinning combination
- 4 – Astrobleme

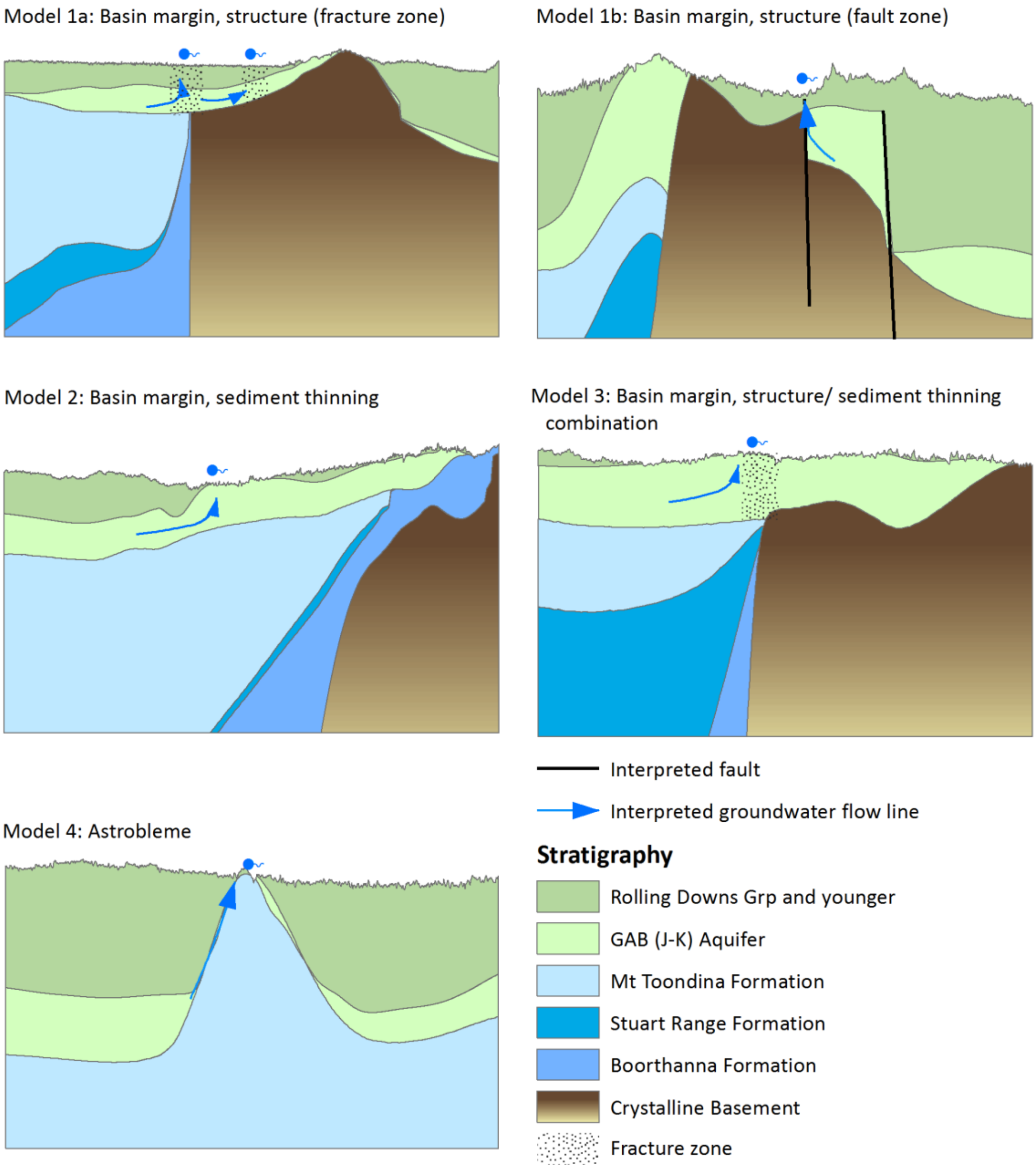


Figure 4-1: Structural models for the regional structural setting of springs within the Neales River and Lake Cadibarrawirracanna regions

There may be localised conditions with respect to the geomorphology, structural geology or hydrological environment that may have localised influence on spring formation, but these are considered secondary. Where appropriate, such secondary influences will be discussed.

4.1.2.1 Structural model 1a – Basin margin, structure (fracture zone)

Conceptual model 1a appears to be a common component with respect to spring locality, especially within the Peake Creek West, Mount Dutton and Lake Cadibarrawirracanna spring complexes (Figure 2-1 and Figure 2-2). Further afield, this model also appears applicable when discussing springs further to the south associated with the Torrens Hinge Zone (Keppel et al. 2013). In these instances, spring localities are closely correlated spatially to either the eastern margin of the Arckaringa Basin or in the case of the Lake Cadibarrawirracanna springs, the margin of a major trench structure in the vicinity of the Mount Woods Inlier. Such margins represent zones where large changes in thickness of unconsolidated to consolidated younger sedimentary rocks overlying crystalline basement rocks occur. The proximity of springs at these locations suggest that structural deformation associated with this margin may be responsible for spring formation (Figure 4-1). Interpretation of recently acquired seismic data presented by Keppel et al. (2015) does not provide definitive evidence for faulting in many examples. Structural variations observed in post- Carboniferous strata were commonly interpreted to be minor folding or depositional features, reflective of the glacially scoured terrain into which sediments were originally deposited, such as trenches.

The cause of fracture development may vary. One possibility is that faults prominent in crystalline basement that may have had some influence in determining basinal architecture have only recently extended into overlying strata via a fault 'tip' (Curewitz and Karson, 1997). This contemporaneous development has not had sufficient time to cause deformation to the same extent as observed in crystalline basement. Therefore conceptually, spring propagation is associated with networks of smaller fractures that are concentrated in zones where basement structures are reactivated to form monoclinal flexures and fault propagation folds (Keppel, 2013).

Another possibility where faulting within the crystalline basement cannot be determined is that the associated differences in tensile strength and compressibility may lead to deformation of overlying sedimentary rocks in ways responsive to variations in the crystalline basement architecture. One of these potential responses is gentle slumping of overlying sediments with associated joints, fracture zones and minor fault development.

Given 'overlying sedimentary rocks' in this instance are inclusive of Permian sediments, there appears to be at least a structural relationship between the Arckaringa Basin and springs, even if a hydrogeological relationship remains uncertain.

In some cases, the reasons for fracture development are not clear. The controls on the formation of Keckwick spring group would appear related to a fracture zone given that there appears to be approximately 50 m of Bulldog Shale at this location. That being said, there are no obvious regional structures or basin architectural features to explain the development of such a fracture zone to date. Possible contributions to spring development include the location of Keckwick spring group within the channel of Peake Creek indicating the potential for localised stripping of confining sediments. Additionally, the association with Peake Creek may also indicate possible groundwater sources from shallow aquifers associated with Quaternary and Cenozoic alluvial sediments, although no direct evidence for this is currently available.

4.1.2.2 Structural model 1b – Basin margin, structure (fault zone)

Conceptual model 1b appears to be most applicable for the Peake Creek East spring complex, as well as springs located on the north-eastern side of Mount Dutton (Figure 2-1). In this conceptual model, the basin margin is synonymous with a fully developed fault zone (Figure 4-1). Tensile secondary fault structures that form within the wider fault zone provide the basis for conduit formation. A more detailed discussion of the influence of faulting on the development of springs at the Freeling south spring group, located within the Peake Creek East spring complex is presented in Keppel (2013), Keppel et al. (2013) and Karlstrom et al (2013). This will be summarised as appropriate here.

In the case of the Peake Creek East spring complex, springs are located very close to the eastern outcropping margin of the Peake and Denison Inlier (Figure 4-2). This margin is defined by a number of major regional faults, in particular the Kingston and Levi faults. Although the stress field primarily governing fault movement in the Kati Thanda-Lake Eyre region is an east–west orientated compression, which primarily exacerbates itself along the Kingston and Levi faults as oblique north-west–south-east shear, lineament and structural mapping indicate that a number of other secondary structural orientations are evident, including those representative of extension fractures that form parallel to the primary east–west far-field stress.

Conceptual models 1a and 1b are similar in that both represent large changes in the depth of basinal sediments and the relationship to large changes in basin architecture. However the primary difference is the consideration of the degree and maturity of active fault movement emanating from the basement structure causing conduit formation in Conceptual model 1b. Faulting in model 1b is mature enough to have caused major displacement of basinal aquifer and confining layer units, potentially leading to a complex hydrogeology, including the development of impermeable barriers to lateral groundwater flow and the potential for multiple sources of groundwater for springs, including from fractured crystalline basement. The potential for groundwater supply to springs in the Feeling South spring complex from crystalline basement is discussed in Wohling et al. (2013a) and Dailey (2011) and is compatible with geophysical modelling (Inverarity, 2014). In contrast, model 1a simply refers to a fracture zone that may or may not be related to early stage fault-propagation.

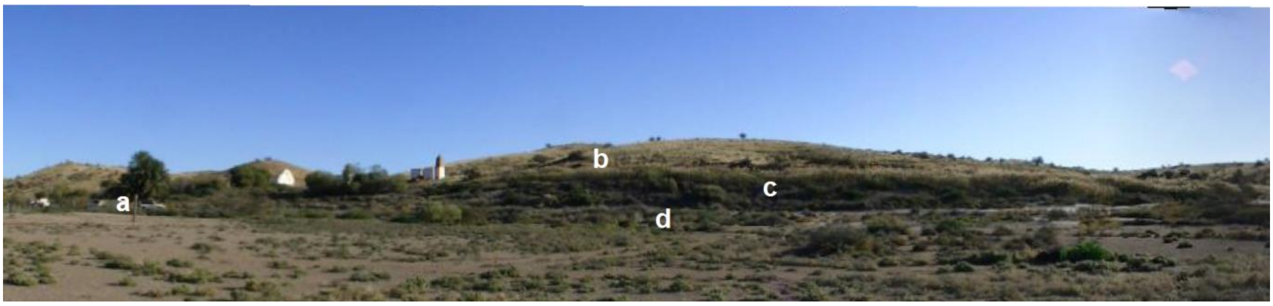


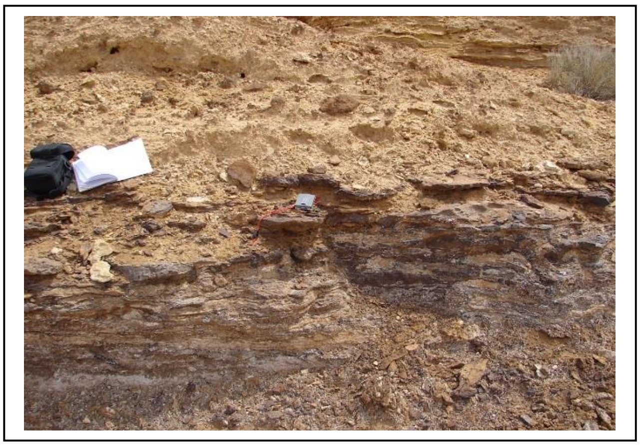
Figure 4-2: Panorama of the Freeling Springs south site, looking west

The largest spring (EFS001) (a) located at the far south of the complex. The Peake and Denison Inlier (b) is composed of up-thrown Adelaidean basement rocks. The Kingston Fault is marked by a large stand of *Phragmites australis* that is supported by discharging groundwater (c). Calcareous spring deposits (d) are present in the foreground. From Keppel (2013)

4.1.2.3 Structural model 2 – Basin margin, sediment thinning

Although a common feature of many springs on a regional scale is their location on the margins of confining layer outcrop or in areas of aquifer unit outcrop, in a number of cases a spring location does not appear related to any major linear deformation structures, such as basinal margins or regional scale faulting. Rather such springs are located in the general vicinity of mountain block structures such as the Peake and Denison Inlier, where associated crystalline basement is covered by thinning Mesozoic sediments (Figure 4-1). Consequently, this suggests that the primary reason for spring formation is the thinning and possible breaching of the confining layer.

A number of examples of such spring groups sampled during this study include Cootabarcoola, Old Nilpinna and Birribirriana spring groups (Figure 2-1 and Figure 3-1). The location of these spring groups near the margin of the Bulldog Shale suggests their location is primarily controlled by removal of the confining layer and the development of a shallow spring conduit. In particular, Old Nilpinna and Birribirriana spring groups appear to have formed on or in very close vicinity to outcropping J-K aquifer (Figure 4-3). It is interpreted that weathering and associated regolith processes such as secondary cementation and subsequent hardpan development have combined with gradual removal of confining layer materials and drops in groundwater head, the latter also aiding regolith processes by allowing oxidation of near surface materials, to form the spring environment observed. Further, it is interpreted that discrete spring vents may be formed via minor fracture development within outcropping aquifer material, or local variations in weathering and regolith process. Such areas may be related to deeper regional-scale structures, although given the lack of confining horizons, such structures may be small in scale (Figure 4-3). Consequently, groundwater discharge in such areas is restricted to where maintenance of sufficient porosity and permeability in the spring conduits allows transmission of groundwater to surface, either as free flow or as diffuse discharge.



a)

b)

Figure 4-3: J-K aquifer outcrop a) located near Birribirriana Springs b)

The lack of confining layer at this site strongly indicates that removal of the confining layer is the primary cause of spring formation. A fracture showing minor displacement is evident near the centre of image (A) near the compass.

4.1.2.4 Structural model 3 – Basin margin, structure/ sediment thinning combination

In the case of some springs located on the western side of Mount Dutton and parts of the Peake Creek West spring complex (e.g. Cootanoorina spring vent PCN001), a combination of Conceptual models 1a or 1b and 2 may be appropriate (Figure 4-1). Interpretation of structural surfaces in this region suggest that GAB aquifer sediments have been deposited over a basement high, evidenced by a relatively steep depositional repose of sediments compared to surrounding regions. However, this has also lead to the preferential stripping of Bulldog Shale confining units at this location. Consequently, although the position of springs is highly indicative of a Conceptual model 2 scenario, the influence of structures with respect to conduct formation as described in Conceptual models 1a or 1b may also be a factor.

This particular model may be very common, particularly around the eastern margins of the Peake and Denison Inlier given that both fracturing, faulting and sediment thinning are most likely to occur within the same places structurally, namely in the vicinity of basement highs or basin margins. That being said, evidence for structural control may not be evident using regional scale geophysical data sets. In such cases, the employment of local-scale TEM and SP is used to clarify controls on spring formation (see Sections 4.3 and 5.2).

4.1.2.5 Structural model 4 – Astrobleme

This conceptual model is limited to springs associated with the Mount Toondina Piercement structure (Figure 2-1). The Mount Toondina Piercement Structure occurs within the north-eastern Arckaringa Basin, approximately 45 km south of Oodnadatta. It is one of the few localities where Arckaringa Basin sediments, most notably the Mount Toondina Formation, are known to outcrop. This structure was first interpreted to be a diaper, but since Youles (1976), an alternative astrobleme (impact crater) hypothesis has been the focus of study (Shoemaker and Shoemaker 1988; Plescia et al., 1994; University of New Brunswick, 2009). More recently, Haines (2005) stated that existing seismic data over the piercement structure clearly shows no evidence for a diaper. Consequently springs closely associated with the Mount Toondina Piercement structure are related to features prevalent to an astrobleme (Figure 4-1).

Springs associated with astroblemes are well known. A detailed summary of known astrobleme-associated spring occurrences in the context of the Mount Toondina Piercement structures is presented by Dressler (2010). Deformation caused by the impact in the form of upturned sedimentary beds and fracturing form the structural architecture of the spring complex. Dressler (2010) states that fluid flow is primarily controlled by permeability associated with lithology, whereas fractures may be limited to influencing fluid flow to surface. Numerical modelling used to describe possible groundwater flow scenarios to account for findings of a resistivity survey suggested that the Algebuckina Sandstone had relatively high permeability compared to Bulldog Shale units found around the perimeter of the structure and Mount Toondina Formation units found within the centre (Figure 4-1). Spring formation may therefore be related to where high permeability units such as the Algebuckina Sandstone outcrop or where fracturing has increases permeability and allowed for groundwater migration to surface. Added to this Dressler (2010) hypothesised that groundwater flow within the Mount Toondina spring complex is controlled by advective flow from the subsurface to the ring of vegetation around the springs, but also that the central portion of the impact crater is influenced by free convective processes (Figure 4-4). Free convective processes involve fluid motion not generated by an external source but only by density differences in the fluid.

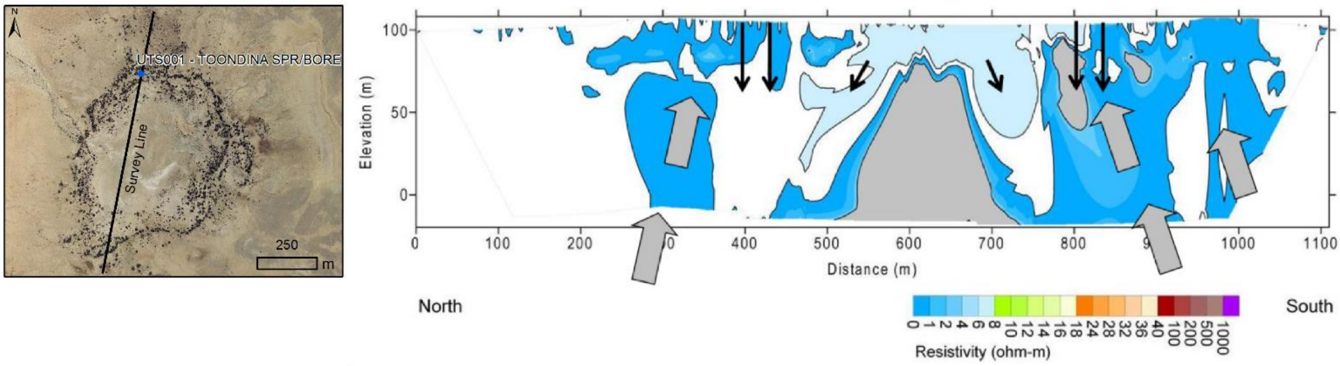


Figure 4-4: Hydrogeological conceptual model of Mount Toondina using electro-resistivity image as background (From Dressler, 2010)
Arrows indicate direction of fluid transport through the J-K aquifer within the crater. Salt build-up within near surface groundwater leads to the potential development of free convective processes. Conductive fingers within electro-resistivity image could be interpreted as fluids sinking back into the central portion of the crater (Dressler, 2010).

4.2 Geophysics

4.2.1 Cootanoorina TEM

A cross-section of the inverted models developed from the Cootanoorina TEM data is shown in Figure 4-5. Fits to data are good for early and middle time windows; the latest window for which responses were modelled is around 400 µs and the depth of investigation is approximately 50 m.

The resistivity model is dominated by two layers. The shallow conductive layer is approximately 5 m to 10 m thick. It has a resistivity ranging between 1 Ωm and 4 Ωm. It is comparatively more resistive between stations 700 and 860, which closely aligns with the 'spring' area (defined as the carbonate mound structure towards the north-eastern end, and the thickly vegetated area over the spring discharge tail, towards the south-western end). The slightly more resistive area is likely to be caused by a combination of:

1. carbonate precipitated in the subsurface as a result of spring discharge;
2. a lower proportion of highly conductive clay minerals, which typically cause resistivities of less than 2 Ωm in this region;, and
3. potentially lower salinity (higher resistivity) pore water from the spring discharge, compared to pore water in the surrounding near-surface sediments that is likely to be affected by the high regional evapotranspiration rate and therefore is more saline.

The lower layer appears in the TEM resistivity model as a transition zone towards higher resistivities at depths of 30 m or more. In reality the ground may contain a sharp boundary across which the resistivity increases, but the modelling conducted here is not able to resolve this kind of feature, instead smoothing it out. Therefore the more resistive lower layer likely begins at a depth of between 10 m and 15 m and extends to the maximum depth of investigation of the survey method, approximately 50 mbgs. The resistivity of this layer varies between 60 Ωm and 160 Ωm. Previous TEM and Audio-magnetotellurics (AMT) surveys over mound springs in the region (Beresford, Warburton, and Freeling springs) have shown that the Cadna-owie Formation is generally between 50 Ωm and 80 Ωm (Inverarity, 2014), which is compatible with the resistivity of the lower layer observed here.

Note that in the lower layer there are two sections which are more resistive: between stations 800 and 860 (beneath the mound and spring vents), and from station 910 to station 1000. In particular, the section between stations 800 and 860 coincides with a shallower base (or zone of high resistivity) to the more conductive surface layer at station 820. This is further accentuated by the local topography (not shown) which contains a mound at stations 820 to 860 about 5 m high at station 820. This means there is a significantly more resistive area (160 Ωm compared to surrounding 60 Ωm) at depth, coming to a slightly higher elevation than the surrounding layer, directly underneath the spring vents. A more resistive area might be caused by a number of things such as fresher pore water, lower porosities, or a lower proportion of conductive minerals such as clay in the material. However, the preferred explanation in this case is that the spring vents lie on a geological structure, such as a fault, which strikes roughly north–south. The fault may occur between two zones of different resistivities (e.g. a more resistive eastern block against a more conductive western block).

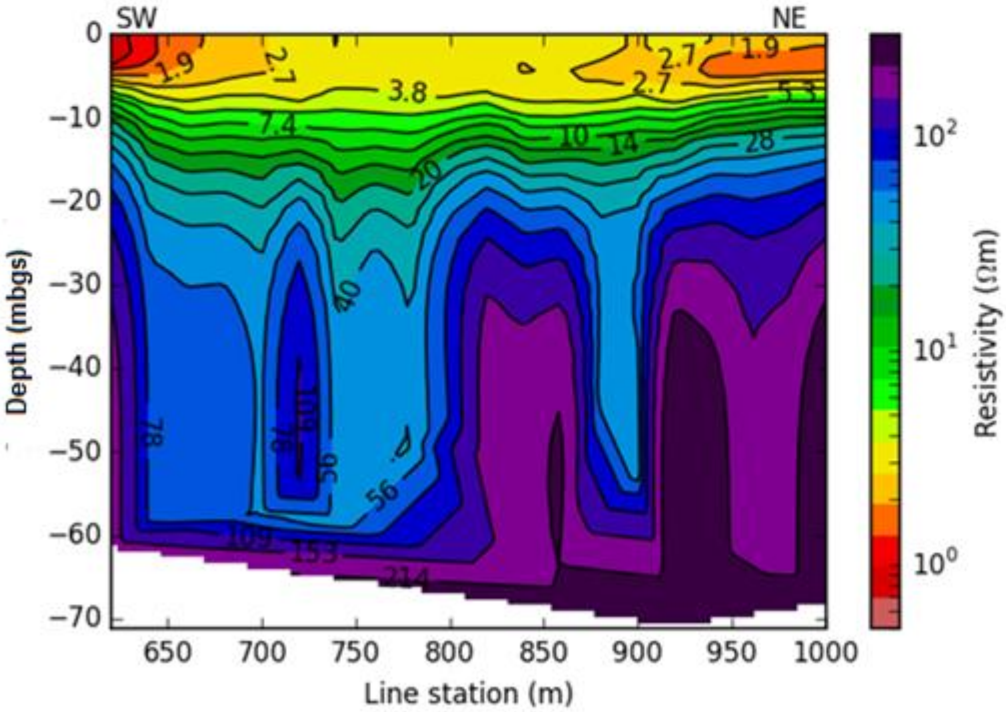


Figure 4-5: Resistivity model obtained by 1D inversion of TEM data over Cootanoorina spring vent site PCN001

The spring vent is at station 820 and the mound extends from station 800 to 860, with mound/tail-related vegetation extending further south-west to station 740.

4.2.2 Cootanoorina SP

SP data for the Cootanoorina springs complex site are shown in Figure 4-6. An overlapping section was recorded on both days in order to adjust for overnight changes in SP. These changes are due to the existence of potentials between individual electrodes which are caused by small differences in the composition of the copper sulphate solution in the electrode and changes in temperature. The first day's data was adjusted by +20 mV, which was derived from comparison of the overlapping section.

There is a large positive peak in voltages at station 815, close to the spring vents, with another sharp but lower amplitude peak at station 950. There is a broad positive feature between stations 700 and 850. This latter feature is correlated to the location of the mound spring. Voltages peak at the spring vents at 62 mV and then remain steady at approximately 45 mV immediately to the south-west until they begin to drop west of station 740. This is contrasted with an extremely steep rise in voltage on the eastern side of the spring vents. Such asymmetry can be explained by the majority of subsurface fluid flow occurring vertically underneath the vent, with some related lateral flow outward on the western side of the vents. Given the steadily dropping voltages further west, there is no evidence for other conduit paths, beyond the unexplained peak in voltages at station 950 (i.e. 100 m northeast of the spring vents). This is correlated with a subtle high resistivity feature in the TEM resistivity model, and may represent groundwater flow and/or structure related to the mound, but would require more detailed SP surveys to confirm and further investigate the anomaly.

The consistently low voltages between stations 1300 and 1700 (and associated peaks on either side at 1200 and 1800) are related to the clay minerals and infiltrating moisture in the drainage depression that was crossed in this area.

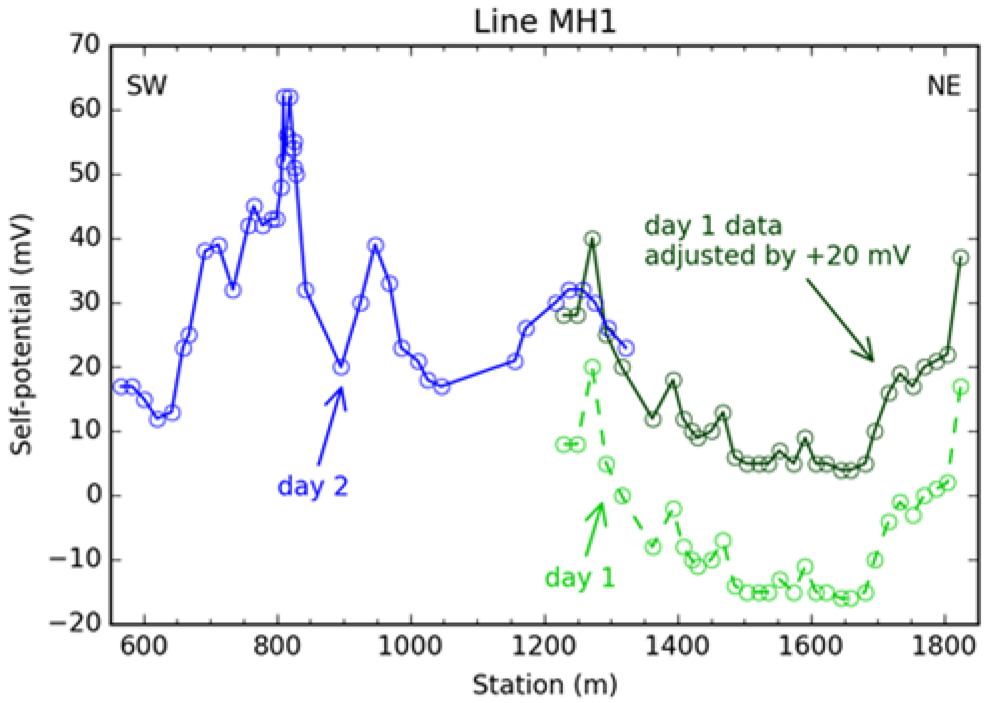


Figure 4-6: Self potential data over Cootanoorina spring vent site PCN001

The spring vent is at station 820 and the mound extends from station 800 to 860, with mound/tail-related vegetation extending further south-west to station 740. The regional drainage depression is between stations 1430 and 1820.

4.2.3 Old Nilpinna TEM

A cross-section of the resistivity model inverted from the Old Nilpinna TEM data is shown in Figure 4-7. Spring vent POS007 (see Section 6.2) occurs at station 2000. Fits to data are good for early and middle time windows; the latest window for which responses were modelled is around 400 µs and the depth of investigation is approximately 50 m.

The resistivity model contains increasing resistivity with depth, varying from resistivities of between 3 Ωm and 8 Ωm at the surface, down through 20 Ωm at 10 m to 20 mbgs (below ground level) to between 60 Ωm and 200 Ωm at depths of 30 m to 50 m. Some important features within the model are described below:

1. The surface layer is more resistive than at Cootanoorina. This is ascribed to the generally more elevated nature of the land at Old Nilpinna and fits with field observations during the survey that there was scant soil moisture in comparison to Cootanoorina.
2. The spring tail ran parallel and immediately south of the TEM survey line for most of its length until station 1740, which was recorded in the centre of the tail. This station recorded much more conductive surface readings, consistent with the presence of completely saturated soil, but also recorded significantly more resistive underlying material down to 50 mbgs. This may be directly due to infiltration of less saline spring water. Note that the fit of the modelled responses to those observed is excellent across this part of the model, indicating that the high resistivity model feature here is required by the observations (although may not necessarily extend to the full depth shown).
3. There is a transition to higher resistivities occurring at a depth ranging from 10 mbgs at the western end of the line to nearly 20 mbgs at the eastern end (taken as the 20 Ωm contour line from Figure 4-7. The thickness of the layer overlying this transition increases between stations 1800 and 2080, with a deeper base, and an interruption consisting of a slightly more resistive ‘plume-like shape’ occurs at station 2000 (i.e. underlying the spring vent). This ‘plume-like shape’ may be sediments containing less saline pore water related to water in the conduit flowing up the spring vent. The gradual increase in depth of the transition to the west may be related to dipping stratigraphy, but further information, such as either drilling data, a longer TEM line, an additional TEM survey with stations placed further apart

or the application of another geophysical method such as magnetotellurics would be needed to confirm this interpretation.

4. There is significant lateral variation in the resistivity of the lower layer (from 60 Ωm to 200 Ωm), with conductive intervals at stations 1800 to 1840, 1900, 2000 to 2040, 2100, and 2240. Additionally, it is noted that the 'deep' vertical conductor at station 2020 (correlating with the position of a spring vent) is wider than similar features observed elsewhere on the profile.

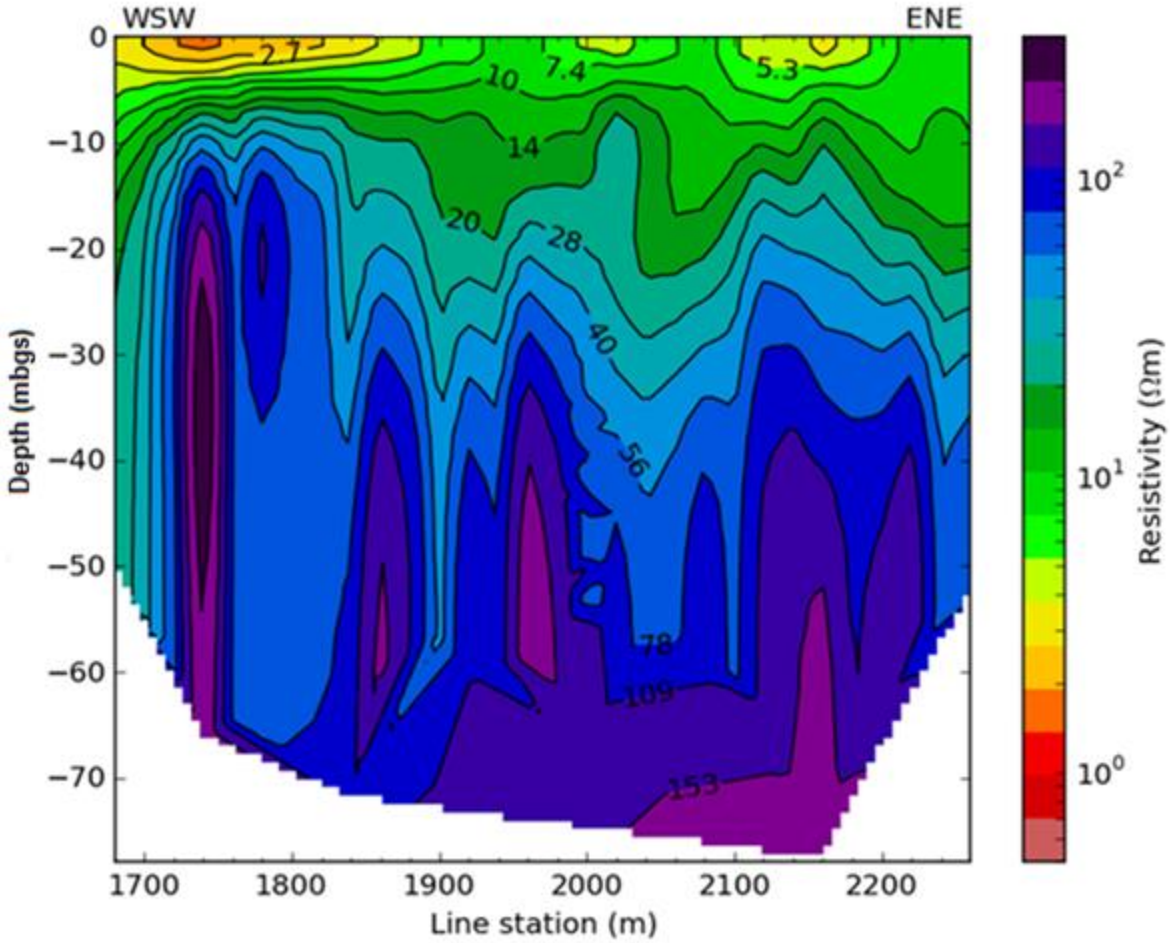


Figure 4-7: Resistivity model obtained by 1D inversion of TEM data over Old Nilpinna spring vent POS007.

The spring vent is at station 2000.

4.2.4 Old Nilpinna SP

SP data for the Old Nilpinna spring vent site POS007 are shown in Figure 4-8 and Figure 4-9. Note that data were recorded in continuous stints and no adjustments have been made to the observed voltages. Many difficulties were encountered in obtaining suitable contact resistances due to high ambient temperatures and extremely low soil moisture (some level of moisture is required to accurately observe the electrical potential present in the ground; high levels of contact resistance interfere with the measurement and optimal results occur with resistances less than 10 kΩ) (Inverarity, 2014).

The SP data from Line ONS1 (Figure 4-8) shows no obvious features correlated with the spring vent. Voltages decrease gradually with distance to the west. Unfortunately the presence of sandy soil and slightly higher land surface elevations in the eastern part of the surveyed area made it difficult to obtain reliable measurements, as seen by the contact resistance data in Figure 4-8, but a number of measurements suggest that the potential did decline to the east of the POS007 vent. Nonetheless a reliable but low amplitude peak in voltage was observed at station 1940, approximately 60 m west of the vent, and a small peak was also observed on the far side of the tail at station 1690.

The most reliable feature that requires explanation on the ONS1 line is the gradual decrease of potential to the west. This may be caused by either:

1. variation in the self-potential cross-coupling coefficient to the west (i.e. gradual lithological variation), with little lateral variation in flow;
2. lateral flow from west to east combined with upwelling at the vent; and
3. increased downward infiltration to the west resulting in lower potentials.

The preferred explanation, given the TEM observations above, is a combination of (1) and (3): upward flow is occurring within a lithological unit which becomes thicker to the east and has a higher amplitude cross-coupling coefficient, with the upward flow therefore generating a higher amplitude potential in the east. Furthermore the TEM station recorded in the tail provides evidence that infiltration is occurring, and this fits with the SP data. The lack of obvious structure interpretable in both SP and TEM data suggests that the structural Conceptual model 2 (Basin margin, sediment thinning) is the most appropriate classification for this example. This is further discussed in Section 5.1.

The SP data from Line ONS2, which runs perpendicular to the TEM profile line and extends between the POS007 and POS001 spring vents (see Section 6.2), is shown in Figure 4-9. This data contains a positive peak at the POS007 vent (station 2000) and drops to a minimum at station 2150, in between the two spring structures, before rising again to steady values across the carbonate mound surrounding the POS001 vent (closest to station 2260). Note that unlike POS007, measurements could not be taken directly in the POS001 vent due to extremely thick date palm vegetation. The moderate amplitude drop between the springs suggests the upward subsurface flow to the vents is not broadly distributed along any structures oriented approximately parallel to the ONS2 line. Flow to the two vents appears to be occurring independently, at least with respect to flow from depths of up to approximately 100 m, which is the range of depths to which the measured SP data are sensitive.

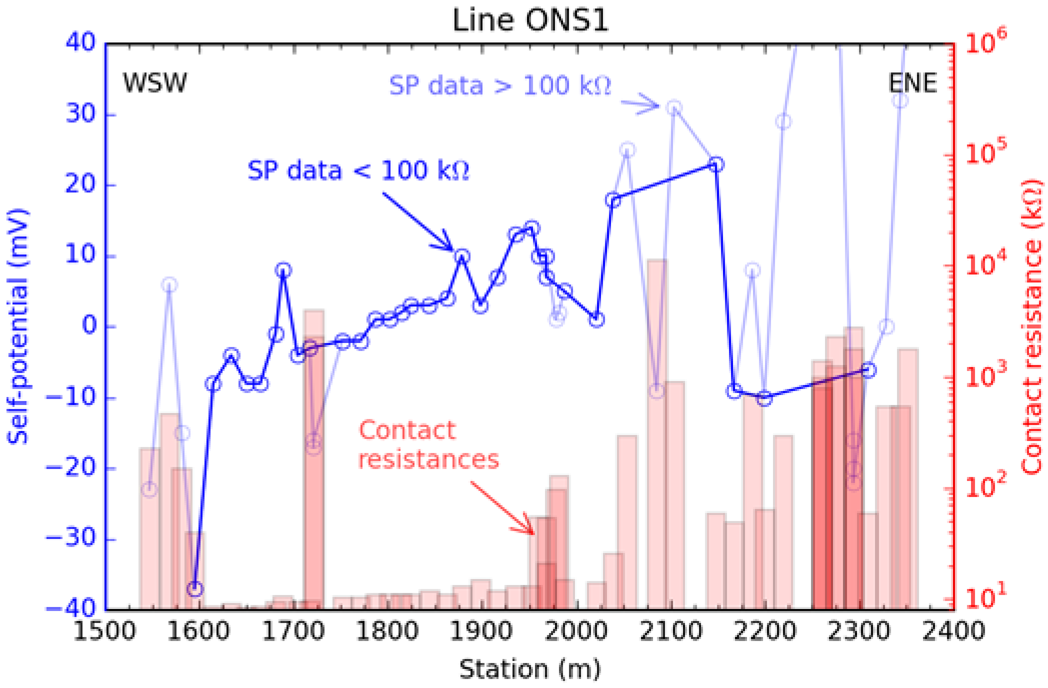


Figure 4-8: Self-potential data over Old Nilpinna spring vent site POS007

The spring vent is at station 2000.

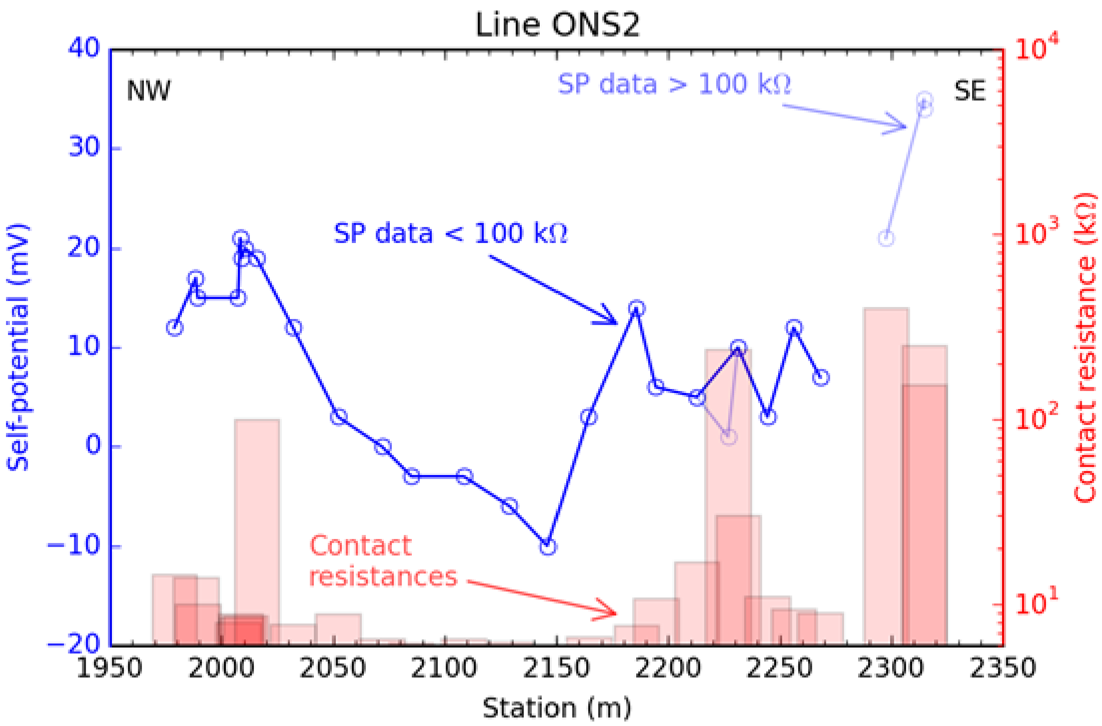


Figure 4-9: Self-potential data over Old Nilpinna spring vent site between POS007 and POS001

The POS007 vent is at station 2000 and the POS001 vent is adjacent to station 2260.

4.3 Hydrochemistry

4.3.1 Major ions, stable isotopes, $^{87}Sr/^{86}Sr$ of groundwater

Variability of major ion concentrations from all spring and well samples from the investigation area was not large when their proportional distribution relative to one another is examined using a Piper diagram. The majority of samples appear to be Na^{+}+Cl^{-} type, with only a few samplings displaying enough variation in cation concentration to be considered Na^{+} +Ca^{2+}+Mg^{2+}+Cl^{-} type waters (Figure 4-10).

That being said, groundwater groupings based on spatial distribution could still be interpreted. Within the study area, three general groupings based largely on the relative proportions and distributions of Mg^{2+}, K^{+}, SO_4^{2-} and Cl^{-} and to a lesser extent Ca^{2+} were identified that correspond with a distinct spatial distribution.

Additionally, stable isotopes of deuterium (δD) and oxygen-18 ($\delta^{18}O$) and isotopic strontium ratios ($^{87}Sr/^{86}Sr$) also proved beneficial with respect to defining different groundwater groupings within the area of investigation.

4.3.1.1 Group 1: Peake Creek East

Groundwater east of the Peake and Denison Inlier is fresh to brackish. Proportional major ion hydrochemistry of Peake Creek East groundwater samples can be described as predominantly Na^{+}+Cl^{-}(+ HCO_3^{-}) dominant with the use of a Piper diagram (Figure 4-10). Jack (1923) and Habermehl (1980) descriptions of GAB groundwater are one that is predominantly sourced from east of the Peake and Denison Inlier.

Concentrations of cations K^{+}, Ca^{2+} and Mg^{2+} appear to be independent of Cl^{-}. (Figure 4-11A, Figure 4-11B and Figure 4-11C). Additionally, Ca^{2+}, Mg^{2+} and SO_4^{2-}exceed concentrations that would be expected from seawater aerosol input, whereas K^{+} is below. The independent relationship to seawater input suggests that variations in concentration are not related to evapotranspiration, but rather water-rock interactions (Figure 4-11A, Figure 4-11B, Figure 4-11C and Figure 4-11D).

Similarly, the ratio of Na^{+}: Cl^{-} concentrations within the Peake Creek East group are typically elevated when compared to the ratio found in seawater (Figure 4-12A). Comparison of the Br^{-}: Cl^{-} ratio suggests that some mineral dissolution may be contributing to elevated Na^{+}: Cl^{-} ratios; although the Br^{-}: Cl^{-} ratios for Peake Creek East samples are lower than what might be expected form seawater derived aerosols, they are not low enough to indicate dissolution of evaporites (Figure 4-12B). Therefore, although marine aerosols are interpreted to be the most significant contributor to groundwater salinity within the Peake Creek East group, mineral dissolution may still be significant enough to account for elevated Na^{+}: Cl^{-} ratios. Stable isotope concentrations of water also reflect this narrow range with all results bar one falling within a range of -6.93‰ to -5.74‰ for $\delta^{18}O$ and –48.84‰ and -43.7‰ for δD. This range of results suggests that evaporation is not a significant factor with respect to the majority of samples within this group. The one exception is a spring water result from North Freeling Spring, which appears enriched. This enrichment may be a function of evaporation within the spring pool prior to collection (Figure 4-13). The narrow range of ratios for δD and $\delta^{18}O$ for the Peake Creek East group is similar to GAB samples collected east of the Torrens Hinge Zone approximately 150 km to the south-south east. Here, Keppel et al. (2015) suggested that the old age of these groundwater has led to an attenuation of stable isotope ratios toward an average. The similar location of Peake Creek East sampling sites east of the Peake and Denison Inlier (which form part of the Torrens Hinge Zone) suggest that a similar conclusion can be reach for these samples

It is noted that one sample 604200012 (Cootabarcoola Spring) has a major ion concentration profile indicative of the Peake Creek East grouping despite apparently being located west of the Peake and Denison Inlier. This being said, the extent of where the Peake and Denison Inlier has completely penetrated the GAB J-K aquifer is limited to predominantly areas of crystalline basement outcrop. Additionally, sample site 604200012 is only 3 km from the inlier. Consequently there is scope for GAB groundwater from the north and east to flow through to the western side of the Peake and Denison Inlier where the aquifer is not completely penetrated, even if this is over only short distances, such as the distance of sample point 604200012 from the Peake and Denison Inlier.

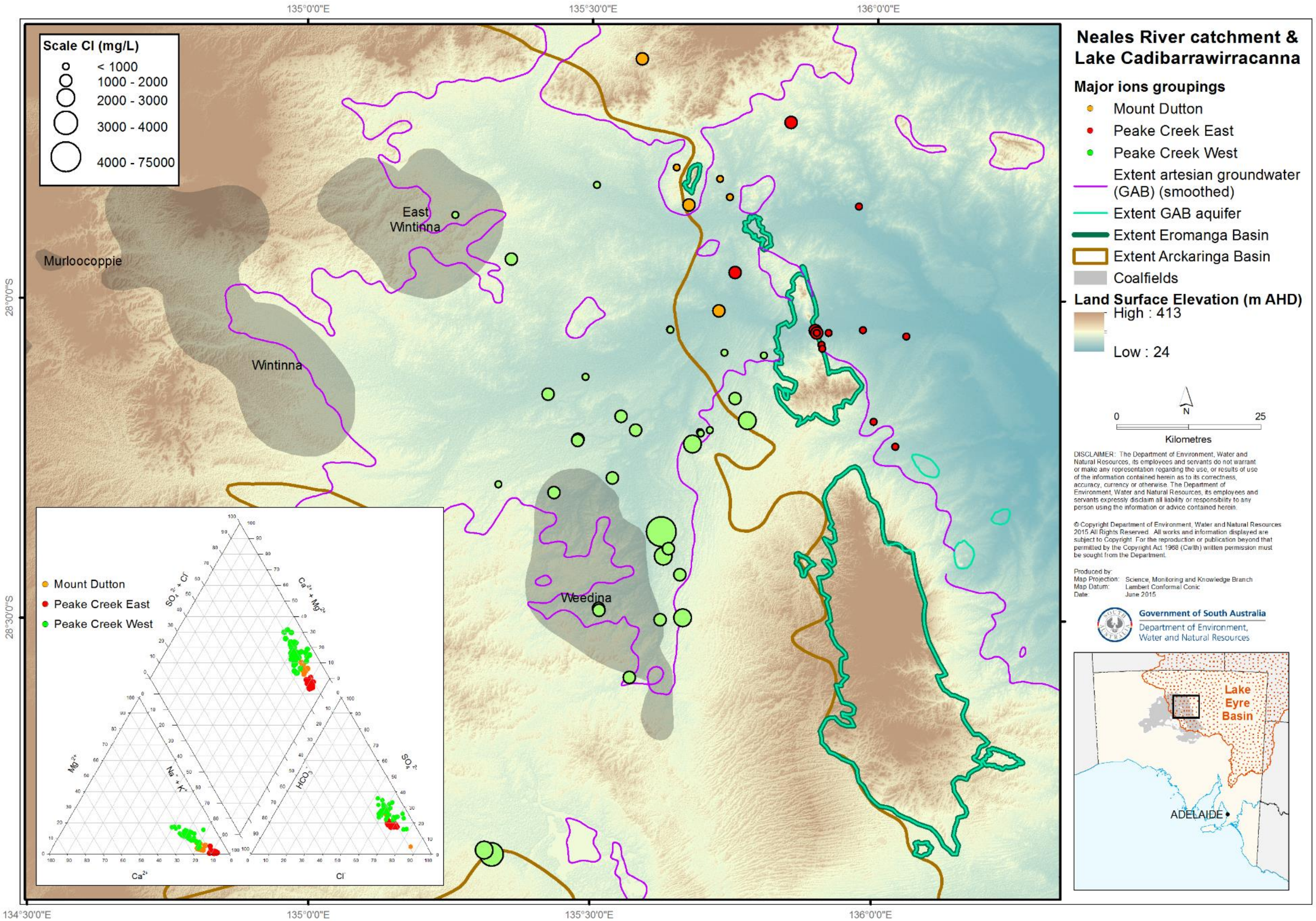


Figure 4-10: Hydrochemistry groupings, Cl^- results as a description of salinity, and a Piper diagram of major ion data

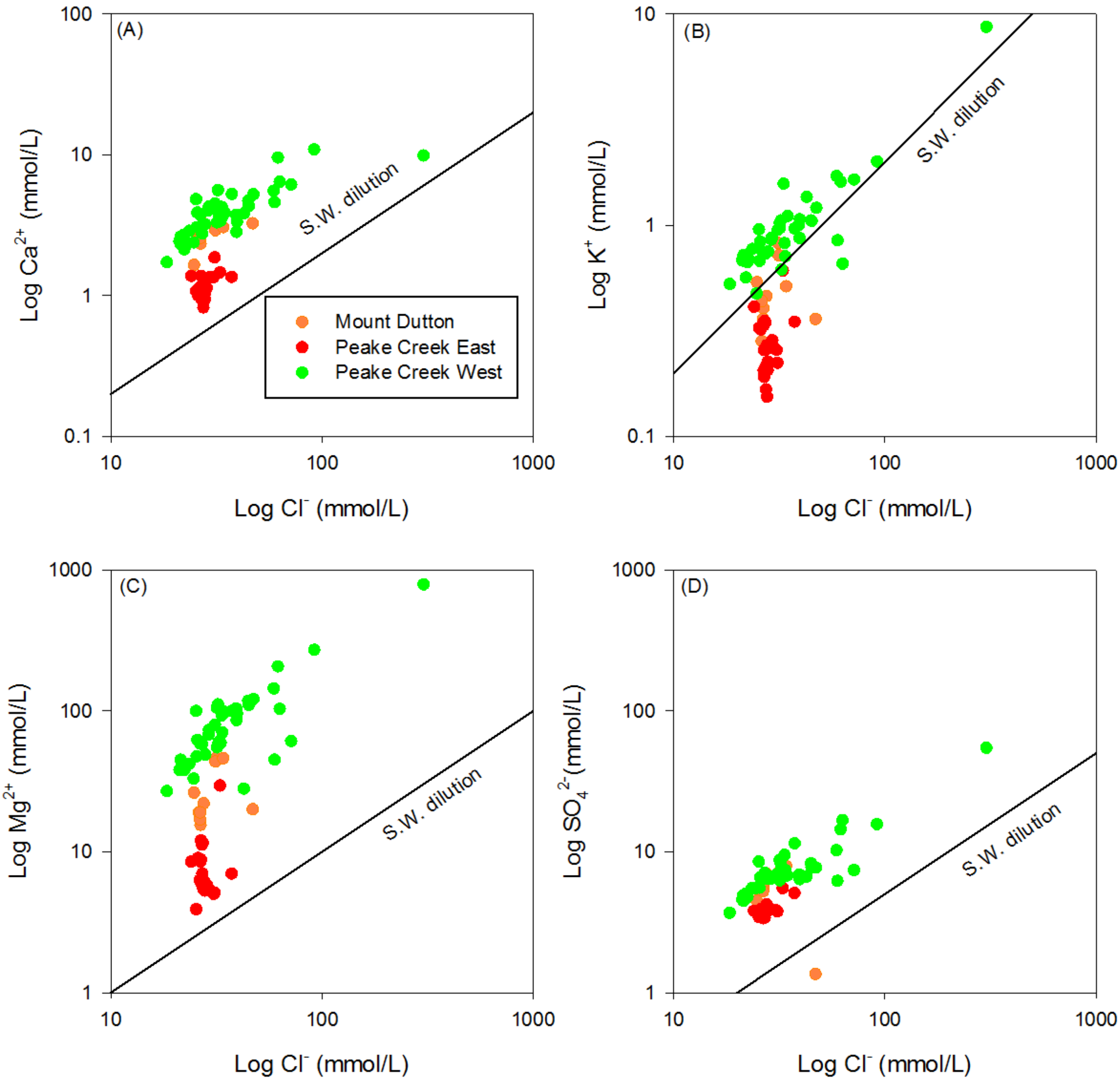


Figure 4-11: Scatter plots for Ca^{2+} versus Cl^- (A), K^+ versus Cl- (B), Mg^{2+} versus Cl^- (C) and SO_4^{2-} versus Cl^- (D). Lines represent the approximate seawater dilution line

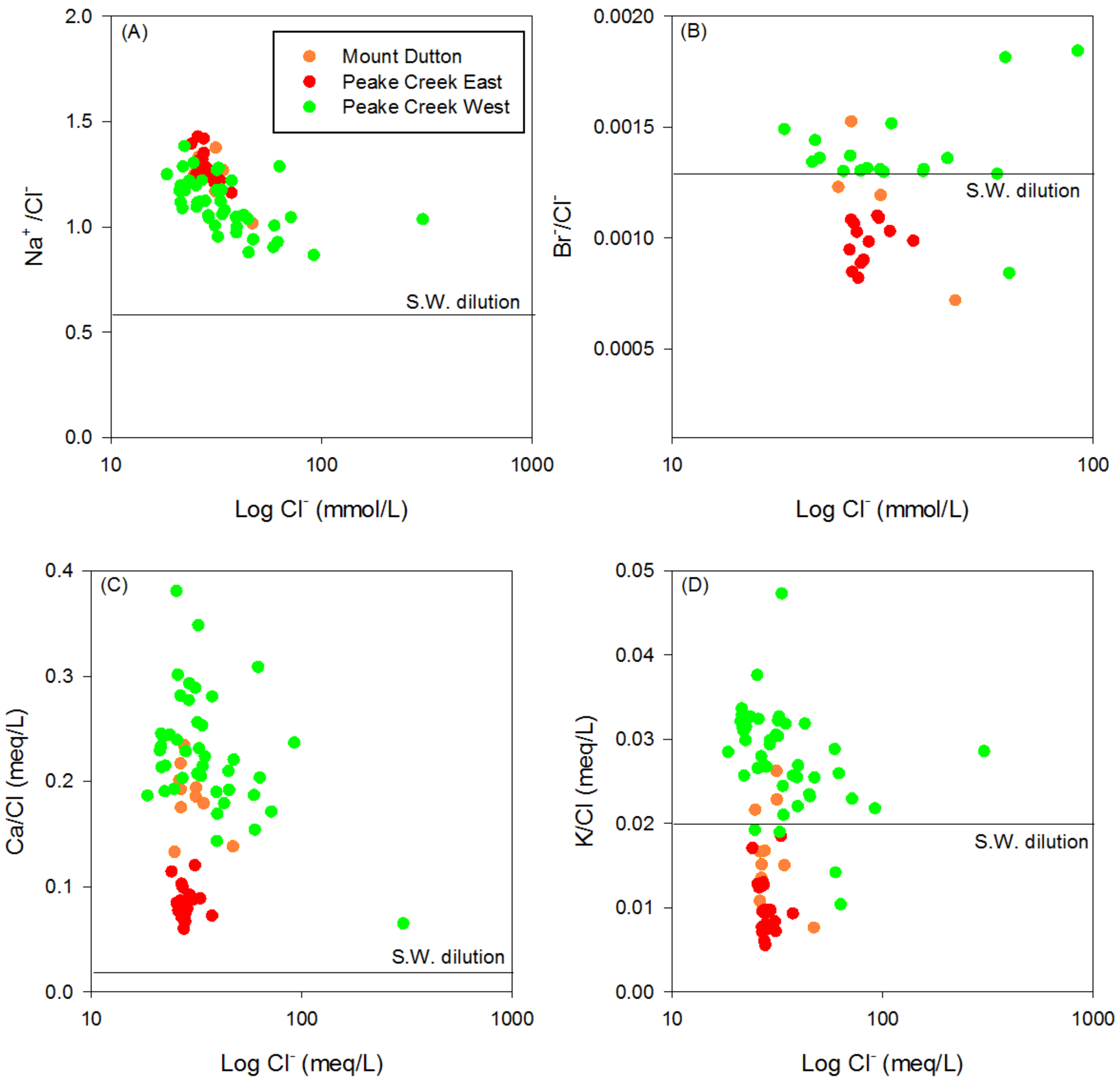


Figure 4-12: Scatter plots for Na^+/Cl^- versus Cl- (A), Br^-/Cl^- versus Cl- (B), Ca^{2+}/Cl^- versus Cl- (C) and K^+/Cl^- versus Cl- (D).

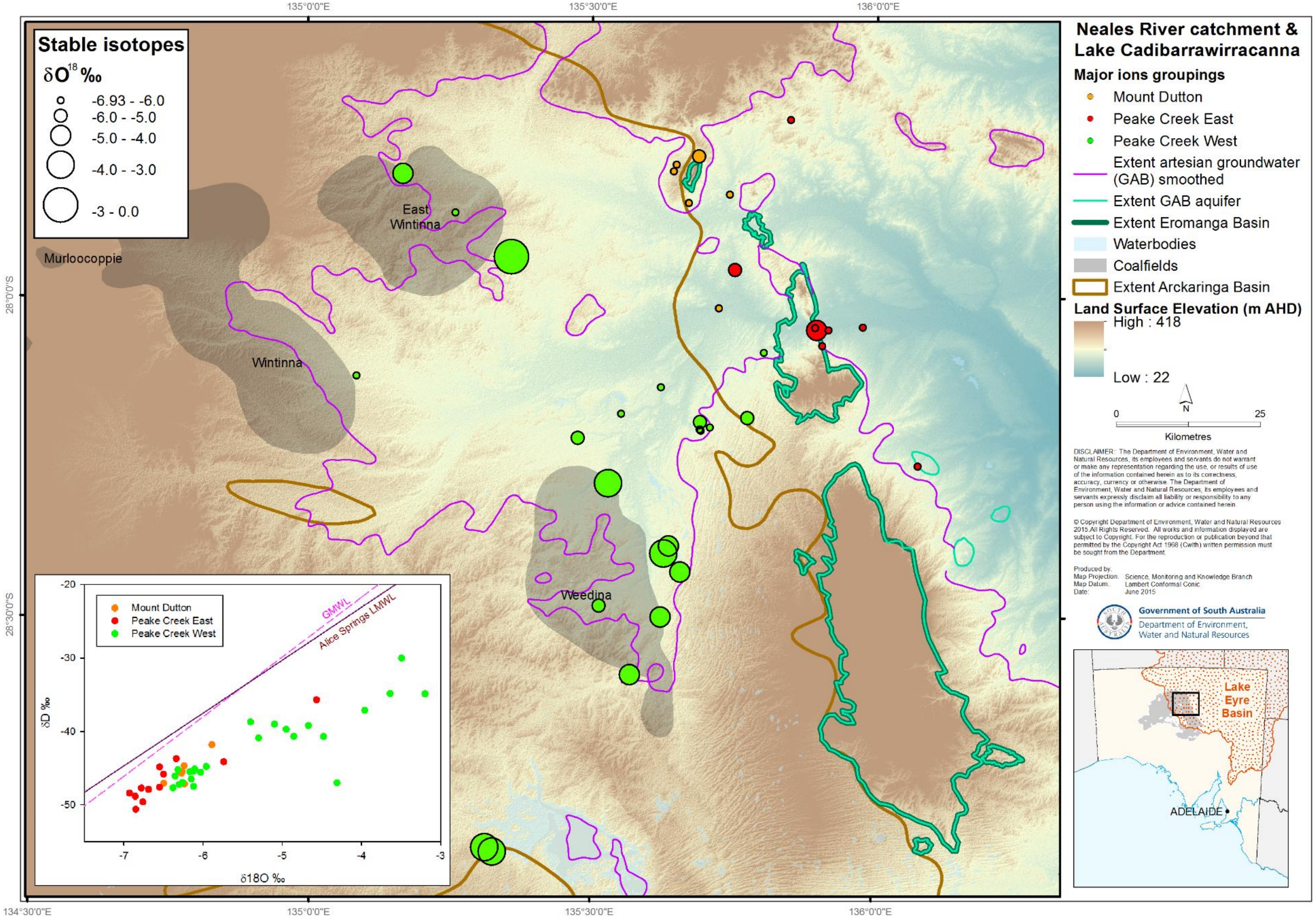


Figure 4-13: Stable isotope ratios of groundwater

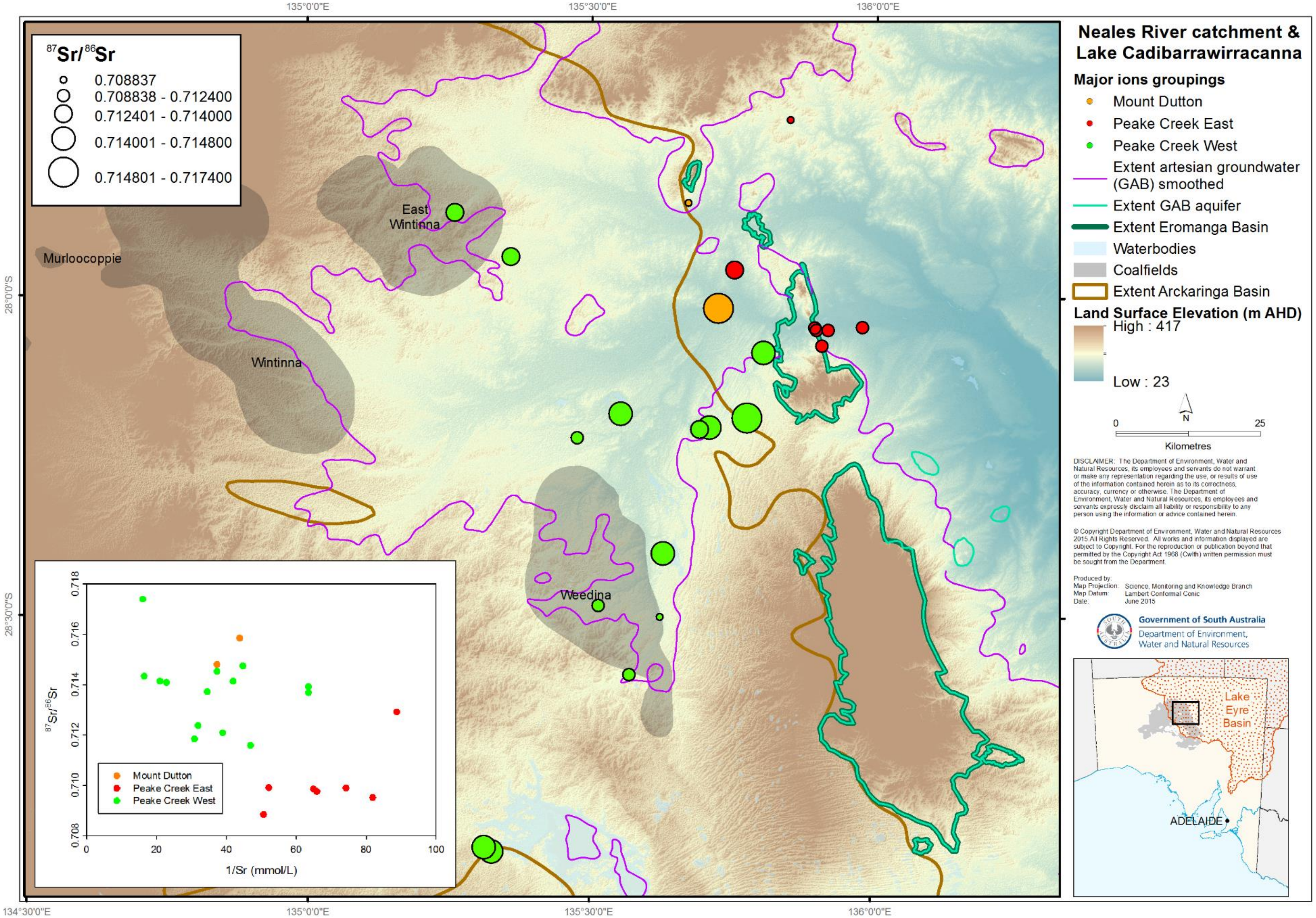


Figure 4-14: $^{87}Sr/^{86}Sr$ and $1/Sr^{2+}$ (mmol/L) results

Most $^{87}Sr/^{86}Sr$ results plot within a very narrow range of 0.7095011 (Century Bore) and 0.709905 ('new' North Freeling Spring) (Figure 4-14). The narrow range of results may be indicative of a common groundwater source for these samples and therefore these samples might be regarded as an end-member groundwater type. One result (Cootabarcoola Spring) plotted outside the range of other results within this group (0.71368‰) and is more indicative of the Peake Creek West or Mount Dutton hydrochemistry groups (see Sections 4.3.1.2 and 4.3.1.3). Consequently, this may be an argument to shift the classification of this spring, although as other hydrochemical analytes suggest the classification as Peake Creek East; further analysis is considered necessary to make such a change.

4.3.1.2 Group 2: Peake Creek West

West of the Peake and Denison Inlier, groundwater is brackish to salty, with salinity displaying a weakly defined increase from the north to the south within the investigation area (Figure 4-10). The much larger range in salinity within this grouping compared to Peake Creek East is also reflected in the concentrations of major ions (Figure 4-10). Concentrations of K^+ suggest primary input from seawater aerosols (Figure 4-11B), whereas Ca^{2+} and Mg^{2+} suggest a mix of aerosol and potentially other inputs such as mineral dissolution (Figure 4-11A and Figure 4-11C). However, the lack of any discernable correlation between the ratio of Ca^{2+}, K^+, Mg^{2+} and SO_4^{2-} to Cl^- to Cl^- (Figure 4-12C, Figure 4-12D, Figure 4-15A and Figure 4-15B), suggests water-rock interaction is providing the primary cause of salinity increase, rather than evapotranspiration (Harrington et al. 2015).

The ratio of Na^+: Cl^- concentrations within the Peake Creek West group are typically elevated when compared to the ratio found in seawater, although not as elevated on average as the Peake Creek East group (Figure 4-12A). Comparison of the Br^- : Cl^- ratio suggests that halite (NaCl) concentrations are largely derived from marine aerosols (Figure 4-12B). This is notably different to groundwater samples from the Peake Creek East group, where lower Br^- : Cl^- ratios indicate a notable, although still minor contribution to salinity of mineral dissolution.

It is also notable that K^+, Mg^{2+}, and to a lesser extent Ca^{2+}, make up a larger proportion of total salinity and sodium a lesser proportion within the salinity range that overlaps with the sample group collected east of the Peake and Denison Inlier; this feature is observable using both a Piper diagram (Figure 4-10) and a Schoeller plot (Figure 4-16). The Schoeller plot in particular highlights the major proportional change in Mg^{2+} to other major ions between the Peake Creek East and Peake Creek West groups.

Additionally, a clear curvilinear trend observed between Ca^{2+} and SO_4^{2-} concentrations in groundwater appear to be primarily controlled by the dissolution of gypsum (Figure 4-15C), an observation confirmed by a very similar trend observed when the saturation index for gypsum (SI_G) is compared to Cl^- (Figure 4-15D). The dissolution of gypsum would therefore appear to be an important groundwater evolutionary process within the Peake Creek West group. In contrast, the concentration of Ca^{2+} appears to be independent of alkalinity (Figure 4-17A) and there is no discernable trend with respect to the saturation of calcite and salinity, with the majority of samples displaying calcite oversaturation (Figure 4-17B). These last two relationships are not indicative of a system where carbonate hydrochemistry has a primary controlling role. The importance of gypsum in influencing groundwater hydrochemistry can be explained by the significant presence of sulphur-bearing minerals such as gypsum, anhydride and sulphides within the sediments of the region (Drexel and Preiss, 1995); particularly the Bulldog Shale and Stuart Range Formation aquitards (Keppel et al. 2015).

The stable isotope results from groundwater samples collected from the south western portion of the study area appear relatively enriched in heavy isotopes compared to most other samples to the north and east (Figure 4-13). This is in keeping with the aforementioned salinity and changes in major ion distributions observed. The enrichment of stable isotopes is suggestive of evaporative impacts on groundwater at the time of recharge within the south-west of the investigation area and may be indicative of local influences on hydrochemical evolution. Such influence may relate to the proximity of this region to potential groundwater recharge zones within the south western portion of the GAB. Groundwater collected in close proximity to the point of recharge will potentially retain more enrichment variation that is a function of seasonal differences compared to groundwater that has migrated far from the point of recharge, which is more inclined to attenuate toward an average value (Clark and Fritz, 1997). Exceptions to this were results from Toondina Spring (UTS001) and Nasa Bore. In the case of Toondina Spring (-26.0 ‰ δD, -1.19 ‰ $\delta^{18}O$), difficulties locating the spring vent at the time of sampling may have resulted in a spring pool sample that had undergone evaporation prior to sampling. The result from Nasa Bore is historical and therefore there is uncertainty regarding this result.

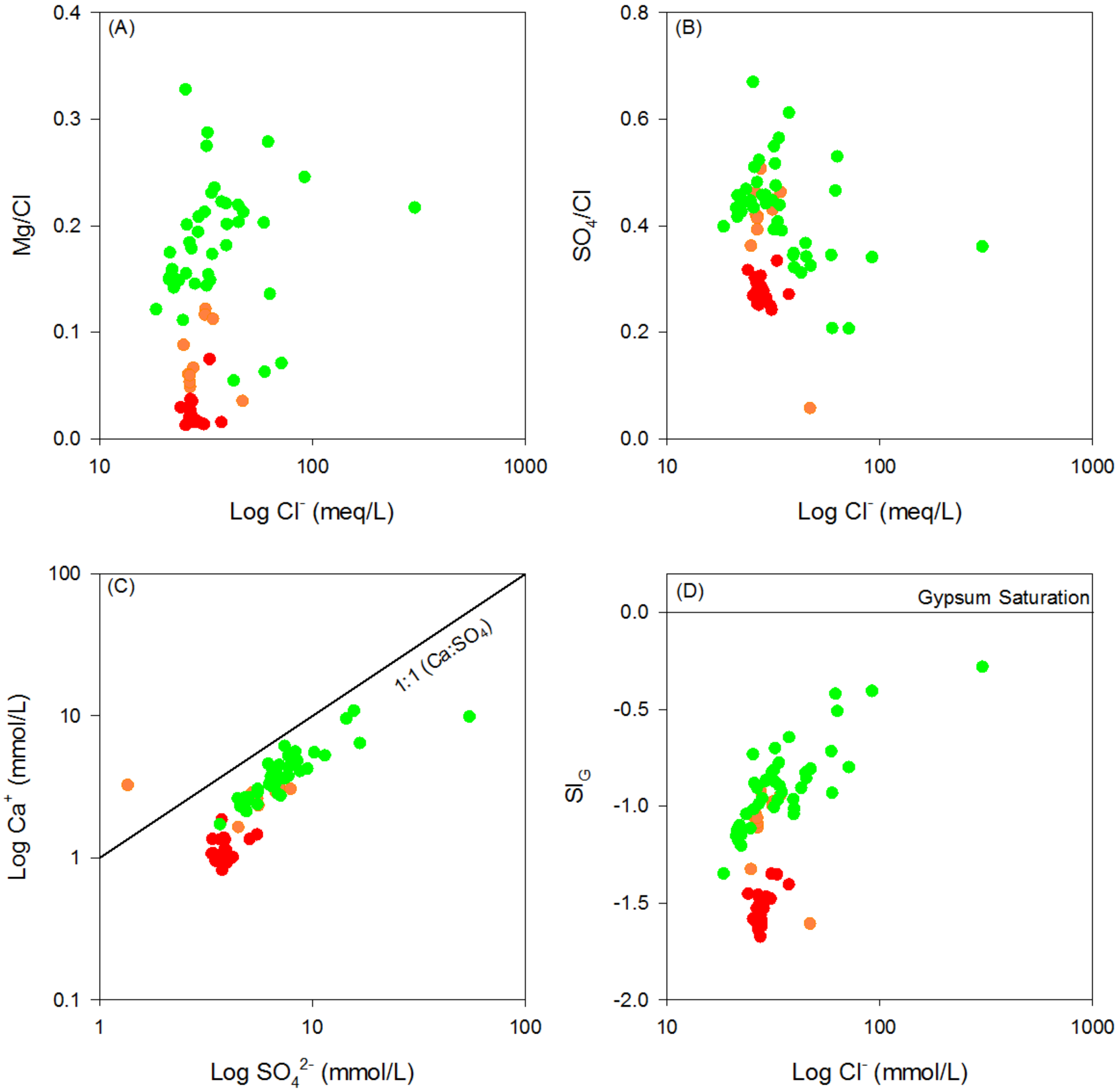


Figure 4-15: Scatter plots for Mg^{2+}/Cl^- versus Cl^- (A) and SO_4^{2-}/Cl^- versus Cl^-(B), Log Ca^{2+} versus Log SO_4^{2-} (C) and Saturation Index of gypsum (SI_G) versus Log Cl^-(D)

Results from $^{87}Sr/^{86}Sr$ analysis typically show higher ratios than samples from Peake Creek East group, as well as a greater variance, with results ranging from 0.71159 (Weedina Bore) to 0.717396 (Kelpie Bore) (Figure 4-14). The higher ratios found on average within the Peake Creek West dataset would appear to indicate a groundwater source different to that found within the Peake Creek East group, with the source of $^{87}Sr/^{86}Sr$ being more enriched for the former group. This implies that there is a discernable heterogeneity with respect to the rock material within the GAB aquifer within the study area with this distinction spatially demarcated by the Peake and Denison Inlier. That being said, the greater variance may also be related to the wider region from which samples were collected and thus more scope for localised water/ rock interaction, west of the Peake and Denison Inlier compared to the eastern side.

It is noted that the ratio of Sr^{2+}: Ca^{2+}increases west to east along the generally inferred flow path for GAB groundwater (Figure 4-17B). This may be indicative of incongruent precipitation of calcium carbonate in that the less stable and larger Sr^{2+} element in calcium carbonate minerals in the aquifer are incongruently replaced by Ca^{2+} elements over time, thus increasing the ratio of Sr^{2+} to Ca^{2+} as water migrates through the aquifer.

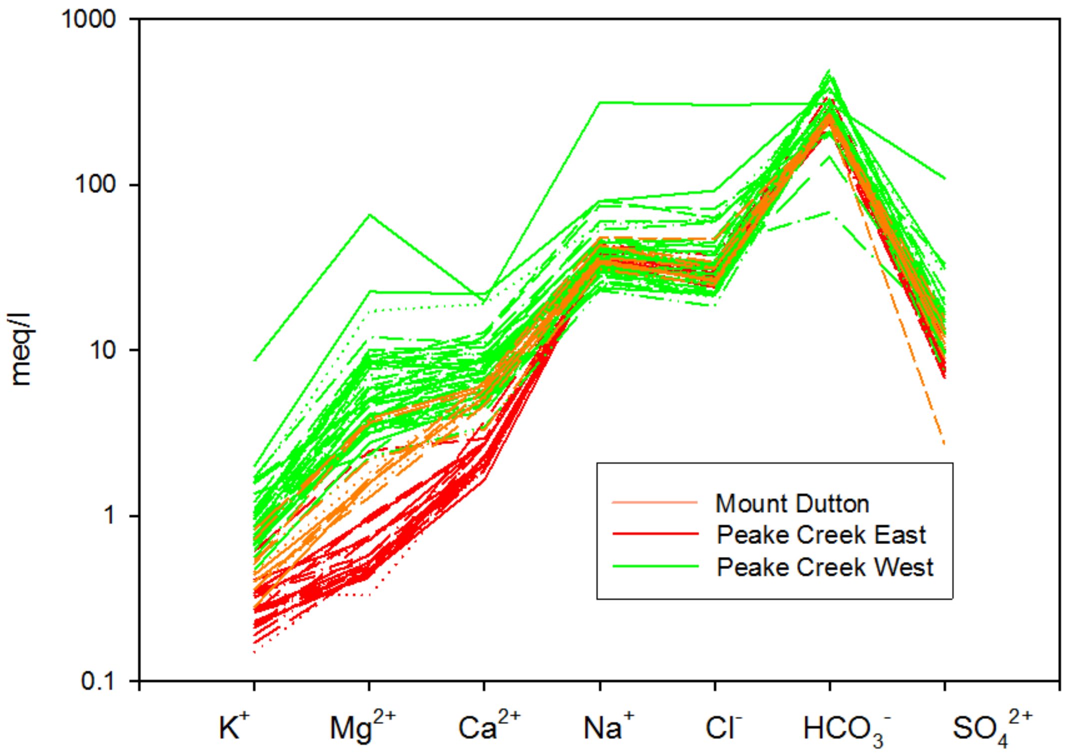


Figure 4-16: Schoeller plot of major ion hydrochemistry from samples from the investigation area

4.3.1.3 Group 3: Mount Dutton

There may be a zone of mixing to the north-west of the Peake and Denison Inlier, particularly in the vicinity of Mount Dutton, between the previous two groups described. Major ion concentrations from this groundwater group when displayed either in a Piper diagram (Figure 4-10) or when presented against Cl^- (Figure 4-11 and Figure 4-12) overlap the more clearly demarcated groundwater types from the Peake Creek East and Peake Creek West groupings. Similarly the ratio values in δD ‰ and $\delta^{18}O$ ‰ for the Mount Dutton group also appear to overlap both the preceding two groups, although the small variation in ratios is most similar to the characteristics of the Peake Creek East group. (Figure 4-13). In contrast, $^{87}Sr/^{86}Sr$ results and SO_4^{2-} concentrations from samples classified as Mount Dutton group are more in keeping with Peake Creek West than the Peake Creek East grouping (Figure 4-14 and Figure 4-15B). It is this difficulty in distinguishing definitive hydrochemical characteristics and the general observation that samples within the group tend to display characteristics that overlap with groundwater samples from the Peake Creek East and Peake Creek West groups that strongly suggests that this group represents a mix, rather than a distinct groundwater type. This mixing trend may describe groundwater migration with the GAB aquifer from the north, mixing with groundwater migrating from the west or south-west (Figure 4-10).

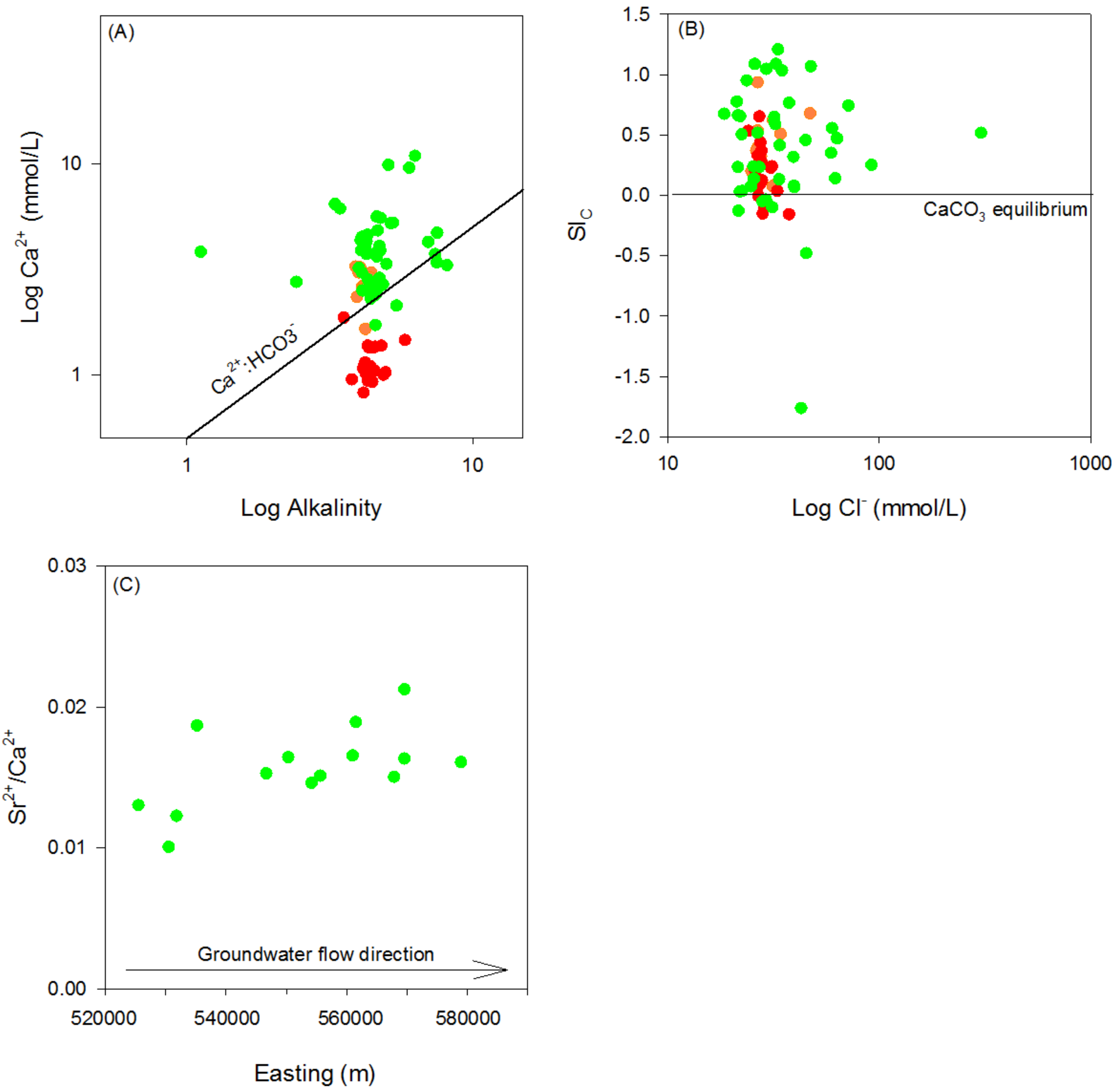


Figure 4-17: Scatter plots for Ca^{2+} versus Alkalinity (A), Saturation Index of calcite (SI_C) versus Cl- (B) and Sr^{2+}/Ca^{2+} versus distance for the Peake Creek West group of samples (D)

5 Discussion

5.1 Geophysics

TEM and SP data from the Cootanoorina and Old Nilpinna spring vent sites could be used to describe at least two of the structural models presented in Section 4.1. Variations in the resistivity model at depth at Cootanoorina spring vent PCN001 could be interpreted to describe the development of a minor fault that has breached a thin layer of Bulldog Shale that confines the underlying J-K aquifer. This scenario most resembles structural model 3, where thinning of the confining layer combined with minor fracturing and faulting (possibly related to underlying basin architecture) has caused spring development. Concepts developed from the Cootanoorina spring vent PCN001 TEM and SP data are also applicable to Conceptual models 1a and 1b, as the techniques are able to provide evidence of potential structures regardless of the degree of confining layer stripping.

In contrast, the significant lateral variation in TEM, more resistive surface, and no obvious spring vent interpretable using SP are possibly indicative of spring development on J-K aquifer outcrop at Old Nilpinna spring vent site POS007. This would most resemble processes consistent with Conceptual model 2, where the primary cause of spring development is removal of the confining layer. Spring development occurs because the depth to the J-K aquifer is small. Restriction of spring development is related to regolith processes and localized fracturing to form spring conduits. Weathering and secondary cementation ('hardpan' development) are interpreted to have removed much of the porosity within the outcropping portions of the aquifer. The effects of weathering, surface water infiltration and regolith development are, however, variable across the area, leading to variations in geophysical response. Minor fracturing of the upper weathered horizons may allow for spring vent development, as well as contributing to the heterogeneity observed in TEM data. However, such processes may be localized and not dependent on the existence of large regional-scale deformation; notably, evidence for a link to larger structures in such examples is either absent or difficult to deduce.

It should be noted that further work is required to clarify linking variations in regolith permeability and porosity to geophysical response.

5.2 Hydrochemistry

5.2.1 General characteristics of groundwater hydrochemistry

Groundwater emanating from springs sampled within the Toondina, Peake Creek West and Lake Cadibarrawirracanna spring complexes is interpreted to be sourced from aquifers west of the Peake and Denison Inlier, and the Peake Creek East spring complex is supplied with groundwater from aquifers located to the east of the Peake and Denison Inlier. The Mount Dutton spring complex is interpreted to be supplied from both area. Consequently three hydrochemistry groupings were developed to describe potential source groundwater to springs and wells within the study area, namely the Peake Creek West, Peake Creek East and Mount Dutton hydrochemistry groupings.

It is recognised that some of the variations described between the Peake Creek East and Peake Creek West hydrochemistry groupings may be a function of the differing sample numbers and spatial extents of the two groups. However, consideration of sampling locations with respect to basin architecture, the prevalence or otherwise of confining layers and relationship to flow paths for each group, as well as comparison of the analyte concentrations of samples from each group, all demonstrate that the differences observed are related to the hydrogeological setting rather than sampling anomalies. Additionally, the broad spatial distribution of samples within each group and the hydrochemical characteristic observed correlate with previous findings by Jack (1923), Habermehl (1980) and Priestley et al (2013).

5.2.2 Comparison between springs and nearby wells

Four areas were identified where well and spring samples have been collected in close proximity (< 10 km radius). These groups are in the vicinity of the Cootanoorina, Old Nilpinna, Warrangaranna and Freeling spring groups (Figure 2-1). In general, where wells and springs occur in close proximity, there is not a significant difference between groundwater samples from springs and wells completed within the J-K aquifer in either the absolute or proportional concentration of hydrochemical analytes examined during this study (Figure 5-1). In some instances, the variance is comparable to what may be expected from results of samples collected from the same well over time.

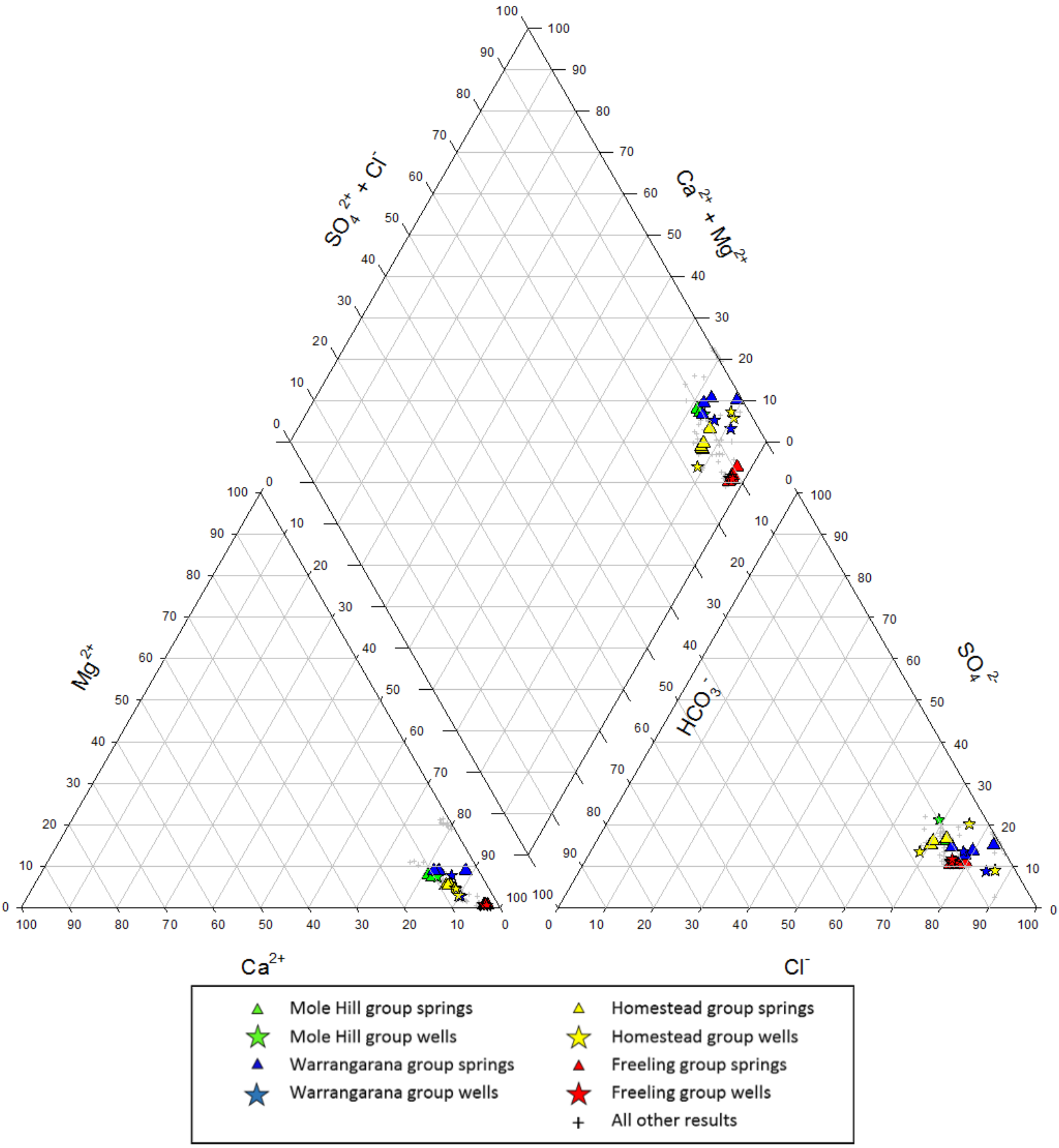


Figure 5-1: Major ion data presented as a Piper diagram, with springs and bores grouped where sample sites are located <10 km apart

Within the Old Nilpinna spring group and to a lesser extent the Cootanoorina spring group, nearby wells do appear to have elevated salinity, with an apparent trend toward further Na^+/Cl^- dominance over other major ions compared to spring samples (Figure 5-1). This distribution of salinity between wells and springs in reasonably close proximity would imply that evapotranspiration within the spring environment is not the cause of discrepancy, rather there is a subsurface cause, such as a secondary source of water that is either slightly diluting spring water or slightly elevating the salinity found in wells. Further work in the form of non-GAB aquifer characterization or groundwater dating may aid understanding.

In general, these observations demonstrate a close link between the GAB and the supply of groundwater to springs, as any difference could be used to imply a secondary source. What remains unclear is the relationship between other aquifers in the investigation area and the GAB, and most notably amongst these relations is between the GAB J-K aquifer and the underlying Mount Toondina Formation within the Arckaringa Basin. Substantial connectivity between other aquifers and the GAB may lead to a homogenisation of groundwater hydrochemistry, whereas any substantive differences in hydrochemistry may be used as evidence of disconnectivity. A significant impediment to determining the level of connectivity between the GAB J-K aquifer and those within this portion the Arckaringa Basin within the area of investigation is that there are no wells of adequate construction within the Arckaringa Basin. Consequently there is no appropriate hydrochemistry end member data to which spring hydrochemistry may be compared. Without hydrochemical data from these other aquifers, it is difficult to determine the potential impacts to any springs as a consequence of their development.

5.2.3 Evidence for modern groundwater within springs

With respect to potential secondary sources of groundwater to springs, historical radiocarbon data could indicate that some springs located near the Peake and Denison Inlier may have at least a small contribution of modern groundwater. It is notable that four springs within the general vicinity of the area of investigation (Edith Springs, Tarlton Springs, Big Cadna-owie Springs and Warrangarana Spring) contained percent modern carbon (pmC) in excess of 10%, whereas none of the bores sampled within the same area have a radiocarbon value of >10% (Figure 5-2).

Two of the spring samples (Big Cadna-owie Springs and Warrangarana Spring) are within the specific area of focus of this study. The hydrodynamics that potentially give rise to modern groundwater found in spring discharge nor the significance of this are known. In contrast, for the other two springs (Edith Springs and Tarlton Springs) modern groundwater can be interpreted as evidence of groundwater supply emanating from fractured rock aquifers associated with outcropping crystalline basement (Late Phanerozoic and older) rocks associated with the Peake and Denison Inlier (Wohling et al., 2013a). Based on this evidence for modern groundwater contribution to spring discharge, there is an argument for further radiocarbon-based investigations to determine the magnitude of input and hydrogeological circumstances that allow this to occur. Such indications of modern groundwater suggest either some local connectivity between the supplying aquifer and surface water or multiple sources of groundwater to particular springs.

5.2.4 Evidence for localised variations

Despite the relatively small distance (~7 km) between the two springs, Cootabarcoola and Keckwick spring groups appear to cluster differently with respect to their major ion chemistries (Figure 4-9). Whereas Cootabarcoola Spring can be classified as part of the Peake Creek East group, Keckwick Spring hydrochemistry is better categorized as the Mount Dutton mixed groundwater group. Both localities are relatively close to the Peake and Denison inlier, are not underlain by any Permian sediments and do not appear associated with any obvious basin architecture of faulting structures using the available regional geophysics. Consequently any structure associated with Keckwick and Cootabarcoola spring groups is likely to be minor and therefore the source groundwater input to these springs may be restricted, with respect to the depth of the source aquifer. This point combined with a setting close to the confluence between GAB groundwaters migrating from both the east and west (Figure 2-5) may explain the hydrochemical differences observed.

It is noted that $^{87}Sr/^{86}Sr$ results for Cootabarcoola Spring resemble those from the Peake Creek West or Mount Dutton hydrochemistry groupings, so it is conceivable that a reclassification of this particular spring may be necessary upon further analysis.

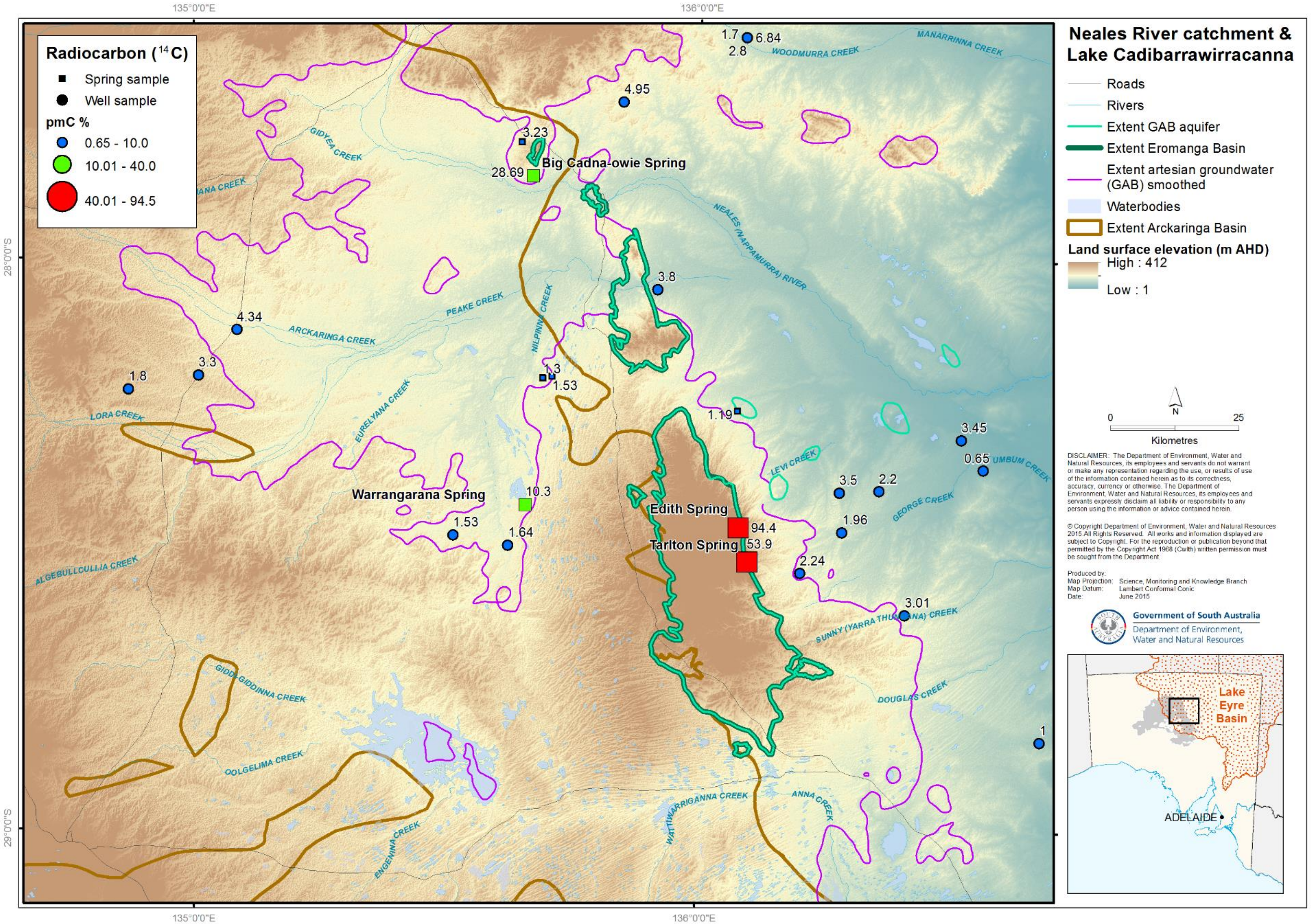


Figure 5-2: Historical radiocarbon values for springs and wells within the general vicinity of the area of investigation

6 Overview

6.1 Determination of hydrogeology-based risks to springs

Risks to spring wetland environments from developments impacting groundwater in the general vicinity are influenced by the following factors:

1. pressure head supporting the spring;
2. source of groundwater, whether this is from multiple sources or a single source;
3. nature of groundwater flow supporting the spring; and
4. geological controls of spring formation and how this influences conduit morphology.

All these factors may contribute variably between different spring groups altering the risk profile individually. For instance, a large pressure head may be reportable in the vicinity of a particular spring complex, however conduit formation reliant on secondary fracture sets though a thick confining layer may ultimately lead to small groundwater flows at the spring. Conversely, a lower pressure head may support comparatively larger flows if the confining layer is thin and structures are well developed. It is generally recognised that in complexes where a large number of flowing springs may be found, there is a notable variability between spring flows, which may be a consequence of regolith development.

In some cases, key hydrogeological information is not known. For instance the nature of connectivity between the GAB and underlying aquifers, and what this means with respect to groundwater supply to springs, is still largely unknown. Likewise, little is known regarding shallow aquifers in the Cenozoic in the vicinity of many spring groups, which may be important to springs located in areas where there is a significant accumulation of such sediments. An example of where such a multiple-aquifer supply scenario is purported to exist is the Peake Creek East spring complex where Dailey (2011) used electrical resistivity imaging (ERI) and hydrochemistry data to demonstrate that groundwater emanating from springs was a mixture of GAB and groundwater emanating from fractured crystalline basement. Additionally, Wohling et al. (2013b), Kleinig et al (2015) and Keppel et al. (2015) provided lithological and hydrochemical evidence for possible hydrogeological connectivity between the GAB and aquifer units in the underlying Arckaringa Basin. However in the absence of direct hydrochemical or hydraulic evidence, one cannot imply from these studies that multiple sources of groundwater to springs west of the Peake and Denison Inlier occurs, only that the possibility requires consideration.

6.2 Summaries for springs

A number of tables and figures are provided below which summarise the structure, hydrogeological and hydrochemical characteristics of a number of spring groups located within the Neales River catchment and Lake Cadibarrawirracanna regions. Table 6-1 below defines terminologies used within the summaries for structural and hydrochemical characterisations.

Table 6-1: Terminology definitions used in summaries

Model Type	Terminology	Explanation
Structure	Model 1a	Basin margin, fracture structures
Structure	Model 1b	Basin margin, regional fault-related structure
Structure	Model 2	Basin margin, sediment thinning and outcropping aquifer unit
Structure	Model 3	Basin margin, sediment thinning and structure combination
Structure	Model 4	Astrobleme
Hydrochemistry	Group 1	Peake Creek East
Hydrochemistry	Group 2	Peake Creek West
Hydrochemistry	Group 3	Mount Dutton

Group name	Spring Complex	No. of springs	Structural model	Hydrochemical characterisation	Geology/Regolith	Est. SWL (mbgs) & flow (l/s)	Notes
Oolgelima (XOS)	Lake Cadibar-rawirracanna	2	Primary: Model 3	Group 2	Highly to moderately weathered Bulldog Shale bedrock. Spring deposits, Quaternary lacustrine, alluvial and aeolian sediments nearby. Erosional environment.	-0.8, no flow estimated	Oolgelima Springs group is located near the southern margin of Lake Cadibarrawirracanna. Although the springs are mapped to occur on weathered Bulldog Shale outcrop, Quaternary lacustrine, alluvial and aeolian sediments. All occur in the near vicinity. Additionally the confining layer is interpreted to be very thin. The depth to the J-K aquifer at this location is approximately 2 mbgs. XOS-001 is associated with a mound structure composed of spring-related calcareous precipitate. The springs' position on the southern margin of a basement trough suggests that fractures that have developed near the margins of this trough are a primary cause of conduit formation at this particular location. Thinning of the confining layer, possibly associated with the development of Lake Cadibarrawirracanna has also contributed to spring development in the vicinity of underlying structure. Regional groundwater flow and hydrochemistry suggests a source from the west or south-west of the springs. Groundwater is currently thought to be primarily sourced from the GAB, although there is little in the way of hydrochemical characterisation of local Arckaringa Basin groundwater to ascertain a relationship

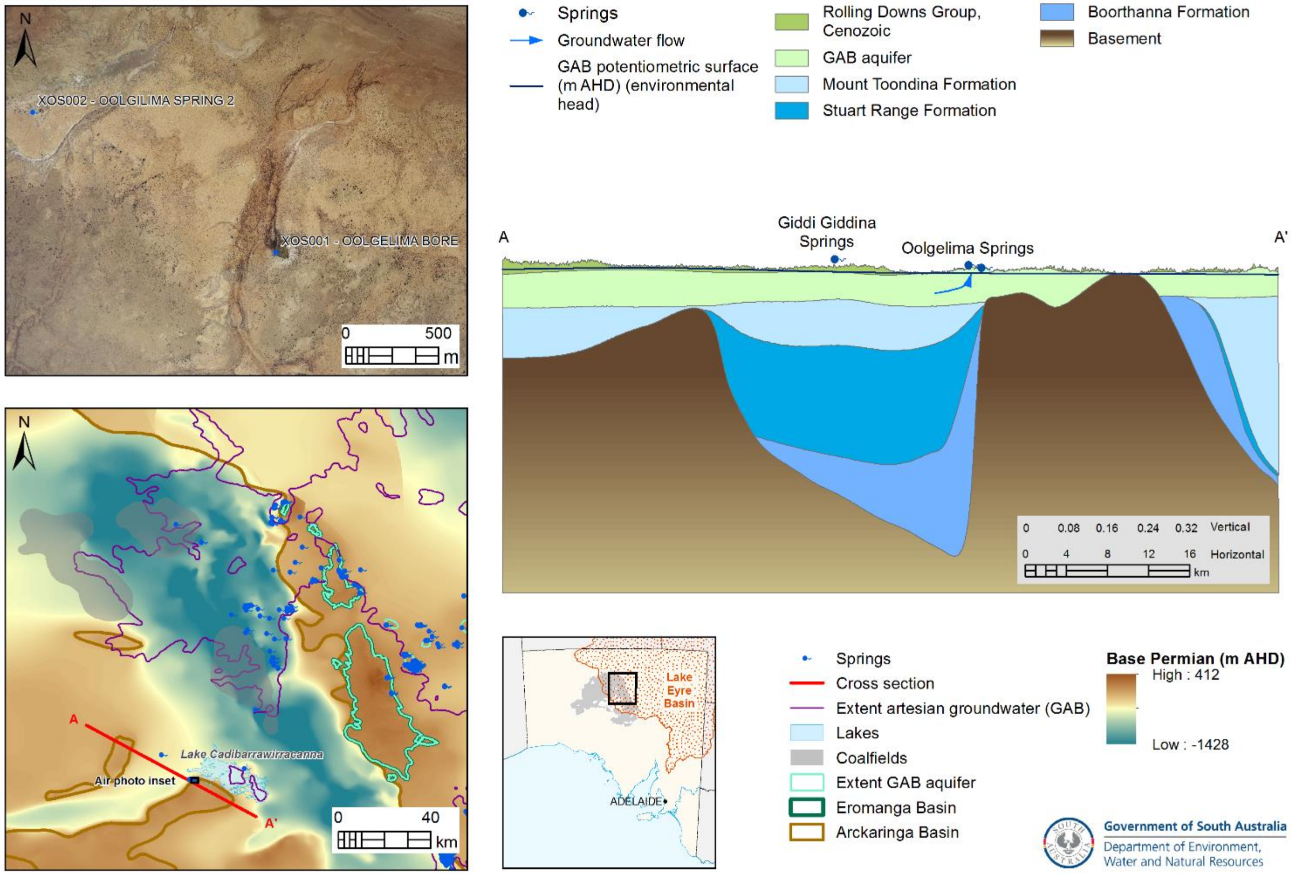


Figure 6-1: Oolgelima Spring Group summary

Group name	Spring Complex	No. of springs	Structural model	Hydrochemical characterisation	Geology/Regolith	Est. SWL (mbgs) & flow (l/s)	Notes
Cootanoorina (PCN)	Peake Creek West	7	Primary: Model 3	Group 2	Highly to moderately weathered Bulldog Shale bedrock. Spring deposits. Quaternary, lacustrine, alluvial and aeolian sediments nearby. Erosional environment.	-8.5, flow of 1.5 l/s estimated at PCN-001	Cootanoorina Springs group is located to the west of the Peake and Denison Inlier, approximately 30 km from basement outcrop. The springs are interpreted to occur on weathered Bulldog Shale covered by a thin layer of Quaternary aeolian and alluvial sediments. Lacustrine sediments occur to the north. The depth to the J-K aquifer at this location is interpreted to be between 6 and 20 mbgs. PCN-001 is associated with a mound structure composed of spring-related calcareous precipitate. A notable inflection in Mesozoic sediments has resulted in erosion-caused thinning of the confining layer (Bulldog Shale) at this point, contributing to spring formation. Additionally, a minor fault corresponding to the spring location was interpretable using TEM and SP data. The inflection may be caused by a regional structure; it is noted that a subsurface high in basement is located directly beneath this spring location, however the depth to this basement high and the lack of conclusive evidence for deformation within the overlying Permian sedimentary rock limits the applicability of this model. Regional groundwater flow and hydrochemistry suggests a source from the west or northwest of the springs. Groundwater is currently thought to be primarily sourced from the GAB, although there is little in the way of hydrochemical characterisation of local Arckaringa Basin groundwater to ascertain a relationship

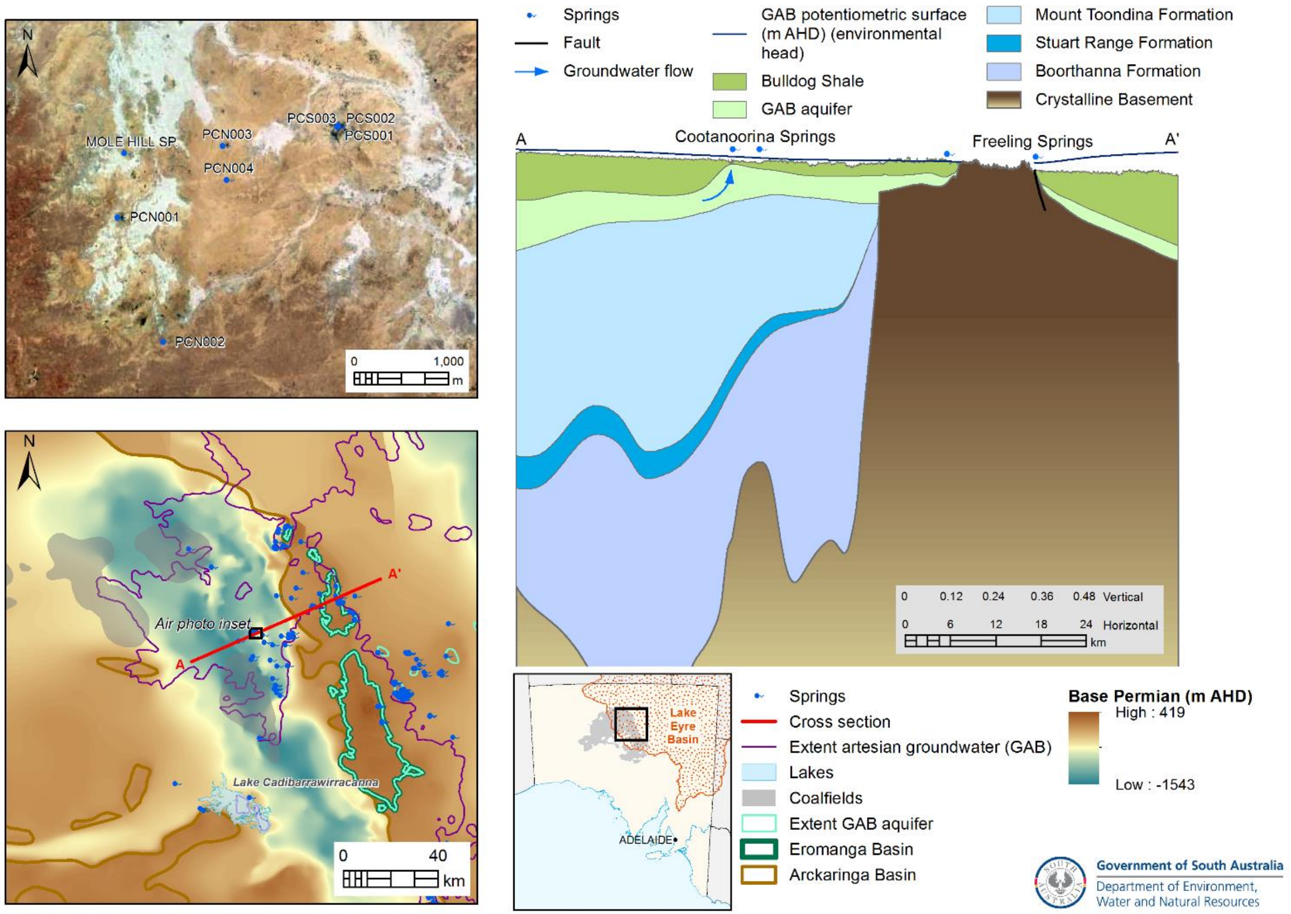


Figure 6-2: Coolanoorina Spring Group summary

Group name	Spring Complex	No. of springs	Structural model	Hydrochemical characterisation	Geology/Regolith	Est. SWL (mbgs) & flow (l/s)	Notes
Mount Toondina (UTS)	Mount Toondina	8 (including seeps. Only major vent shown)	Primary Model 4	Group 2	High to moderately weathered Eromanga and Arckaringa basins bedrock. Spring deposits. Erosional environment.	-12, no flow estimated	Mount Toondina Springs group is located to the west of the Peake and Denison Inlier, approximately 40 km from basement outcrop. Outcrop geology at Mount Toondina is complex, consisting of Mount Toondina Formation, J-K aquifer, Bulldog Shale and Quaternary sediments. Mount Toondina has most recently been interpreted to be the remnants of an astrobleme (Shoemaker and Shoemaker 1988; Plescia et al., 1994; University of New Brunswick, 2009). It is one of the few localities where Arckaringa Basin sediments, most notably the Mount Toondina Formation, are known to outcrop. Regional groundwater flow and hydrochemistry suggests a source from the west or north-west of the springs. Groundwater is currently thought to be primarily sourced from the GAB. Modelling by Dressler (2010) suggests that Mount Toondina Formation sediments at the centre of the structure are less porous and permeable than the GAB aquifer rocks at this location. Added to this Dressler (2010) hypothesised that groundwater flow within the Mount Toondina spring complex is controlled by advective flow from the subsurface to the ring of vegetation around the springs, but also that the central portion of the impact crater is influenced by free convective processes. Groundwater is currently thought to be primarily sourced from the GAB, although there is little in the way of hydrochemical characterisation of local Arckaringa Basin groundwater to ascertain a relationship

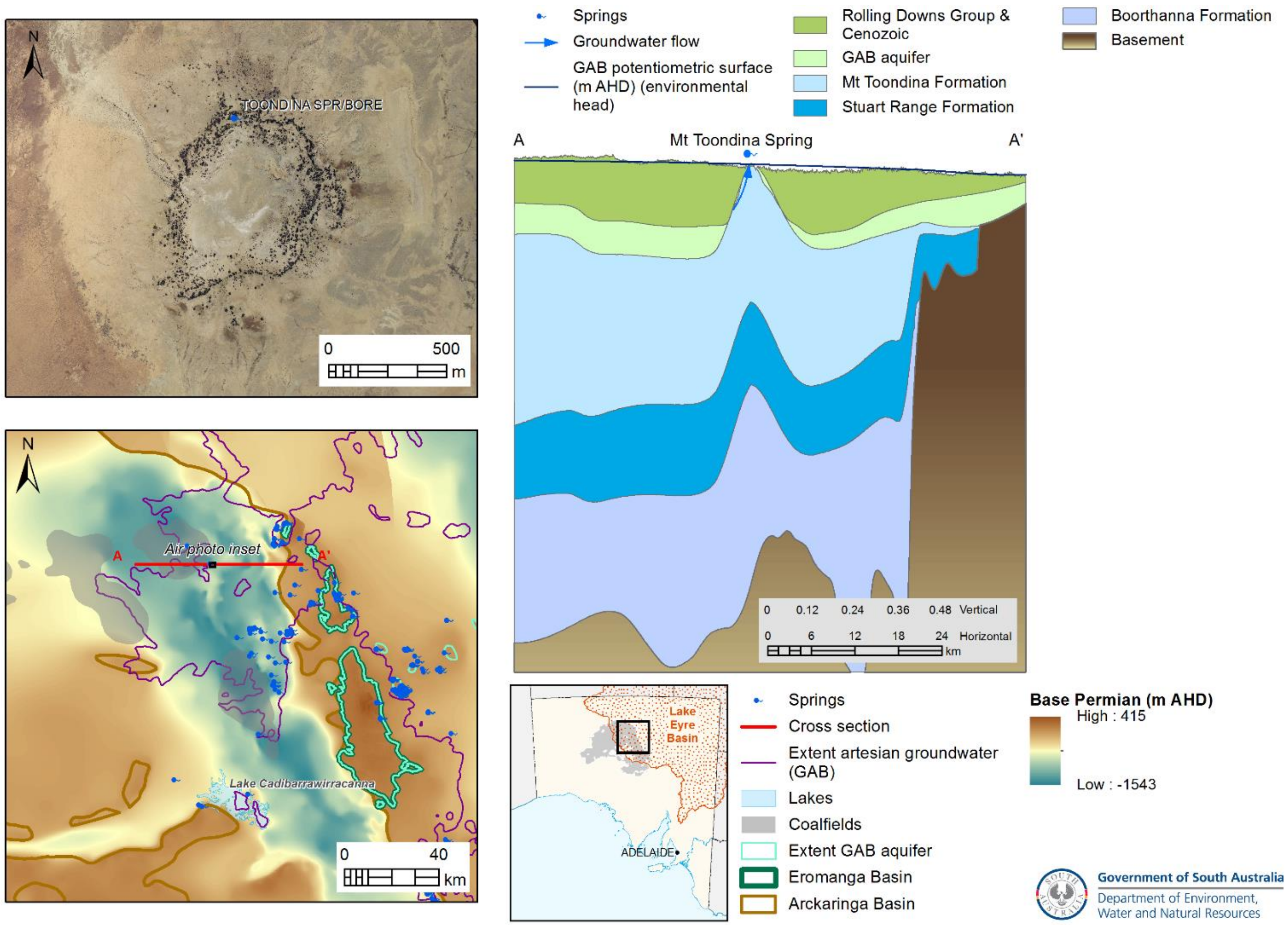


Figure 6-3: Toondina Spring Group summary

Group name	Spring Complex	No. of springs	Structural model	Hydrochemical characterisation	Geology/Regolith	Est. SWL (mbgs) & flow (l/s)	Notes
Birribirriana (PBI)	Peake Creek West	2	Primary: Model 2	Group 2	Highly to moderately weathered Bulldog Shale and J-K aquifer bedrock. Spring deposits Quaternary alluvial and aeolian sediments nearby. Erosional/ depositional environment.	-6.1, flow of 0.28 l/s est. at PBI-001	Birribirriana Springs group is located to the west of the Peake and Denison Inlier, approximately 11 km from basement outcrop. Outcropping J-K aquifer is noted in close vicinity to the springs, which appear to have been exposed via stream erosion. Bulldog Shale outcrop also occurs nearby. Recent sediments are predominantly aeolian. Depth to the J-K aquifer is interpreted to be between 0 and 1 mbgs. PBI-001 is associated with a mound structure composed of spring-related calcareous precipitate. Interpretation of structural surfaces in this region suggest that GAB aquifer sediments have been deposited over a basement high, evidenced by a relatively steep depositional repose of sediments at a regional scale. The close proximity of J-K aquifer outcrop to these springs indicates that confining layers have been extensively removed. Consequently, sediment thinning is thought to be the main cause of spring formation, although secondary cementation and fracture development in exposed J-K Aquifer outcrop in combination with the regional structural setting suggests that basin margin-related fracture development may play a role as well. Regional groundwater flow and hydrochemistry suggests a source from the west or north-west of the springs. Groundwater is currently thought to be primarily sourced from the GAB, although there is little in the way of hydrochemical characterisation of local Arckaringa Basin groundwater to ascertain a relationship

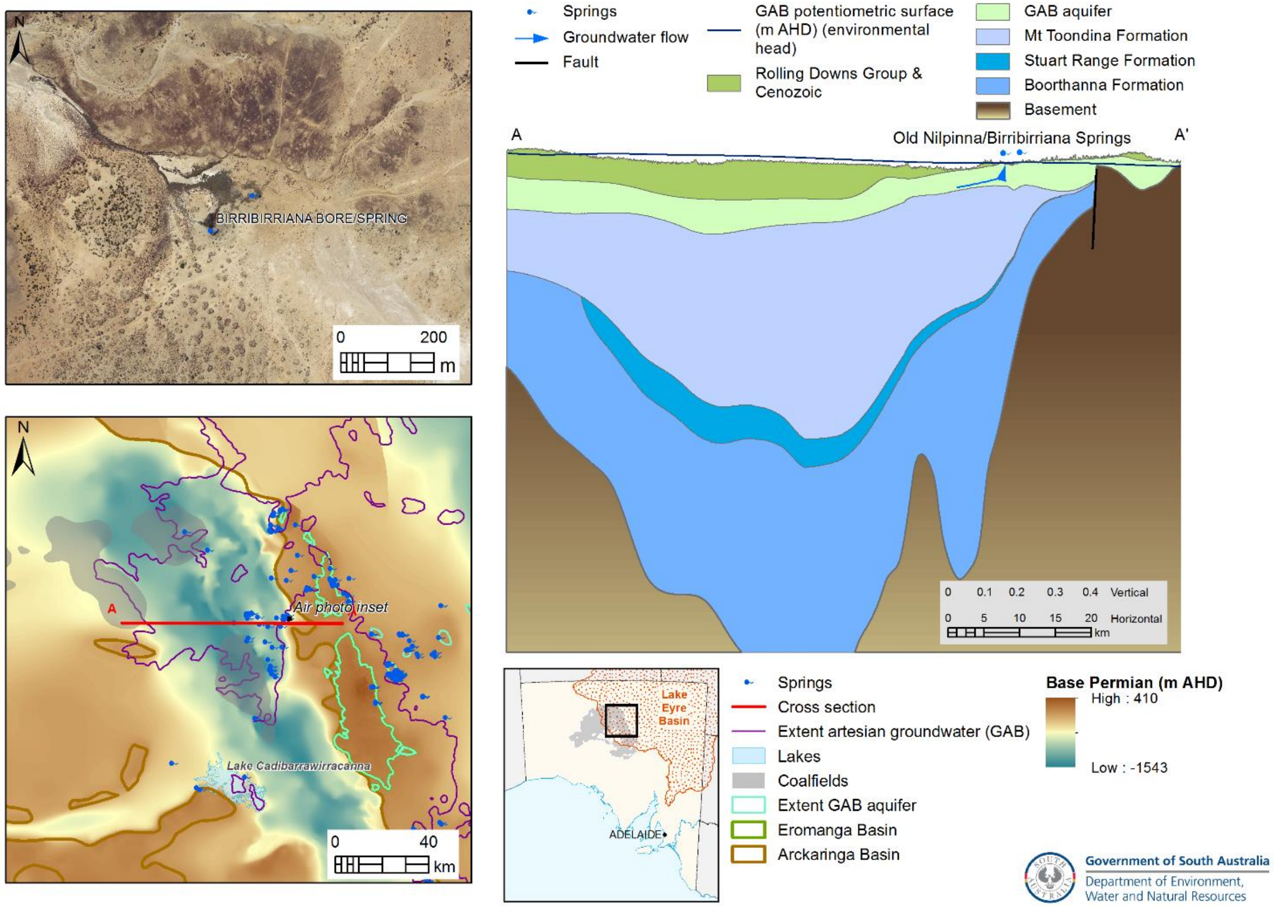


Figure 6-4: Birribirriana Spring Group summary

Group name	Spring Complex	No. of springs	Structural model	Hydrochemical characterisation	Geology/Regolith	Est. SWL (mbgs) & flow (l/s)	Notes
Old Nilpinna (POS)	Peake Creek West	10	Primary: Model 2	Group 2	Highly to moderately weathered Bulldog Shale and J-K aquifer bedrock. Spring deposits Quaternary alluvial and aeolian sediments nearby. Erosional/ depositional environment.	-8.8 - 12.6, flow of 2.5 l/s at POS-003	Old Nilpinna Springs group is located to the west of the Peake and Denison Inlier, approximately 13 km from basement outcrop. Outcropping J-K aquifer is noted in close vicinity to the springs, which appear to have been exposed via stream erosion. Bulldog Shale outcrop also occurs nearby. Recent sediments are predominantly aeolian. Depth to the J-K Aquifer is interpreted to be between 0 and 1 mbgs. Interpretation of structural surfaces in this region suggest that GAB aquifer sediments have been deposited over a basement high, evidenced by a relatively steep depositional repose of sediments at a regional scale. The close proximity of J-K aquifer outcrop to these springs indicates that confining layers have been extensively removed. Consequently, sediment thinning is thought to be the main cause of spring formation, although secondary cementation and fracture development in exposed J-K aquifer outcrop in combination with the regional structural setting suggests that basin margin-related fracture development may play a role as well. Regional groundwater flow and hydrochemistry suggests a source from the west or north-west of the springs. Groundwater is currently thought to be primarily sourced from the GAB, although there is little in the way of hydrochemical characterisation of local Arckaringa Basin groundwater to ascertain a relationship

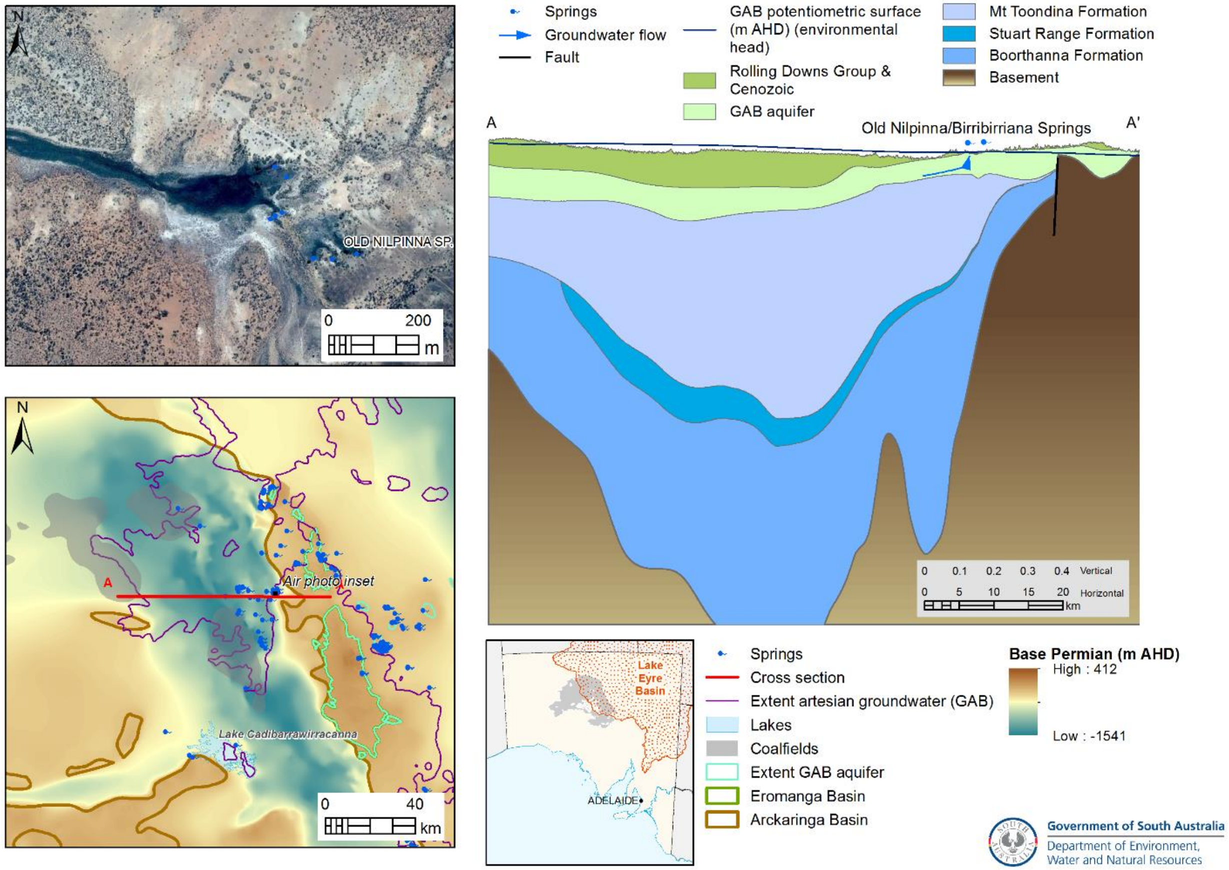


Figure 6-5: Old Nilpinna Spring Group summary

Group name	Spring Complex	No. of springs	Structural model	Hydrochemical characterisation	Geology/Regolith	Est. SWL (mbgs) & flow (l/s)	Notes
Big Cadna-owie (UBC)	Mount Dutton West	9	Primary: Model 2	Group 3	Highly to moderately weathered Bulldog Shale and J-K aquifer bedrock. Spring deposits Quaternary alluvial, colluvial and aeolian sediments nearby. Erosional/ depositional environment.	<0, no flow estimated	Big Cadna-owie Springs group is in the vicinity of Mount Dutton, approximately 3 km south from basement outcrop. Springs in this group all appear in close proximity to outcropping J-K aquifer rocks. More recent sediments are predominantly alluvial, colluvial and aeolian. A large accumulation of spring related deposits have also been interpreted. Depth to the J-K aquifer is between 0 and 35 mbgs. GAB aquifer sediments appear to have a have a steep repose in the vicinity of the Peake and Denison Inlier. The position of springs is coincident with the exposed contact between the Bulldog Shale and Cadna-owie Formation. This point is also coincident with the margin of artesian groundwater conditions. There may be structure related to the basin margin contributing to spring formation, particularly with respect to springs in locations with interpreted thicknesses of Bulldog Shale up to 35 m. Regional groundwater flow and hydrochemistry suggests that a source for groundwater may come from the either side as well as north of the Peake and Denison Inlier. Groundwater is currently thought to be primarily sourced from the GAB, although ^{14}C of 28 pmC suggest some modern contribution from another aquifer could be occurring.

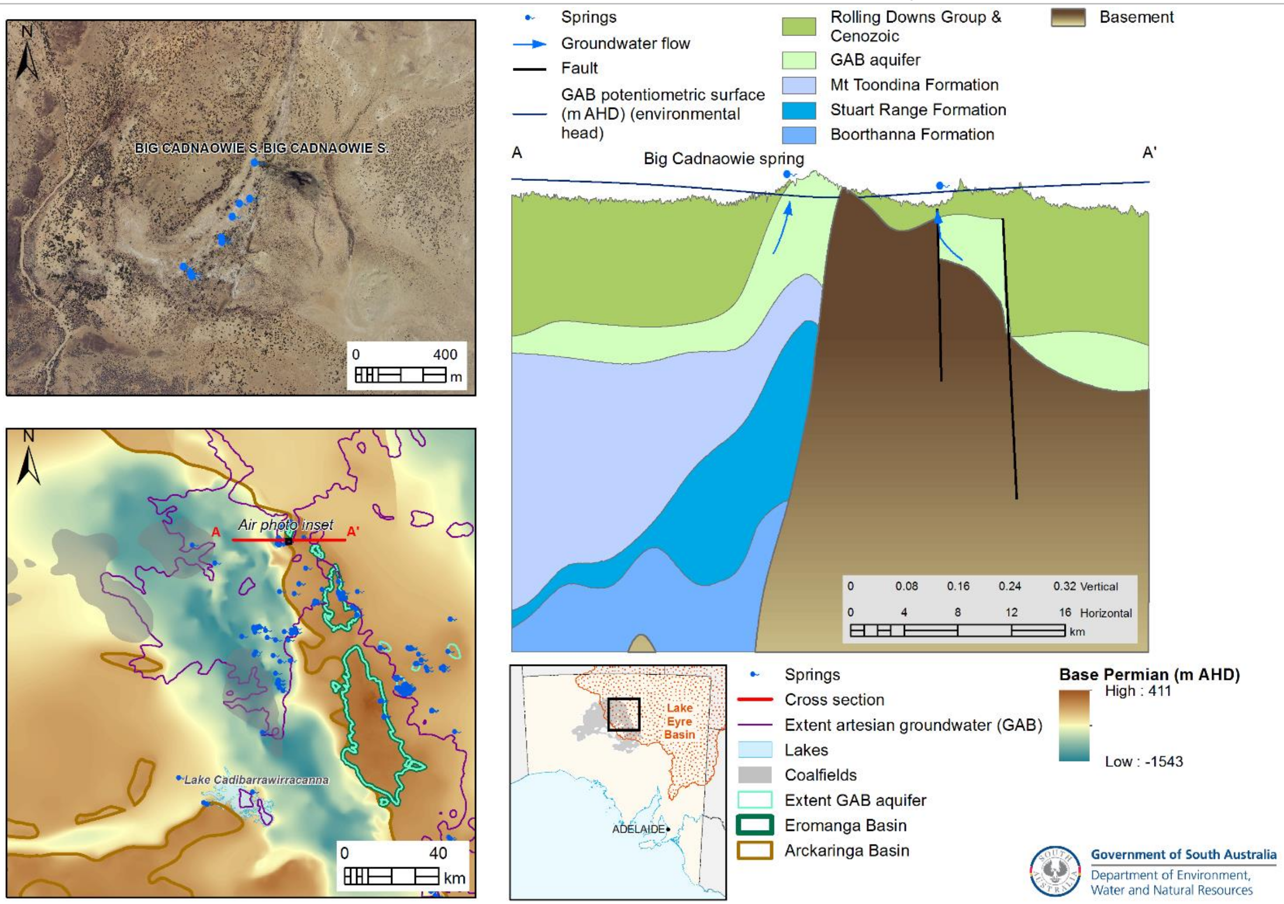


Figure 6-6: Big Cadna-owie Spring Group summary

Group name	Spring Complex	No. of springs	Structural model	Hydrochemical characterisation	Geology/Regolith	Est. SWL (mbgs) & flow (l/s)	Notes
Ockenden (UOS)	Mount Dutton East	1	Primary: Model: 1b	Group 3	Highly to moderately weathered Bulldog Shale and J-K aquifer bedrock. Spring deposits Quaternary alluvial sediments nearby. Erosional/ depositional environment.	-22.1, no flow estimated	Ockenden Springs group is located to the east of the Peake and Denison Inlier, approximately 4 km away from basement outcrop. The springs are located near the margin of a 0.5 km wide ephemeral stream. The surrounding area is predominantly weathered Bulldog Shale. Depth to the J-K aquifer is interpreted to be approximately 15 mbgs. Interpretation of structural surfaces in this region suggest that Eromanga Basin sedimentary rocks have been deformed by faults. The position of Ockenden Springs appears closely associated with this faulting and appears to have provided a means of migration through the overlying confining layer. Regional groundwater flow and hydrochemistry suggests that a source for groundwater may come from the eastern, northern and western portions of the J-K aquifer (GAB) around the Peake and Denison Inlier. Groundwater is currently thought to be primarily sourced from the J-K aquifer, although there is little in the way of hydrochemical characterisation of the local basement fractured rock aquifer groundwater to ascertain a relationship.

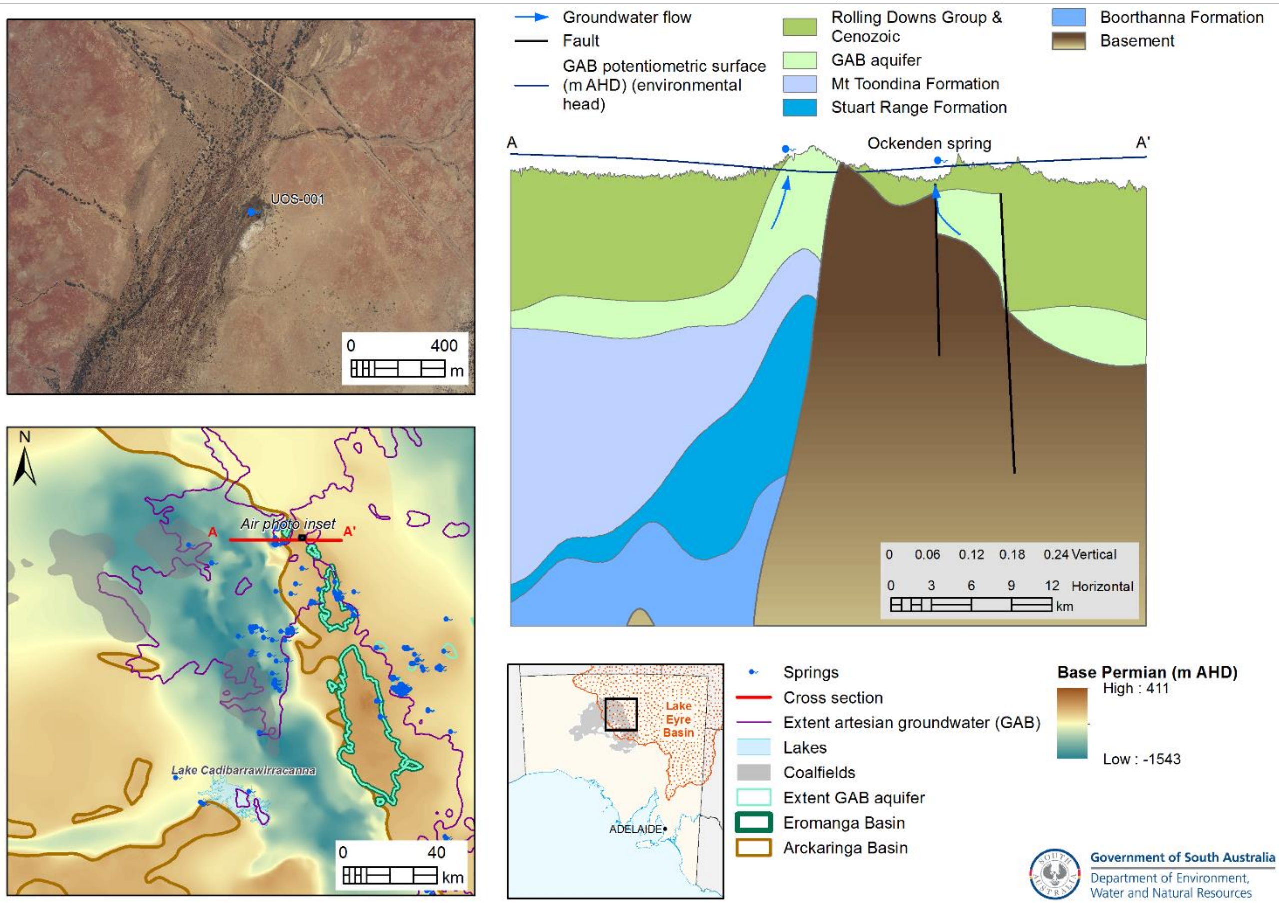


Figure 6-7: Ockenden Spring Group summary

Group name	Spring Complex	No. of springs	Structural model	Hydrochemical characterisation	Geology/Regolith	Est. SWL (mbgs) & flow (l/s)	Notes
North Freeling (EFN)	Peake Creek East	23	Primary: Model 1b	Group 1	Highly to moderately weathered crystalline basement bedrock. Spring deposits. Quaternary alluvial and colluvial sediments. Erosional/ depositional environment.	-15.9 to -21.3, flow of 0.79 l/s estimated at EFN-022	North Freeling Springs group is located on the eastern margin of the Peake and Denison Inlier, abutting the Kingston Fault and outcropping crystalline basement rocks to the west. To the east of the fault, colluvial, alluvial and spring sediments predominate on surface. Depth to the J-K aquifer is interpreted to be approximately 18 mbgs. Springs within Peake Creek are associated with coppice mound structures composed of alluvial and aeolian silt and sand. Interpretation of structural surfaces and geology in this region suggest that basement and Eromanga Basin sedimentary rocks have been deformed by faults. The position of springs and a large wetland appears closely associated with this faulting and appears to have provided a means of migration through the overlying confining layer. In particular, the orientation of the large wetland is complimentary to that of expected tensile faulting within the strain field interpreted for this region. Regional groundwater flow and hydrochemistry suggests that a source for groundwater may come from the J-K aquifer (GAB) east and north-east of the Peake and Denison Inlier. Groundwater is currently thought to be primarily sourced from both the J-K aquifer and the underlying fractured rock aquifer based on work conducted to the south (Dailey, 2011; Wohling et al. 2013a).

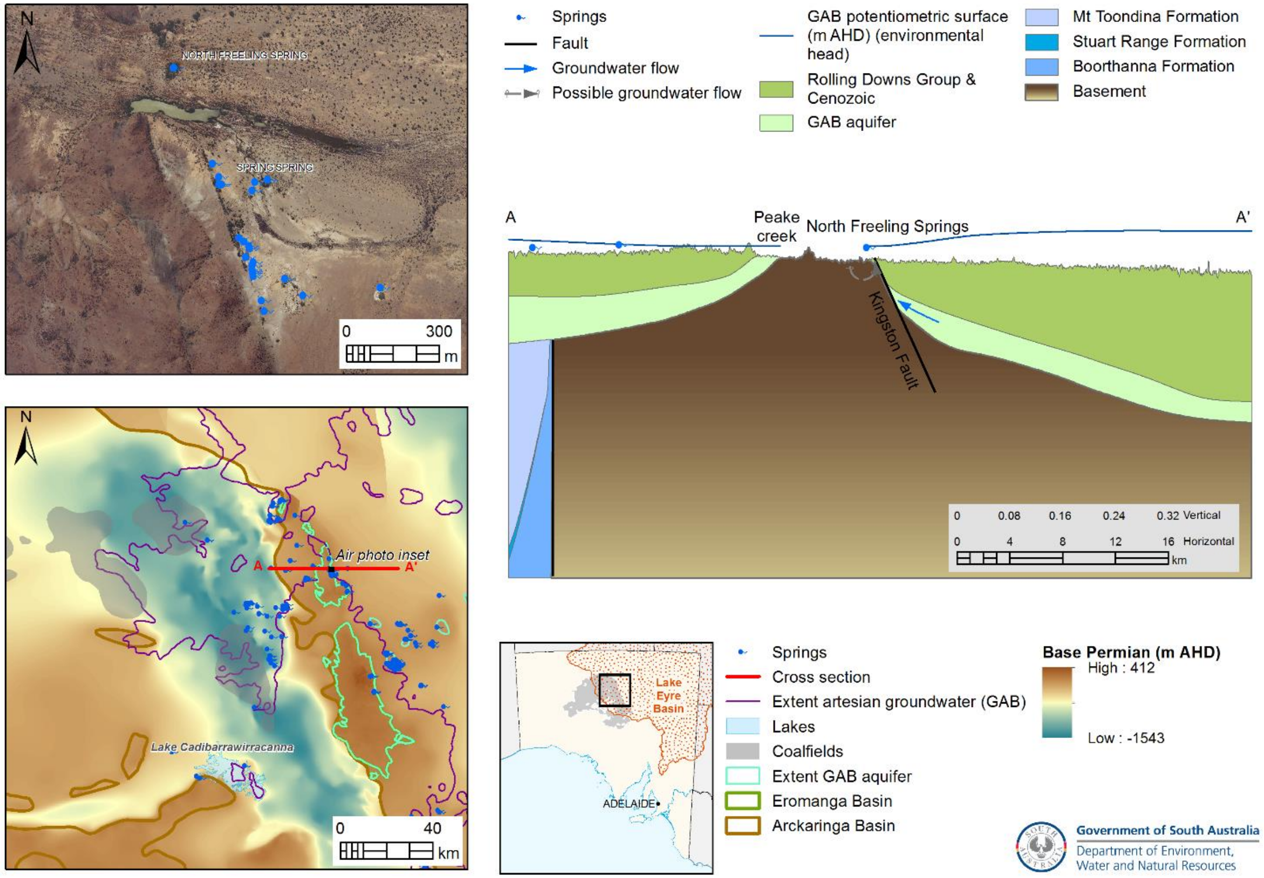


Figure 6-8: North Freeling Spring Group summary

Group name	Spring Complex	No. of springs	Structural model	Hydrochemical characterisation	Geology/Regolith	Est. SWL (mbgs) & flow (l/s)	Notes
South Freeling (EFS)	Peake Creek East	100	Primary: Model 1b	Group 1	Highly to moderately weathered crystalline basement bedrock. Spring deposits. Quaternary alluvial and colluvial sediments. Erosional/ depositional environment.	-4.4 to -9.2, flow between 0.2 – 1 l/s (Dailey 2011)	South Freeling Springs group is located on the eastern margin of the Peake and Denison Inlier, abutting the Kingston Fault and outcropping crystalline basement rocks to the west. To the east of the fault, colluvial, alluvial and spring sediments predominate on surface. Depth to the J-K aquifer is interpreted to be between 44 and 53 mbgs. Springs are associated with terracing and mound-like structures composed of spring-related calcareous precipitate. Interpretation of structural surfaces, geology and geophysics in this region suggest that basement and Eromanga Basin sedimentary rocks have been deformed by faults and related folding. The position of springs appears closely associated with this faulting and appears to have provided a means of migration through the overlying confining layer. In particular, groundwater seepage and stands of *phragmites* are observed along the margin of basement outcrop. Regional groundwater flow and hydrochemistry suggests that a source for groundwater may come from the J-K aquifer (GAB) east and north-east of the Peake and Denison Inlier. Groundwater is currently thought to be primarily sourced from both the J-K aquifer and the underlying fractured rock aquifer based on work conducted to the south (Dailey, 2011; Wohling et al. 2013a).

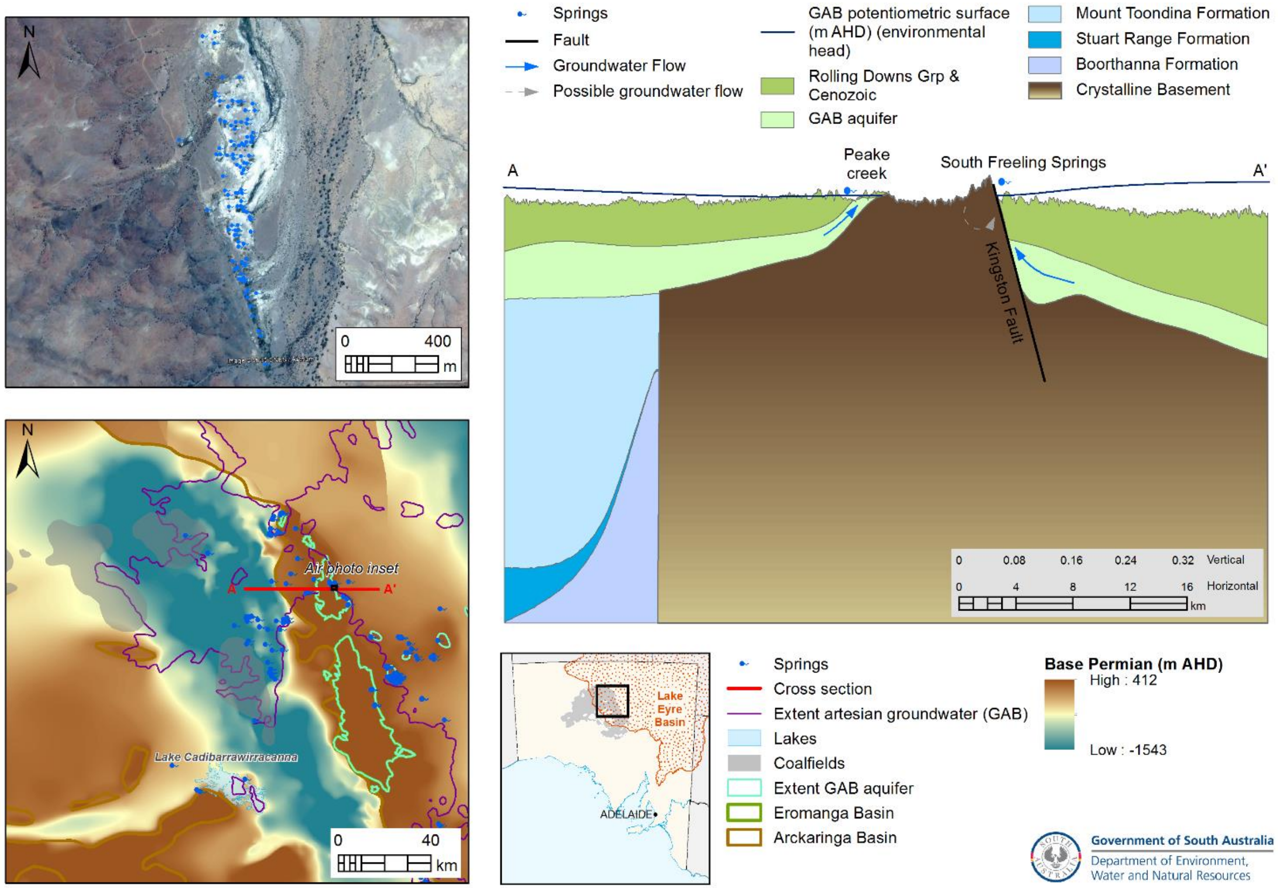


Figure 6-9: South Freeling Spring Group summary

Group name	Spring Complex	No. of springs	Structural model	Hydrochemical characterisation	Geology/Regolith	Est. SWL (mbgs) & flow (l/s)	Notes
Keckwick (PKS)	Peake Creek West	3	Primary: Model 1a	Group 2	Quaternary alluvial sediments. Highly to moderately weathered Bulldog Shale bedrock in vicinity. Depositional environment.	-17.4 to -19.2, no flow estimated	Keckwick Springs group (also known as Peake Creek and Allandale Springs) is located to the west of the Peake and Denison Inlier, approximately 8 km away from basement outcrop. The springs are located within the Peake Creek overbank area. As the Bulldog Shale is estimated to be 50 m thick at this location, a fracture-related structure is interpreted to be the primary cause of spring formation. However, as there are no obvious regional structures interpreted here, such structures are likely to be localised. The location of springs within the Peake Creek overbank area indicates the potential for some localised stream erosion contributing to confining layer stripping. Springs are associated with coppice mounds composed of alluvial and aeolian silt and sand. It is notable that the position of nearby Boundary Camp Spring appears in a location that strongly suggests a relationship to a major fracture zone, in that they are located directly above the margin of a basement high. Regional groundwater flow and hydrochemistry suggests a source from the west or north-west of the springs. Groundwater is currently thought to be primarily sourced from the GAB, although there is little in the way of hydrochemical characterisation of local Arckaringa Basin groundwater to ascertain a relationship

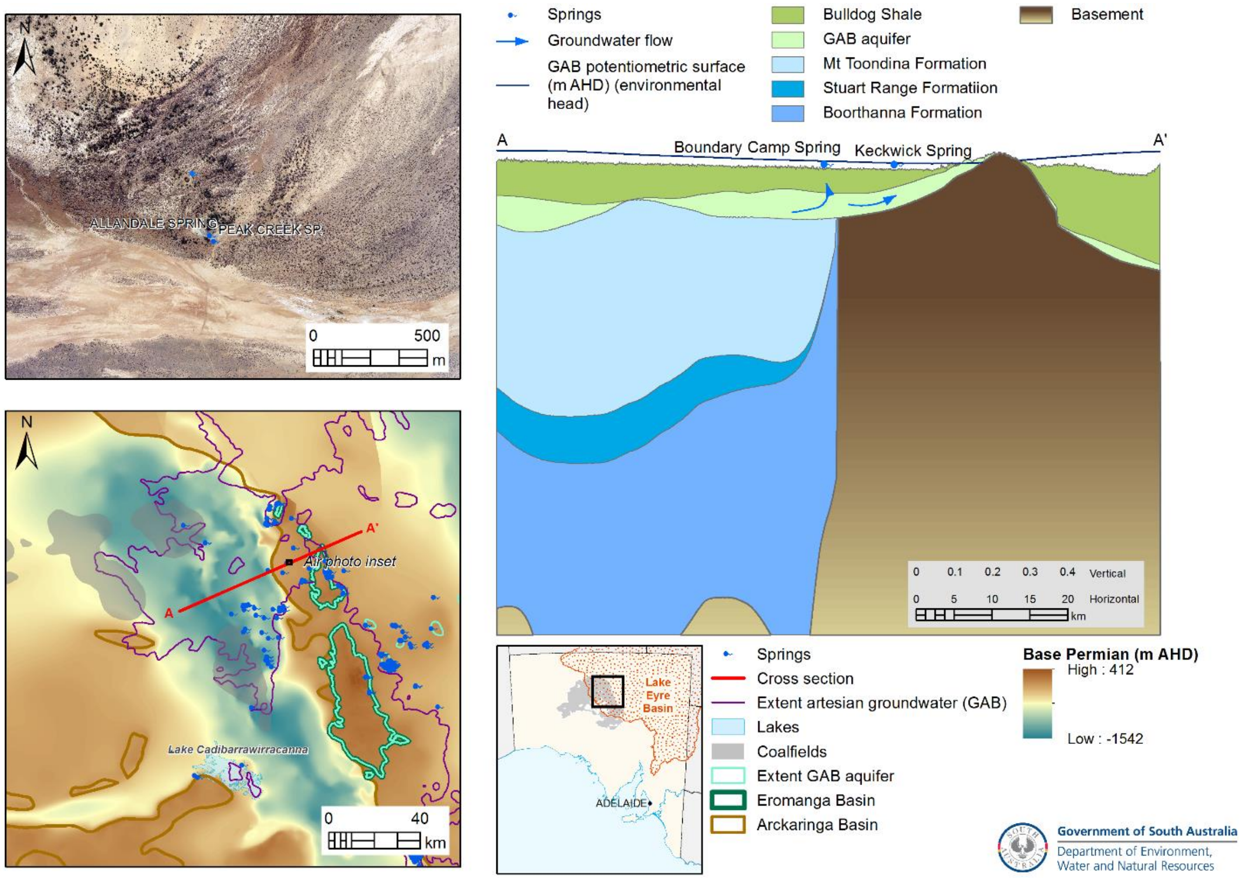


Figure 6-10: Keckwick Spring Group summary

Group name	Spring Complex	No. of springs	Structural model	Hydrochemical characterisation	Geology/Regolith	Est. SWL (mbgs) & flow (l/s)	Notes
Cootabarcoola (PCT)	Peake Creek West	1	Primary: Model 2	Group 2	Highly to moderately weathered Bulldog Shale bedrock. Quaternary alluvial, colluvial and aeolian sediments. Erosional/ depositional environment.	-16, no flow estimated	Cootabarcoola Springs group is located to the west of the Peake and Denison Inlier, approximately 3 km away from basement outcrop. The spring occurs near the margin of a tributary ephemeral stream (approximately 0.4 km wide) to Peake Creek, consequently surface geology is predominantly Quaternary alluvial sediments and weathered Bulldog Shale. Colluvial sediments are mapped to occur on the opposite bank to that of the spring. Depth to the J-K aquifer is interpreted to be approximately 9 mbgs. Springs are associated with coppice mound structures composed of alluvial and aeolian silt and sand. There are no obvious structures interpreted at this location, suggesting that if there are structural controls present, they are likely to be localised. The spring is located close to the margin of Bulldog Shale occurrence, suggesting strongly that the primary cause of formation is sediment thinning. Regional groundwater flow and hydrochemistry suggests a source from the west or north-west of the springs. Groundwater is currently thought to be primarily sourced from the GAB, although there is little in the way of hydrochemical characterisation of local Arckaringa Basin groundwater to ascertain a relationship

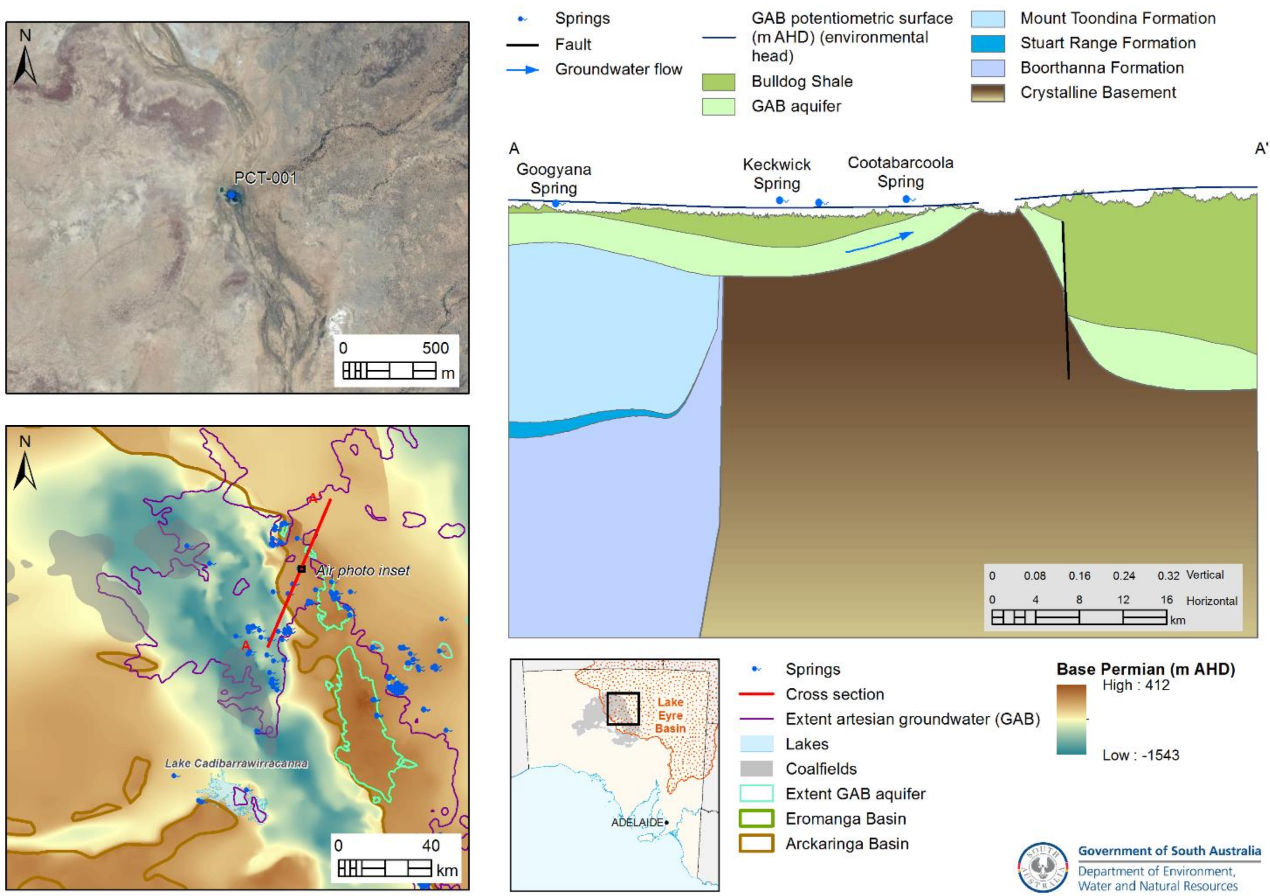


Figure 6-11: Cootabarcoola Spring Group summary

Group name	Spring Complex	No. of springs	Structural model	Hydrochemical characterisation	Geology/Regolith	Est. SWL (mbgs)	Notes
Warrangarana Edadurrana, &Weedina (PWA, PWE & PES)	Peake Creek West	21	Primary: Model 2	Group 2	Quaternary lacustrine sediments. Aeolian sediments and highly to moderately weathered J-K aquifer bedrock nearby. Depositional environment	0 to -15.2, no flow estimated	Warrangarana Springs group is located to the west of the Peake and Denison Inlier, approximately 10 km away from basement outcrop. Surface geology is predominantly Quaternary ephemeral lacustrine sediments that have accumulated near the eastern margin of Weedina Creek. J-K aquifer outcrop occurs in close vicinity to the spring group. Other surface geology materials are predominantly aeolian. Depth to the J-K aquifer is between 0 and 3 mbgs. South Well Springs are associated with coppice mound or nebkha structures composed of alluvial and aeolian silt and sand. A notable inflection in Mesozoic sediments has resulted in erosion-caused thinning of the confining layer (Bulldog Shale) at this point, contributing to spring formation. There are no obvious structures interpreted at this location, suggesting that if there are structural controls present, they are likely to be localised. The setting suggests strongly that the primary cause of formation is sediment thinning. Regional groundwater flow and hydrochemistry suggests a source from the west or north-west of the springs. Groundwater is currently thought to be primarily sourced from the GAB, although there is little in the way of hydrochemical characterisation of local Arckaringa Basin groundwater to ascertain a relationship

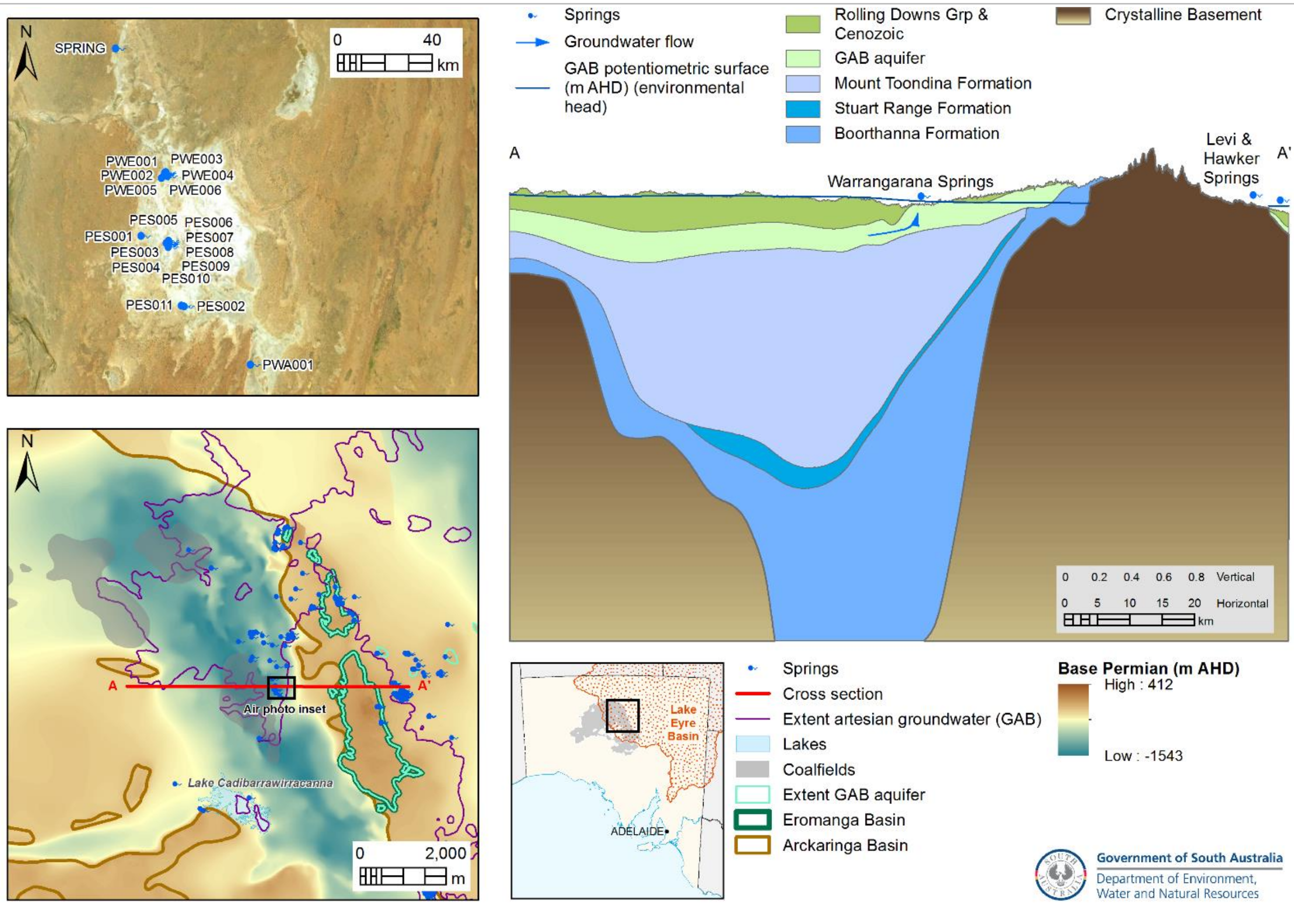


Figure 6-12: Warrangarana Spring Group summary

7 Conclusions

The specific objectives of this study were to provide an initial description of structural setting and primary controls on spring formation using recently developed basinal architecture interpretations (Keppel et al. 2015), an interpretation of near surface conditions using acquired geophysical data, and a description of the primary groundwater source based on hydrochemistry data. These descriptions were to provide input towards the compilation of a conceptual model for a number of spring groups that would also include ecological, geomorphological and risk profile considerations. With these objectives in mind, the following conclusions were drawn.

7.1 Structural setting and primary controls on spring formation

A number of conceptual structural models describing the regional architecture primarily responsible for spring formation within the investigation area were developed. The models are:

- 1a – Basin margin, structure (fracture zone)
- 1b – Basin margin, structure (fault zone)
- 2 – Basin margin, sediment thinning
- 3 – Basin margin, structure/ sediment thinning combination
- 4 – Astrobleme.

At face value, springs that are classified as having a primary structural model of 1a, 1b, 3 or 4 are at higher risk to impacts associated with potential CSG or coal mining activities within the Arckaringa Basin than those springs classified as 2. The reason for this is related to the potential for groundwater connectivity between aquifers within the GAB, and those of the underlying Arckaringa Basin afforded by regional deformation structures, such as fracture and fault zones associated with the margins of the Arckaringa Basin. In contrast, springs classified using Conceptual model 2 may have shallow, localised structures, but the lack of evidence for deeper structures linking spring environments with deeper aquifers, such as those found within the Arckaringa Basin, diminishes the risk of development impacting such deep aquifers adversely affecting these springs.

That being said, conceptual model 2 springs may still have a risk profile, given the possibility of lithological connectivity as described by Keppel et al. (2015), still exists. The high level of lithological variability observed within Arckaringa Basin sedimentary rocks suggests that determining the potential impact of any groundwater-altering developments on nearby springs needs to be considered on a case-by-case basis.

7.2 Near surface profiling using geophysics

It is possible to map different structure-based conceptual models using TEM and SP geophysical techniques. Primarily, these techniques proved useful with respect to mapping the nature of the confining layer, and constraining the location and size of conduit structures responsible for springs. Further research is required to clarify linking variations in regolith permeability and porosity to geophysical responses. Such work is particularly pertinent given recent findings presented by OGIA (2015) regarding the importance of regolith processes in the formation and maintenance of springs.

7.3 Hydrochemistry

Three hydrochemical classifications for groundwater were developed:

1. Peake Creek East (GAB east of the Peake and Denison Inlier)
2. Peake Creek West (GAB west of the Peake and Denison Inlier)
3. Mount Dutton (mix zone between Peake Creek East and Peake Creek West).

More localised variations were suggested in data between some spring and well pairs, however much of this variation was poorly constrained in that it was comparable to variations observed in results obtained from single wells over several sampling events. Consequently, such variations could not be confidently used to imply differences in either groundwater supply or evolutionary history within the context of the larger data set. By extension, there is little information concerning potential seasonal or other temporal variations of spring hydrochemistry within the investigation area. Such variation may be worth considering—particularly the possibility of temporary shallow groundwater inputs for those springs located either within watercourses or on outcropping aquifer material. Although there are important differences in climate, geology and groundwater flow paths, it was noted by OGIA (2015) that multiple groundwater inputs are described for many springs located with the Surat Basin Cumulative Management Area (CMA) in Queensland. More specifically, hydrochemistry could be used to identify not only different source aquifers to springs within the GAB, but also inputs from shallow and seasonal groundwater sources.

Additionally, springs located west of the Peake and Denison Inlier, and consequently characterised hydrochemically as Peake Creek West type groundwater, are also considered at higher risk than those springs located east of the Peake and Denison Inlier and characterised hydrochemically as Peake Creek East type. This predominantly relates to the locality of such springs to CSG and coal resources within the Arckaringa Basin that have potential for development. Groundwater classified Peake Creek West type are all found west of the Peake and Denison Inlier, as is the Arckaringa Basin and the coal resources therein. The fact that groundwater east of the Peake and Denison Inlier can be distinguished hydrochemically from those further to the west suggests that these springs predominantly source a different groundwater supply. Consequently any groundwater-impacting developments associated with CSG and coal mining activities within the Arckaringa Basin are not expected to have a direct impact on the groundwater supply of springs east of the Peake and Denison Inlier.

However, this must be prefaced with the fact that very little is known about the hydrochemistry or aquifer connectivity to the Arckaringa Basin in the immediate vicinity of these springs. Further work characterising the hydrochemistry, and determining the extent of any connectivity between the GAB and Arckaringa Basin within the region is required before a thorough assessment can be made. Additionally, evidence from historical radiocarbon data indicate that the hydrogeology of some springs may be complex, with modern, locally recharged groundwater possibly supplying some springs in part. Further research should focus on determining the magnitude of input and hydrogeological circumstances that allow modern groundwater supplies to springs.

8 Appendices

A. Groundwater sampling sites

Unit no.	Spring ID	Name	Depth to water	Max. depth	Easting	Northing	Sampling date
604100017	PCN001	Cootanoorina Spring	-	-	554189	6882089	5/11/2014
594100066		New Hurdle Creek Bore	-	-	546677	6877960	5/11/2014
604100541	POS007	'New' Old Nilpinna Spring	-	-	567863	6879394	5/11/2014
604100022	POS001	'Old' Old Nilpinna Spring	-	-	568023	6879194	6/11/2014
604100327		Kelpie Bore	4.95	70.5	576093	6881361	6/11/2014
604100020	PBI001	Birribirriana Spring	-	-	569583	6879712	6/11/2014
594000064	XOS-002	Oolgelima Spring 2	-	-	530511	6807003	7/11/2014
594000002	XOS-001	Oolgelima Spring 1	-	-	531827	6806243	7/11/2014
604000021		Trevor's Bore	-3.06	-	555636	6836912	7/11/2014
604100033		Wild Dog Creek Bore	<0	-	578958	6892666	8/11/2014
604100003	PKS003	Keckwick Spring (Peake Creek)	-	-	571157	6900383	8/11/2014
604200012	PSC001	Cootabarcoola Spring	-	-	573930	6907017	8/11/2014
592400043		Sanity Bore	-8.16	206	525494	6916941	9/11/2014
592400003	UTS001	Toondina Spring	-	-	535215	6909259	9/11/2014
604100076	EFN023	North Freeling Spring	-	-	588124	6896577	10/11/2014
604100553		'New' North Freeling Spring	-	-	587819	6896940	10/11/2014
604100037		New Peake Bore (LDH15)	-29.65	86.87	590121	6896530	10/11/2014
604100036		Century Bore	-37.13	207.26	596082	6897042	11/11/2014

All co-ordinates use the datum GDA94 Zone 53

B. Major ions, trace elements, total dissolved carbon and water quality

Sample name	Unit No.	Field alk mg/L	pH	Field spec. EC mS/cm	Lab. alk meq/L	E.C. dS/m	Temp °C	Total C mg/L	Inorganic C mg/L	Total organic C mg/L	F^- mg/L	Cl^- mg/L	Br^- mg/L	SO_4^{2-} mg/L	Ca mg/L	NO_3^- mg/L
Cootanoorina Spring	604100017	195	7.6	4622	4.2	4.5	26.3	53	51	2.2	<0.2	1031	3.1	639	161	<0.2
New Hurdle Creek Bore	594100066	204	8.0	5216	4.1	4.7	30.1	46	45	0.4	0.4	1106	3.3	669	180	<0.2
'New' Old Nilpinna Spring	604100541	208	7.8	3471	4.4	3.5	24.9	54	54	0.3	<0.2	764	2.3	441	92	<0.2
'Old' Old Nilpinna Spring	604100022	232	7.6	3292	4.6	3.6	22.6	59	57	1.2	<0.2	795	2.4	459	96	0.5
Kelpie Bore	604100327	144	7.7	9985	3.3	9.4	28.6	39	38	0.6	<0.2	2242	4.3	1607	257	<0.2
Birribirriana Spring	604100020	209	7.7	4081	4.0	4.3	24.1	51	49	1.2	<0.2	994	2.9	615	128	<0.2
Oolgelima Spring 2	594000064	291	7.5	8544	6.0	8.9	25.9	77	75	1.7	<0.2	2196	9.0	1384	382	<0.2
Oolgelima Spring 1	594000002	360	7.7	10958	6.3	12.0	24.3	80	78	1.6	<0.2	3263	14	1504	435	<0.2
Trevor's Bore	604000021	240	8.0	5609.5	5.0	5.4	27.4	60	59	0.5	<0.2	1405	4.2	611	134	<0.2
Wild Dog Creek Bore	604100033	185	7.8	3821	4.1	3.9	25.4	50	49	0.9	<0.2	905	2.7	531	122	<0.2
Keckwick Spring (Peake Creek)	604100003	210	7.5	4604	4.4	4.7	26.7	59	55	3.7	<0.2	1110	3.0	646	116	<0.2
Cootabar-coola Spring	604200012	277	7.7	4664	5.8	4.9	23.4	77	73	4.4	<0.2	1167	2.7	528	58	0.3
Sanity Bore	592400043	220	8.1	4047	4.4	3.5	34.9	53	52	0.5	<0.2	776	2.5	459	106	<0.2
Toondina Spring	592400003	360	8.1	5788	7.5	5.1	29.7	104	92	12	0.3	1178	4.0	650	136	<0.2
North Freeling Spring	604100076	195	7.8	4356	4.2	4.1	27.9	52	52	0.2	0.3	1011	2.1	379	45	<0.2

Sample name	Unit No.	Field alk mg/L	pH	Field spec. EC mS/cm	Lab. alk meq/L	E.C. dS/m	Temp °C	Total C mg/L	Inorganic C mg/L	Total organic C mg/L	F^- mg/L	Cl^- mg/L	Br^- mg/L	SO_4^{2-} mg/L	Ca mg/L	NO_3^- mg/L
'New' North Freeling Spring	604100553	226	7.7	3130	4.4	5.1	24.4	59	54	5.4	0.3	1328	3.0	487	54	<0.2
New Peake Bore (LDH15)	604100037	185	8.1	4504	4.2	4.0	30.7	50	50	0.1	0.3	996	2.0	374	46	<0.2
Century Bore	604100036	209	8.3	4657	4.3	3.9	33.1	52	51	0.7	0.3	982	1.8	371	39	<0.2

Sample Name	K	Mg	Na	S	Al	As	B	Cd	Co	Cr	Cu	Fe	Mn	Mo	Ni
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Cootanoorina Spring	33	68	705	198	<0.1	<0.05	1.0	<0.05	<0.05	<0.05	<0.05	1.5	0.2	<0.05	<0.05
New Hurdle Creek Bore	37	80	721	211	<0.1	<0.05	1.2	<0.05	<0.05	<0.05	<0.05	1.6	0.1	<0.05	<0.05
'New' Old Nilpinna Spring	26	39	590	137	<0.1	<0.05	0.8	<0.05	<0.05	<0.05	<0.05	0.8	<0.1	<0.05	<0.05
'Old' Old Nilpinna Spring	28	41	604	142	<0.1	<0.05	0.9	<0.05	<0.05	<0.05	<0.05	0.4	0.2	<0.05	<0.05
Kelpie Bore	26	103	1870	528	<0.1	<0.05	1.3	<0.05	<0.05	<0.05	<0.05	0.2	0.3	<0.05	<0.05
Birribirriana Spring	29	49	724	188	<0.1	<0.05	0.9	<0.05	<0.05	<0.05	<0.05	0.1	<0.1	<0.05	<0.05
Oolgelima Spring 2	63	207	1320	455	0.1	<0.05	1.6	<0.05	<0.05	<0.05	<0.05	0.8	2.2	<0.05	<0.05
Oolgelima Spring 1	78	271	1830	479	<0.5	<0.25	2.1	<0.25	<0.25	<0.25	<0.25	1.4	0.6	<0.25	<0.25
Trevor's Bore	42	96	910	182	<0.1	<0.05	1.3	<0.05	<0.05	<0.05	<0.05	1.3	0.1	<0.05	<0.05
Wild Dog Creek Bore	26	48	642	159	<0.1	<0.05	0.9	<0.05	<0.05	<0.05	<0.05	0.5	<0.1	<0.05	0.05
Keckwick Spring (Peake Creek)	32	44	841	195	<0.1	<0.05	0.9	<0.05	<0.05	<0.05	<0.05	0.1	<0.1	<0.05	<0.05
Cootabar-coola Spring	24	30	923	156	<0.1	<0.05	0.9	<0.05	<0.05	<0.05	<0.05	0.1	0.1	<0.05	<0.05
Sanity Bore	26	41	547	139	<0.1	<0.05	0.8	<0.05	<0.05	<0.05	<0.05	0.8	<0.1	<0.05	<0.05
Toondina Spring	61	59	856	192	<0.1	<0.05	1.2	<0.05	<0.05	<0.05	<0.05	0.3	0.4	<0.05	<0.05
North Freeling Spring	11	5.8	816	114	<0.1	<0.05	0.9	<0.05	<0.05	<0.05	<0.05	0.1	<0.1	<0.05	<0.05
'New' North Freeling Spring	14	7.0	999	151	<0.5	<0.25	1.1	<0.25	<0.25	<0.25	<0.25	<0.5	<0.5	<0.25	<0.25
New Peake Bore (LDH15)	10	5.4	802	113	<0.1	<0.05	0.8	<0.05	<0.05	<0.05	<0.05	0.3	<0.1	<0.05	<0.05
Century Bore	10	5.4	814	111	<0.1	<0.05	0.7	<0.05	<0.05	<0.05	<0.05	0.1	<0.1	<0.05	<0.05

Sample ID	P mg/L	Pb mg/L	Sb mg/L	Se mg/L	Si mg/L	Sr mg/L	Zn mg/L	NH_4-N mg/L	NO_x-N mg/L	NO_2-N mg/L	PO_4-P mg/L
Cootanoorina Spring	<0.2	<0.05	<0.1	<0.05	5.9	2.4	0.19	0.74	0.021	0.014	<0.005
New Hurdle Creek Bore	<0.2	<0.05	<0.1	<0.05	5.9	2.8	0.33	0.36	0.007	0.011	0.011
'New' Old Nilpinna Spring	<0.2	<0.05	<0.1	<0.05	5.8	1.4	0.22	0.46	0.018	0.010	0.008
'Old' Old Nilpinna Spring	<0.2	<0.05	<0.1	<0.05	6.1	1.4	0.20	0.36	0.24	0.020	0.017
Kelpie Bore	<0.2	<0.05	<0.1	<0.05	5.5	5.5	0.29	4.2	0.028	0.023	0.009
Birribirriana Spring	<0.2	<0.05	<0.1	<0.05	5.8	2.1	0.18	0.33	0.019	0.013	0.009
Oolgelima Spring 2	<0.2	<0.05	<0.1	<0.05	5.4	3.8	0.28	0.13	0.010	0.010	0.009
Oolgelima Spring 1	<1	<0.25	<0.5	<0.25	3.7	5.3	0.37	0.11	0.017	0.011	0.009
Trevor's Bore	<0.2	<0.05	<0.1	<0.05	5.7	2.3	0.40	0.40	0.026	0.010	0.008
Wild Dog Creek Bore	<0.2	<0.05	<0.1	<0.05	8.3	2.0	0.43	0.47	0.022	0.011	0.008
Keckwick Spring (Peake Creek)	<0.2	<0.05	<0.1	<0.05	6.1	2.0	0.37	0.48	0.34	0.198	0.072
Cootabar-coola Spring	<0.2	<0.05	<0.1	<0.05	8.1	1.0	0.28	0.28	0.17	0.025	0.048
Sanity Bore	<0.2	<0.05	<0.1	<0.05	6.6	1.4	0.34	0.23	0.020	0.010	0.008
Toondina Spring	<0.2	<0.05	<0.1	<0.05	15	2.5	0.39	0.05	0.045	0.014	0.013
North Freeling Spring	<0.2	<0.05	<0.1	<0.05	7.0	1.4	0.38	0.96	0.11	0.027	0.011
'New' North Freeling Spring	<1	<0.25	<0.5	<0.25	7.9	1.7	0.29	0.37	0.056	0.016	0.009
New Peake Bore (LDH15)	<0.2	<0.05	<0.1	<0.05	7.2	1.3	0.43	1.0	0.026	0.010	0.008
Century Bore	<0.2	<0.05	<0.1	<0.05	7.3	1.1	0.31	0.93	0.035	0.011	0.008

C. Stable isotopes of water and $^{87}Sr/^{86}Sr$ results

Sample ID	Unit no.	δD (per mill VSMOW)	$\delta^{18}O$ (per mill VSMOW)	$^{87}Sr/^{86}Sr$	2se (*1e^{-6})
Cootanoorina Spring	604100017	-45.4	-6.12	.714529	.000003
New Hurdle Creek Bore	594100066	-44.8	-5.96	.712371	.000003
'New' Old Nilpinna Spring	604100541	-47.0	-6.26	.713923	.000002
'Old' Old Nilpinna Spring	604100022	-47.5	-6.12	.717396	.000003
Kelpie Bore	604100327	-38.7	-5.40	.714139	.000003
Birribirriana Spring	604100020	-45.1	-6.11	.714089	.000003
Oolgelima Spring 2	594000064	-34.8	-3.64	.714334	.000003
Oolgelima Spring 1	594000002	-34.9	-3.20	.712085	.000003
Trevor's Bore	604000021	-40.7	-4.85	.714744	.000003
Wild Dog Creek Bore	604100033	-46.5	-6.15	.715853	.000003
Keckwick Spring (Peake Creek)	604100003	-47.1	-6.24	.712917	.000003
Cootabarcoola Spring	604200012	-44.1	-5.74	.713680	.000003
Sanity Bore	592400043	-46.1	-6.35	.713723	.000003
Toondina Spring	592400003	-26.0	-1.19	.709850	.000003
North Freeling Spring	604100076	-35.7	-4.57	.709905	.000003
'New' North Freeling Spring	604100553	-45.8	-6.50	.709750	.000003
New Peake Bore (LDH15)	604100037	-44.8	-6.55	.709511	.000003
Century Bore	604100036	-47.9	-6.69	.714529	.000003

9 Units of measurement

9.1 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
microliter	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

9.2 Shortened forms

~	Approximately equal to
mbgs	metres below ground surface
EC	electrical conductivity (µS/cm)
K	hydraulic conductivity (m/d)
pH	acidity

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