LAKE EYRE BASIN SPRINGS ASSESSMENT PROJECT

A HYDROGEOLOGICAL AND ECOLOGICAL CHARACTERISATION OF SPRINGS NEAR LAKE BLANCHE, LAKE EYRE BASIN, SOUTH AUSTRALIA

DEWNR TECHNICAL REPORT 2016/03

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.

A hydrogeological and ecological characterisation of springs near Lake Blanche, Lake Eyre Basin, South Australia

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Foreword

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

High-quality science and effective monitoring provide the foundation for the successful management of our environment and natural resources. This is achieved by 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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Summary

The Australian Government established an Independent Expert Scientific Committee on Coal Seam Gas (CSG) and Large Coal Mining Development to provide independent expert scientific advice about the possible effects of such developments on water resources. As part of this initiative, the South Australian Department of Environment, Water and Natural Resources was funded to:

- collate and ground-truth groundwater, surface water and ecology information in regions with the potential for CSG and large coalmining developments
- conduct vulnerability assessments in these identified areas.

This report presents the findings of one of a series of investigations in the Lake Eyre Basin in South Australia. Key to any assessment of the impact of developments on water resources in the basin is the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC)-listed Threatened Ecological Community 'the community of native species dependent on natural discharge of groundwater from the Great Artesian Basin'. Many of the springs in which the Threatened Ecological Community occurs are located close to, or down-gradient of, coal resources.

This report presents the hydrogeological and ecological characterisation of a number of spring complexes in the Lake Blanche region that were identified as most at risk to diminished flow or changes in water quality that might occur as a consequence of any potential CSG developments within the Weena Trough of the Cooper Basin. The specific objectives of this study were to provide an initial description of structural setting and primary controls on spring formation using previously published basin architecture interpretations, an interpretation of near-surface conditions using acquired geophysical data and a description of the primary groundwater source based on hydrochemistry data. The report also includes a summary of the current status of the spring ecosystems, including the ecological conditions and biodiversity of the spring complexes in the study area, explanations of the various spring types identified, and examples of possible impacts that could occur in the spring ecosystems as a result of a CSG or coal development. With these objectives in mind, the following conclusions were drawn.

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

1c mid-basin, structure (fault zone)
2 basin margin, sediment thinning
3 basin margin, structure/sediment thinning combination.

At face value, springs classified as having any variation within primary structural model 1c are at higher risk from impacts associated with potential CSG or coalmining activities within the Cooper Basin than those springs classified as 2 or 3. The reason for this is related to the potential for groundwater connectivity between aquifers within the Great Artesian Basin (GAB) and those of the underlying Cooper Basin, through regional deformation structures such as fracture and fault zones.

Three new spring types were observed during the survey. Two have been described in detail here: Erosional Channel Springs and Brine Density Springs. The third type – Mud Springs – was only recorded at Lake Callabonna, and represents the second known occurrence of this type of spring in South Australia.

Five hydrochemical classifications for groundwater were developed that are related to the aquifer from which groundwater is sourced:

- crystalline basement (fractured rock) aquifer
- Patchawarra Formation (Cooper Basin) aquifer
- J-K aquifer (Cadna-owie Formation and Algebuckina Sandstone of the GAB)
- Coorikiana Sandstone (?) aquifer (Shallow GAB)
- Cenozoic aquifers.

Classifications were based on differing proportional major ion compositions and stable isotope ratios, and apparent ages were based on radiocarbon and $^{36}Cl/Cl^{-}$ data. Although most spring water samples can be compared favourably with the J-K aquifer using historical and current hydrochemistry results, results from a number of spring waters are more comparable with other groundwater types and therefore suggest that they are supplied by groundwater from aquifers other than the J-K aquifer. Most notably, hydrochemistry data from the Lake Blanche and Lake Callabonna springs complexes suggest that a significant portion of spring water is supplied from shallow aquifer systems such as the Cenozoic and the Coorikiana Sandstone. In contrast, the Reedy Springs complex, 13 km south of the southern margin of the Cooper Basin, potentially has a slightly higher risk profile, given the relatively short distance to the margin of the Cooper Basin – the source of groundwater identified as predominantly from the J-K aquifer – and a structural model related to a large regional fault structure that extends towards the southern margin of the Cooper Basin. That being said, the 13-km distance between this spring complex and the southern margin of the Cooper Basin could be a mitigating factor for the impacts of groundwater-affecting activity associated with CSG developments in the Weena Trough.

Another major finding of this study was identification of the Coorikiana Sandstone as a potentially important aquifer for supplying groundwater to springs within the investigation area. The Coorikiana Sandstone is a thin sandstone unit between the Bulldog Shale and the Oodnadatta Formation, which are the two most important confining units above the major aquifer unit (the J-K aquifer) in the South Australian portion of the GAB. Although the Coorikiana Sandstone has been previously recognised in parts of the basin to the north of the investigation area, a review of historical logs has found sandstone and other sandy sediments at a similar depth much further to the south. Additionally, the historical logging data indicate that a number of wells within the investigation area have either been completed within the Coorikiana Sandstone or that groundwater from the Coorikiana Sandstone is leaking into the well annulus. Although further work is required to confirm this finding, this interpretation has important implications for our understanding of the geology, basin architecture and hydrogeology of this region, and should be considered in relation to water resource management.

1 Introduction

1.1 Bioregional Assessment Programme and IESC

The Bioregional Assessment Programme is a transparent and accessible program of baseline assessments that increase the available science for decision making associated with potential water-related impacts of coal seam gas (CSG) and large coalmining 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 CSG and large coalmining development on water resources. This program 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 www.bioregionalassessments.gov.au.

The Independent Expert Scientific Committee on Coal Seam Gas and Large Coal Mining Development (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 CSG and large coalmining development proposals.

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

- provide scientific advice to the Commonwealth Environment Minister and relevant state ministers on the water-related impacts of proposed CSG or large coalmining 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
- publish and disseminate scientific information about the impacts of CSG and large coalmining activities.

1.2 Background

In 2012, the Australian Government established the IESC to provide independent expert scientific advice about the effects such developments may have on water resources. As part of this initiative, the South Australian Department of Environment, Water and Natural Resources (DEWNR) received funding to:

- collate and ground-truth groundwater, surface water and ecology information in regions with the potential for CSG and large coalmining developments
- conduct vulnerability assessments in these identified areas.

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' (DoE 2016; Harrison et al. 2013). This Threatened Ecological Community is dependent on discharge springs fed by groundwater from the Great Artesian Basin (GAB) that underlies much of the Lake Eyre Basin (LEB) (Figure 1-1). In this instance, the term 'Lake Eyre Basin' refers to the modern hydrological basin. As will be discussed in Section 2.2.5, 'Lake Eyre Basin' may also refer to a sedimentary basin of predominantly Cenozoic age (Callen et al. 1995).

In general, knowledge of the location, ecology beyond that listed under the EPBC recovery plan (Fensham et al. 2008), surface water and groundwater hydrology of GAB springs is limited. There is a particularly poor understanding of the responses and impacts to spring flows from water extraction from potential coalmining and CSG development from the Cooper Basin, which underlies both the GAB and the LEB in the investigation area. These information gaps place significant constraints on the capacity of regulatory authorities to manage environmental risks associated with CSG and coalmining developments, both individually and cumulatively. An initial 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.

1.3 Objectives

The specific objectives of this study are to provide an initial description of structural setting and primary controls on spring formation using previously published basin architecture interpretations, 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 to a conceptual model for a number of spring groups that would also include ecological, geomorphological and risk profile considerations.

The spring complexes included in this study were identified as those most at risk to either reductions in flow or changes in water quality that might occur as a consequence of any potential CSG or coal resource developments within the Weena Trough of the Cooper Basin. The reason for this risk assessment primarily centres on the close proximity of the springs to known coal resources near the Cooper Basin.

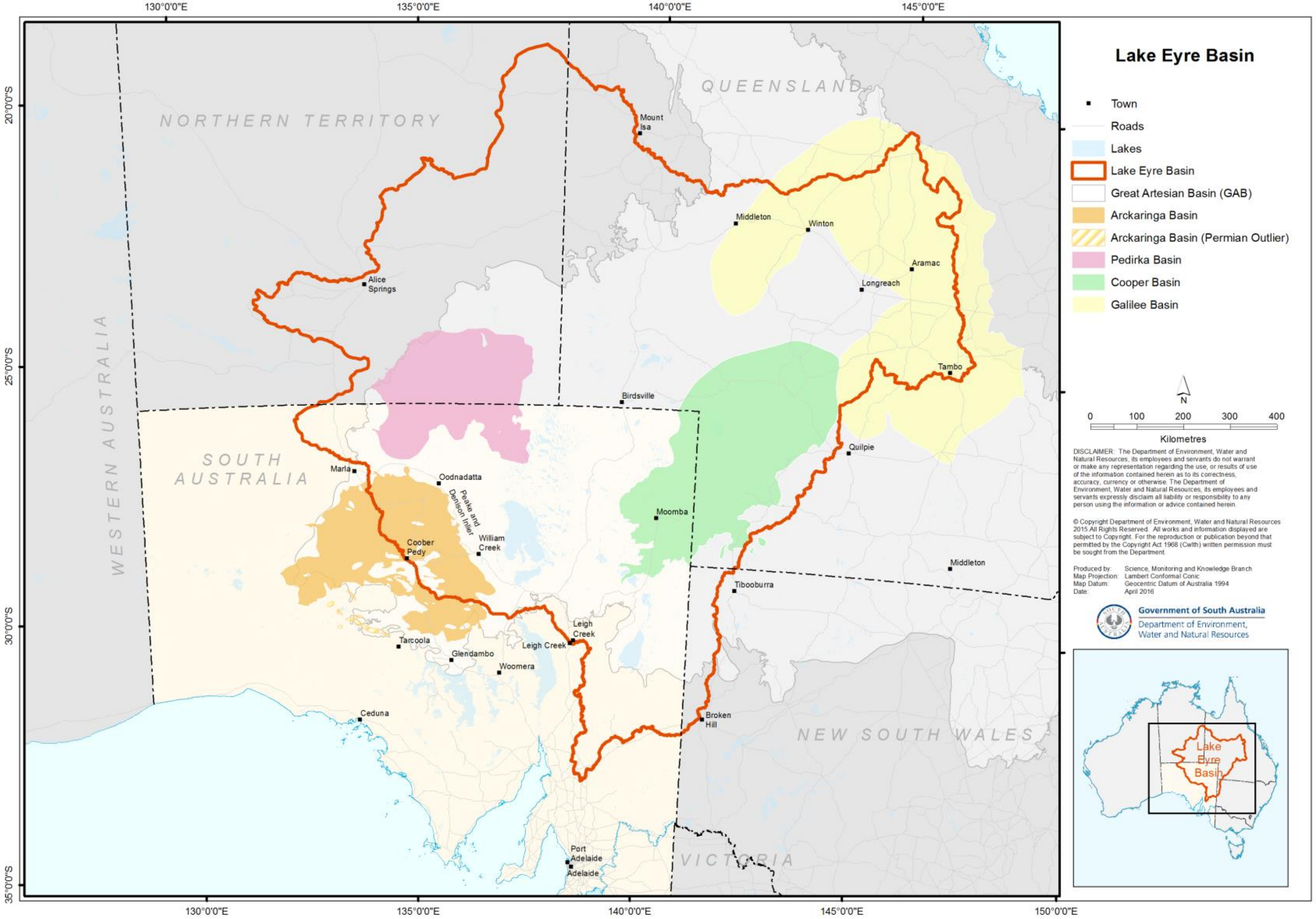


Figure 1-1: Lake Eyre Basin, the Great Artesian Basin and coal-bearing Permo-carboniferous basins that occur nearby

2 Background information

2.1Regional setting

2.1.1 Location and physiography

The investigation area covers approximately 15,100 km^2, from the northern edge of the North Flinders Ranges in the south to Lake Blanche in the north (Figure 2-1). Five spring complexes are covered by this area: Lake Blanche, Reedy, Petermorra, Twelve and Lake Callabonna. All complexes are part of the Lake Frome Springs Supergroup. The investigation area includes the southern extension of the Cooper Basin, which is currently under active coal seam gas (CSG) exploration (Figure 2-1).

The area is in northern South Australia, approximately 600 km north-north-east of Adelaide. The climate is generally arid, with weather patterns dominated by persistent high pressure systems. Rainfall comes predominantly from weak winter cold fronts originating in the Southern Indian Ocean or sporadic summer monsoon rainfall originating in north-west and north-east Australia; rainfall for the nearest weather station at Moomba averages 172 mm per year (BoM 2015), although this can vary significantly from year to year.

Given the arid climate, aeolian-driven erosion as described by Mabbutt (1977) is important in shaping the physiology of the region. The landscape is predominantly flat desert consisting of sand dunes and gibber plains. Exceptions to this include the North Flinders Ranges, a mountain range comprising outcropping basement rocks that are Archean to Cambrian in age, and silt and clay pans associated with Lake Blanche and Lake Callabonna, found along the northern and eastern margins of the study area (Figure 2-1).

The largest town near the study area is Moomba, with a population of approximately 1,200 (Figure 1-1). Moomba is a petroleum and gas exploration and processing town owned and operated by Santos Pty Ltd. Parts of the Pirlatapa, Wadigali, Dieri, Yawarrawarrka and Adnyamathanha Aboriginal language regions occur within the study area.

The pastoral industry represents the predominant land use across the region, while petroleum extraction from the Cooper Basin is an important industry to the immediate north. The Strzelecki track transects the study area and is an important arterial route supplying the oil and gas fields of the Cooper Basin (Figure 2-2). Tourism is a growing industry. Most water supplies for domestic, pastoral, commercial and industrial purposes in the region are derived from groundwater because surface water resources are small and unreliable. Most groundwater is sourced from the Great Artesian Basin (GAB), with some groundwater also sourced from the younger Paleogene and Neogene-aged aquifers of the overlying Lake Eyre Geological Basin.

Of importance are a number of depositional troughs associated with the Permian Cooper Basin north of the study area. These include the Weena, Larrow, Milpera and Battunga troughs, all of which are under active CSG exploration (Figure 2-3).

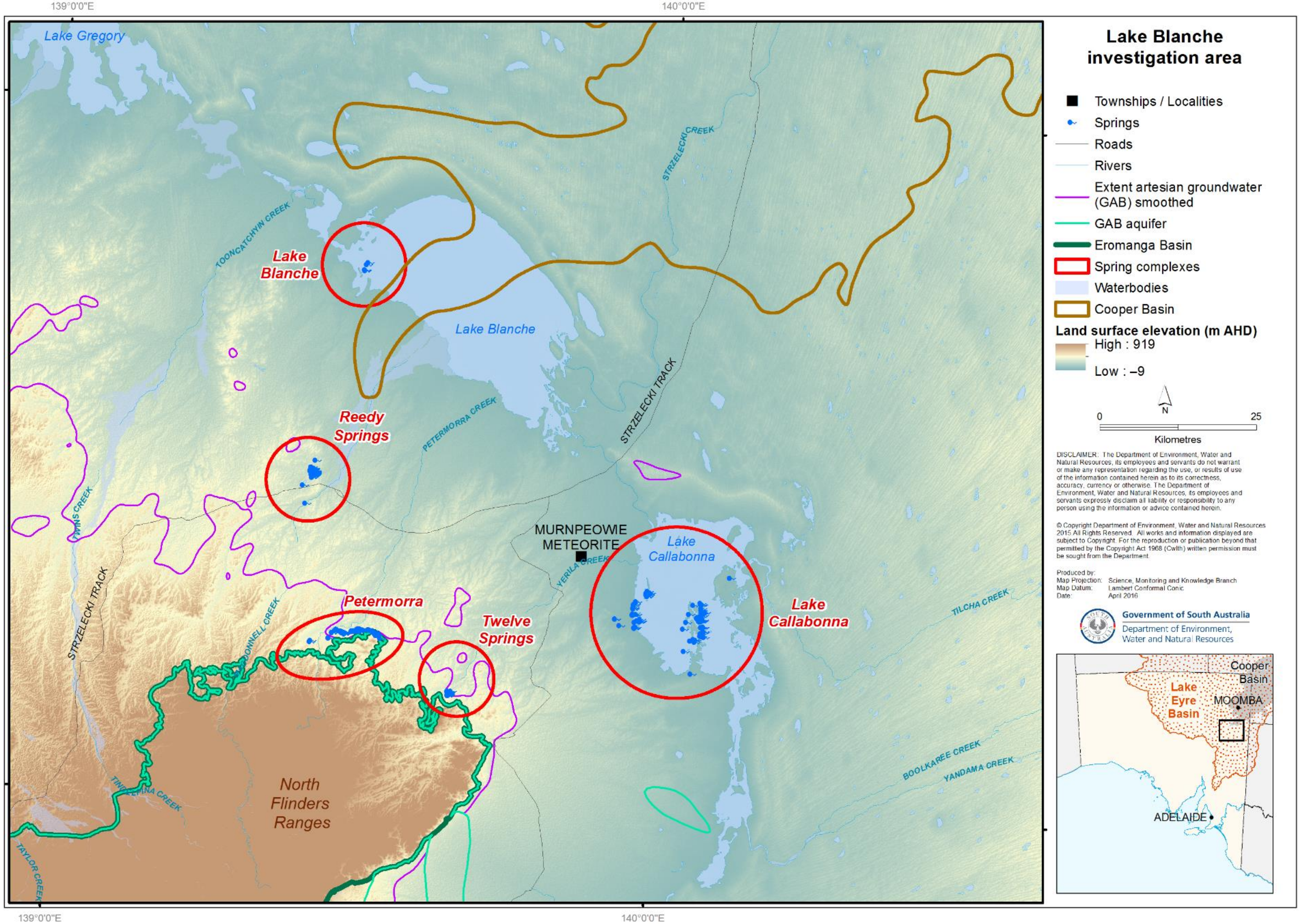


Figure 2-1: Physical geography of the investigation area

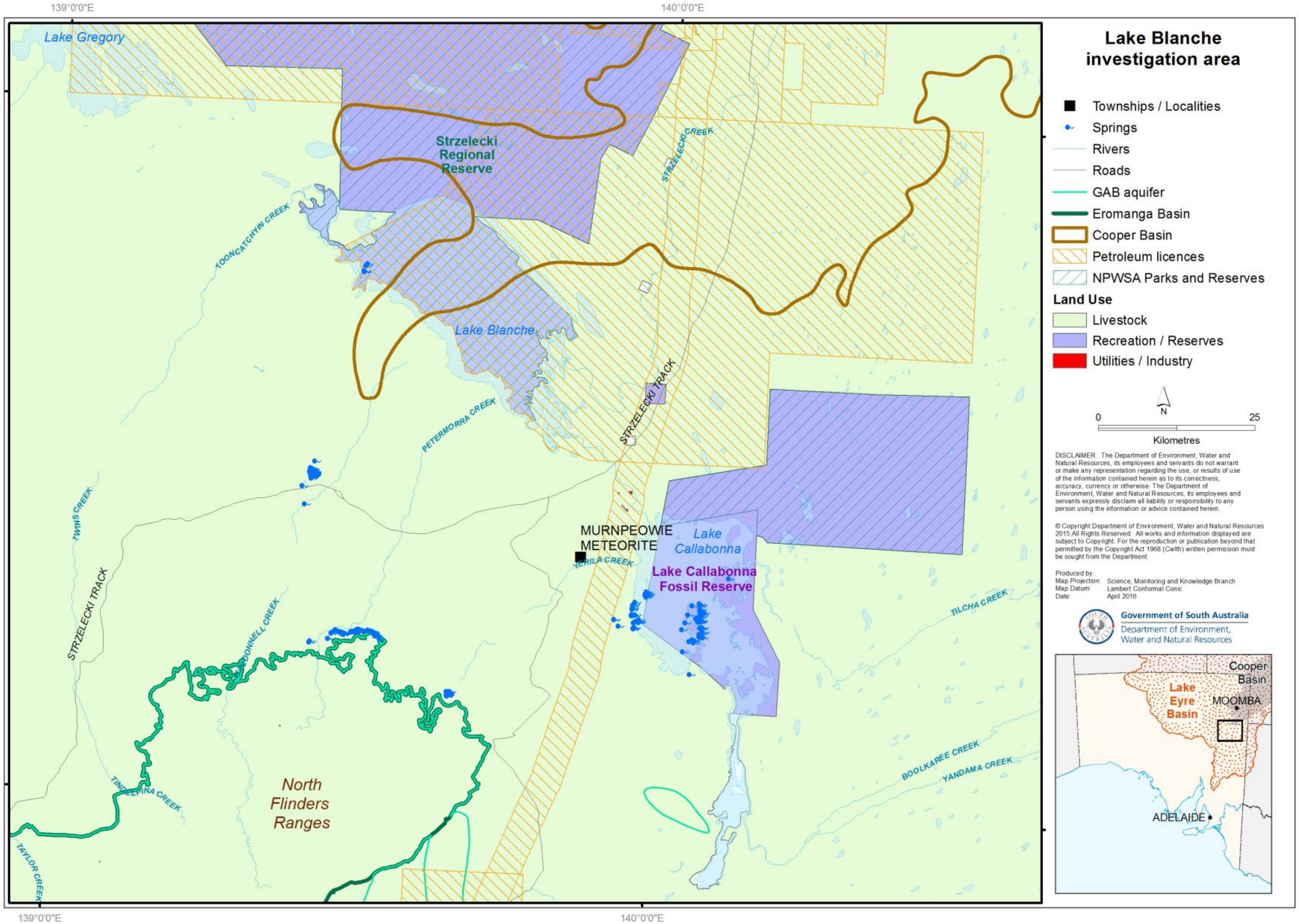


Figure 2-2: Land use within the investigation area

2.2 Geology and hydrostratigraphy

2.2.1 Crystalline basement

A number of fractured rock and karstic (Brighton Limestone) aquifers occur within crystalline, largely Precambrian, but also some early Cambrian, basement rocks in the investigation area (Preiss 1987). They represent predominantly sedimentary rocks deposited within a marine pelagic and continental shelf environment, respectively, and include limestone, sandstone, shale, quartzite, dolomite, tillite, conglomerate and volcanic rocks. These units outcrop within the North Flinders Ranges, abutting the Petermorra and Twelve springs complexes (Figure 2-4).

2.2.2 Warburton Basin

Sedimentary rocks of the Warburton Basin are primarily Cambrian to Ordovician (early Paleozoic) (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 follows into a shallow marine sequence. Furthermore, there are also minor volcanolithic units (Gravestock et al. 1995; Radke 2009). Rocks of the Warburton Basin do not outcrop within the investigation area, but underlie Cooper and Eromanga basin sedimentary rocks over much of the investigation area (Figure 2-3). Little is known about the hydrogeological properties of Warburton Basin rocks within the investigation area, including whether primary or secondary porosity and permeability is most important.

2.2.3 Cooper Basin

The Cooper Basin is an intra-cratonic basin that unconformably underlies the Eromanga Basin in north-eastern South Australia and south-western Queensland (Hill and Gravestock 1995). Approximately one-third of the basin occurs in South Australia (Figure 1-1). The basin has an unconformable contact with the underlying late-Palaeozoic sediments of the Warburton Basin. Extensive petroleum exploration has led to the development of a detailed stratigraphic interpretation. The basic composition of the basin is one of three upwardly fining non-marine sequences that combine to form two groups – the late Carboniferous to late Permian Gidgealpa Group, and the late Permian to middle Triassic Nappamerri Group. A summary is provided in Table 2-1. Sedimentary rocks of the Cooper Basin do not outcrop within the investigation area. However, the Weena Trough region of the Cooper Basin occurs within the northern portion of the investigation area (Figure 2-3). This area is significant for being under active exploration for CSG (see Section 2.2.6).

2.2.4 Great Artesian Basin

Directly overlying the Cooper Basin is the Eromanga Basin. In South Australia, the Eromanga Basin and the GAB are equivalent. Overall, the GAB describes a terrestrial-to-marine Cretaceous–Triassic basin that covers much of eastern and central Australia (Habermehl 1980), and the term 'GAB' has been used to describe both a geological and a hydrogeological basin. Variations in either basin subsidence or up-warp and global sea level changes during the Mesozoic led to the development of a series of transgressive and regressional 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. Very little outcrop of J-K aquifer sediments (Algebuckina Sandstone, Cadna-owie Formation and lateral equivalents) has been found in the investigation area (Figure 2-4); they are predominantly restricted to areas abutting the North Flinders Ranges and areas near the Petermorra and Twelve springs complexes. In contrast, overlying Rolling Downs Group sedimentary rocks, including the Bulldog Shale and the Oodnadatta, Winton and Mackunda formations, outcrop within the central portion of the investigation area.

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

Period	Group name	Formation name	Lithology description	Depositional environment	Hydrogeological characteristics
Late Triassic		Cuddapan Formation	Sandstone in lower unit. Interbedded carbonaceous siltstone, mudstone and coal in upper unit	Floodplain, meandering fluvial	Sandstone units are aquifers; others considered confining layers
Mid-Triassic	Nappamerri Group	Tinchoo Formation	Interbedded sandstone, siltstone, mudstone and minor coal. Sandstone more prevalent in lower portion	Sinuous meandering alluvial and fluvio-lacustrine	Confining layer
Early Triassic		Arrabury Formation	Wimma Sandstone Member consists of sandstone and minor mudstone. Paning Member consists of fining-up sandstone. Callamurra Member consists of siltstone and sandstone. Redbeds and carbonaceous layers also occur	Wimma Sandstone and Paning members formed via braided fluvial channels and floodplains. Callamurra Member formed within floodplains, lakes and fluvial channels	Sandstone units are aquifers; others considered confining layers
Late Permian (Lopingian Epoch)	Gidgealpa Group	Toolachee Formation	Interbedded sandstone, siltstone, mudstone and shale coal	Meandering fluvial, deltaic in part	Aquifer
Mid to Late Permian (Guadalupian Epoch)		Daralingie Formation	Interbedded siltstone, mudstone and coal	Fluvio-deltaic	Confining layer
		Roseneath Shale	Laminated siltstone, mudstone and lesser sandstone (carbonaceous)	Lacustrine	Confining layer
Mid-Permian		Epsilon Formation	Sandstone, siltstone, mudstone and coal	Fluvio-deltaic, shore facies evident in localised occurrences	Aquifer
Early to mid-Permian (Cisuralian Epoch)		Murteree Shale	Laminated, argillaceous siltstone and lesser fine-grained sandstone	Fluvio-deltaic, shore facies evident in localised occurrences	Confining layer
		Patchawarra Formation	Upwardly fining sandstone, siltstone, mudstone and coal, with siltstone and mudstone mainly in upper part of unit	Upper part fluvio-deltaic and lacustrine. Lower part paludal (peat swamp) and fluvio-deltaic	Aquifer
Permo-Carboniferous	Gidgealpa Group	Tirrawarra Sandstone	Mainly fine to coarse-grained massive sandstone. Interbeds of conglomerate. Minor interbeds of carbonaceous siltstone, shale and coal	Pro-glacial outwash and braided fluvial	Aquifer
		Merrimelia Formation	Sandstone, siltstone, coal and conglomerate	Fluvio-glacial, pro-glacial, glacio-lacustrine and aeolian	Aquifer

Sources: DMITRE (2012), DSD (2015), Fry (2014) and GA (2015)

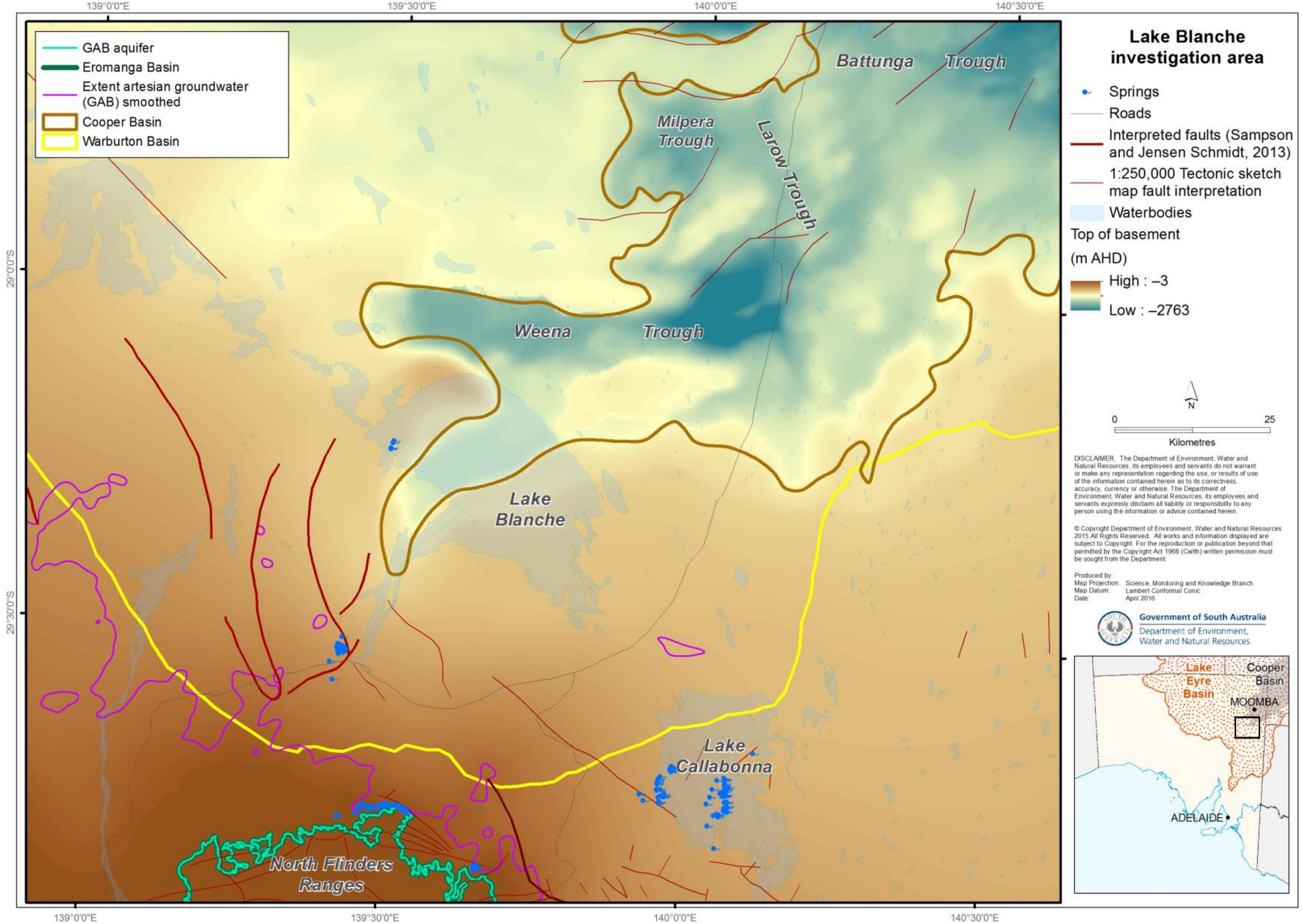


Figure 2-3: Geological structures of the investigation area, showing faults and major Cooper Basin depocentres

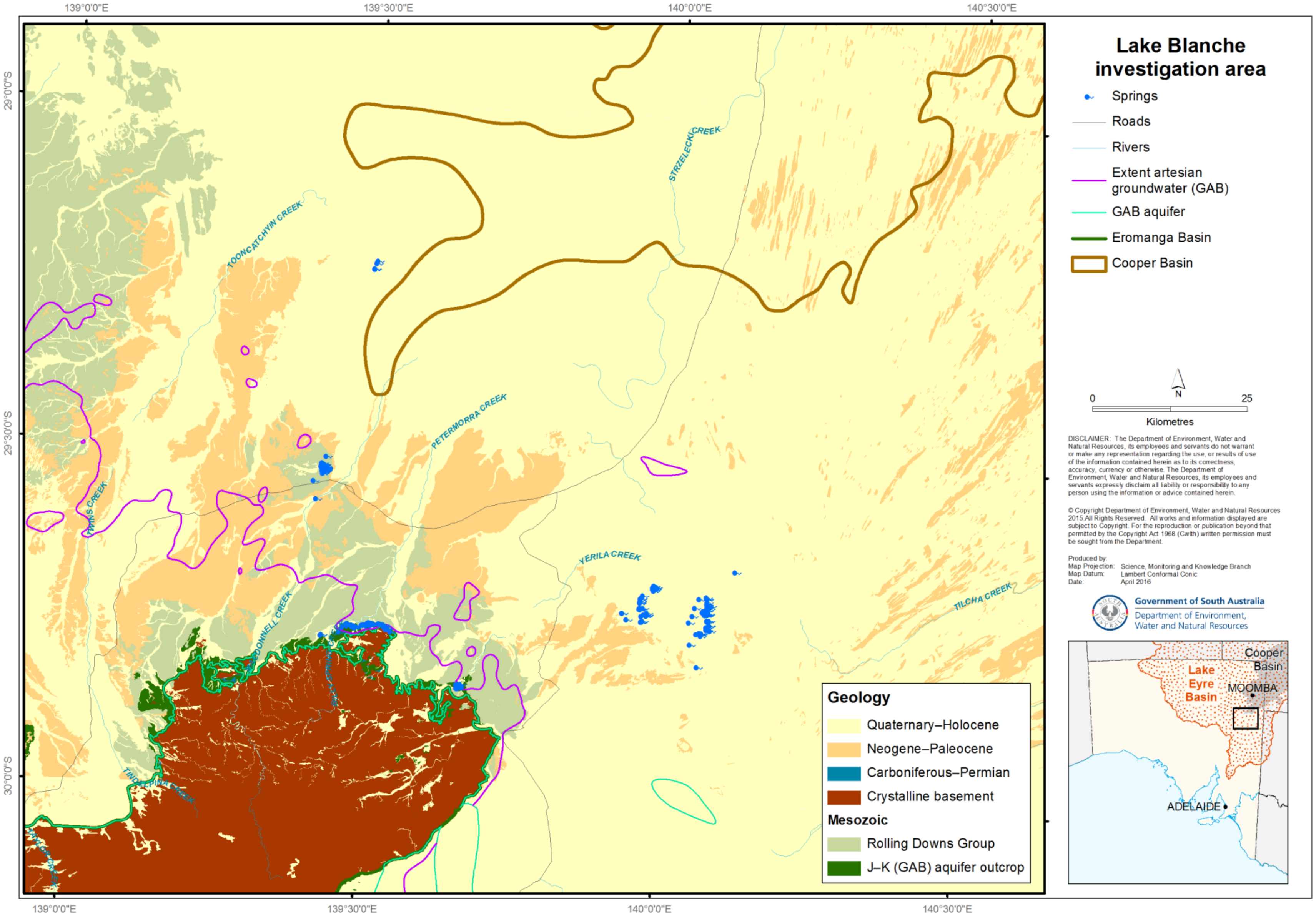


Figure 2-4: Surface geology of the investigation area

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

Period	Formation name	Lithology description	Depositional environment	Hydrogeological characteristics
Cretaceous	Winton Formation	Non-marine shale, siltstone, sandstone and minor coal seams	Low energy, fluvial, lacustrine, and paludal (swamp and marsh)	Confined lenticular aquifers, discharge in eroded anticlines
	Mackunda Formation	Partly calcareous, fine-grained sandstone, siltstone and shale. Marks transition from marine to freshwater	Subtidal marine and shore faces	Confined minor aquifer, no known natural discharge
	Oodnadatta Formation (Rolling Downs Group)	Laminated, claystone and siltstone, with interbeds of fine-grained sandstone and limestone	Low energy, shallow marine	Confining layer with minor aquifers
	Coorikiana Sandstone (Rolling Downs Group)	Predominantly 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
	Parabarana Sandstone	Sandstone, calcareous, with clasts of quartz, quartzite and porphyry; sand, gravel and shale	Fluvial to marginal marine. Time equivalent to Cadna-owie Formation	Aquifer
Jurassic	Algebuckina Sandstone	Fine to coarse-grained sandstone, with granule and pebble conglomerates	Low-gradient fluvial, including rivers and floodplain. Both arid and wet climates	Major aquifer, high-yielding bores

Source: Keppel et al. (2013)

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 before upwarping at 15 to 5 Ma, and sedimentation associated with the current hydrological system. In both cases, basin-wide sedimentation and the modern hydraulic environment are referred to as the 'Lake Eyre Basin'. Sedimentation in terms of geology is referred to as the 'Lake Eyre Geological Basin' to distinguish it from the modern hydraulic (surface water) basin.

The sediments of the Lake Eyre Basin were primarily deposited as episodic braided fluvial and lacustrine sediments and are interpreted to have taken place in three phases. Pliocene to Quaternary-aged sediments largely consist of red–brown arenites, fine-grained lacustrine sediments, and aeolian and evaporite sediments, as well as calcrete and gypcrete horizons. A summary of the major stratigraphic units is provided in Table 2-3, although some units could be limited within the investigation area.

Table 2-3: Summary of hydrostratigraphy of the Lake Eyre Geological Basin

Period	Formation name	Lithology description	Depositional environment	Hydrogeological characteristics
Pliocene to Quaternary	Coonarbine Formation	Dunal sand	Aeolian and alluvial	Aquifer (?)
	Eurinilla Formation	Basal conglomerate; channel sand, gypsiferous clay	Fluvial and fluvio-lacustrine	Aquifer (?)
	Millyera Formation	Clay, thin algal limestone and fine-grained sand	Lacustrine to floodplain	Confining layer
	Willawortina Formation	Sandy mud; silty dolomite, gravel of braided flow origin and matrix-supported clayey gravels	Lacustrine to floodplain and debris flows	Unknown
Mid-Oligocene to Pliocene	Cadelga Limestone	Dolomitic cherty limestone	Lacustrine	Unknown
	Doonbara Formation	Clastics, commonly silicified or ferruginised. Quartzose sandstone and granule conglomerate with maghemite pisolites	Alluvial and colluvial	Unknown
	Namba Formation	Fine to medium-grained, poorly sorted, sand, silt, oolitic dolomite interbeds	Shallow, brackish to fresh water lakes	Leaky aquitard / partial aquifer (variation between subformational units)
	Etadunna Formation	Dolomite and limestone with magnesium-rich claystone and fine-grained sand	Fluvio-lacustrine	Unknown
	Cordillo Silcrete	Silica-indurated sandstone and some conglomerate, chalcedony and opaline rocks	Regolith processes overprinting Eyre Formation	Unknown
Late-Palaeocene to mid-Eocene	Eyre Formation	Quartzose sandstone, minor pebbly sandstone and conglomerate, silcrete	Fluvial and locally lacustrine	Aquifer
	Mount Sarah Sandstone	Sandstone, clastics, commonly silicified or ferruginised	Alluvial and colluvial	Aquifer

Source: GA (2015)

2.2.6 Regolith geology, soils and surface environment

The investigation area is predominantly composed of depositional landforms, with erosional and residual landforms only present near the North Flinders Ranges (Krapf et al. 2012). Three major landforms and associated soil types can be interpreted within the investigation area. The first includes the dune fields of the Strzelecki Desert that cover extensive areas to the north of Lake Blanche and the east of Lake Callabonna. In these regions, siliceous sand and sandy soils predominate on the surface, but may cover other soils of notable variability, including grey floodplain clay and loam. These deeper soil profiles may be exposed in interdunal areas. Sand dunes and ridges can be very long, in some cases up to 250 km, and are mobile to some extent. Vegetation is sparse, and varies from dunes dominated by *Acacia ligulata* (sandhill wattle) in the north of the study area to sand flats dominated by *Nitraria billardierei* (nitre bush) just to the north of Lake Blanche (DEH 2009a).

The second major landform includes the stony tablelands and downs associated with areas of outcropping crystalline basement and Bulldog Shale that occur near and to the north of the North Flinders Ranges (Krapf et al. 2012; MSCB 2004). MSCB (2004) describes the landscape as usually gently rolling with soils largely composed of light clays, loams and red earths, with and without gibbers and clay gilgais. Vegetation in the gibber consists of an overstorey of occasional, sparse *Acacia aneura* (mulga), and an understorey of sparse *Atriplex* saltbush and *Maireana* bluebush, very sparse *Sclerolaena* spp. and ephemeral grasses. Gilgais have a similar vegetation composition, but without *A. aneura*, and tend to be more densely vegetated, especially after rains (DEH 2009b).

A third landform within the investigation area includes the lacustrine and playa lake landforms and sediments that occur extensively near Lake Blanche and Lake Callabonna, as well as in a number of small, isolated places (Krapf et al. 2012) (Figure 2–4). Soils in these lake areas are typically composed of saline clays and silts that are usually highly gypsiferous. Vegetation can absent or quite sparse, including ephemeral grass cover and occasionally moderate densities of samphire.

Other landform, soil and regolith types of importance are the floodplains, channel and outwash areas between the North Flinders Ranges and Lake Blanche. In this area, soils may be heavy, composed of alluvium, red earths or solonised brown soils. Vegetation in these area includes overstorey ranging from *Acacia salicinia* (cooba), *Eucalyptus coolabah* subsp. *arida* (coolibah) to *E. camaldulensis* var. *obtusa* (northern red gum) as water quality improves in quality and frequency. Understorey includes *N. billardierei* and *Duma florulenta* (lignum) (DEH 2009b).

Finally, the southern margin of the investigation area is dominated by arid ranges, which consist of very hilly country with steep slopes, exposed rock and skeletal soil formed predominantly from weathered bedrock.

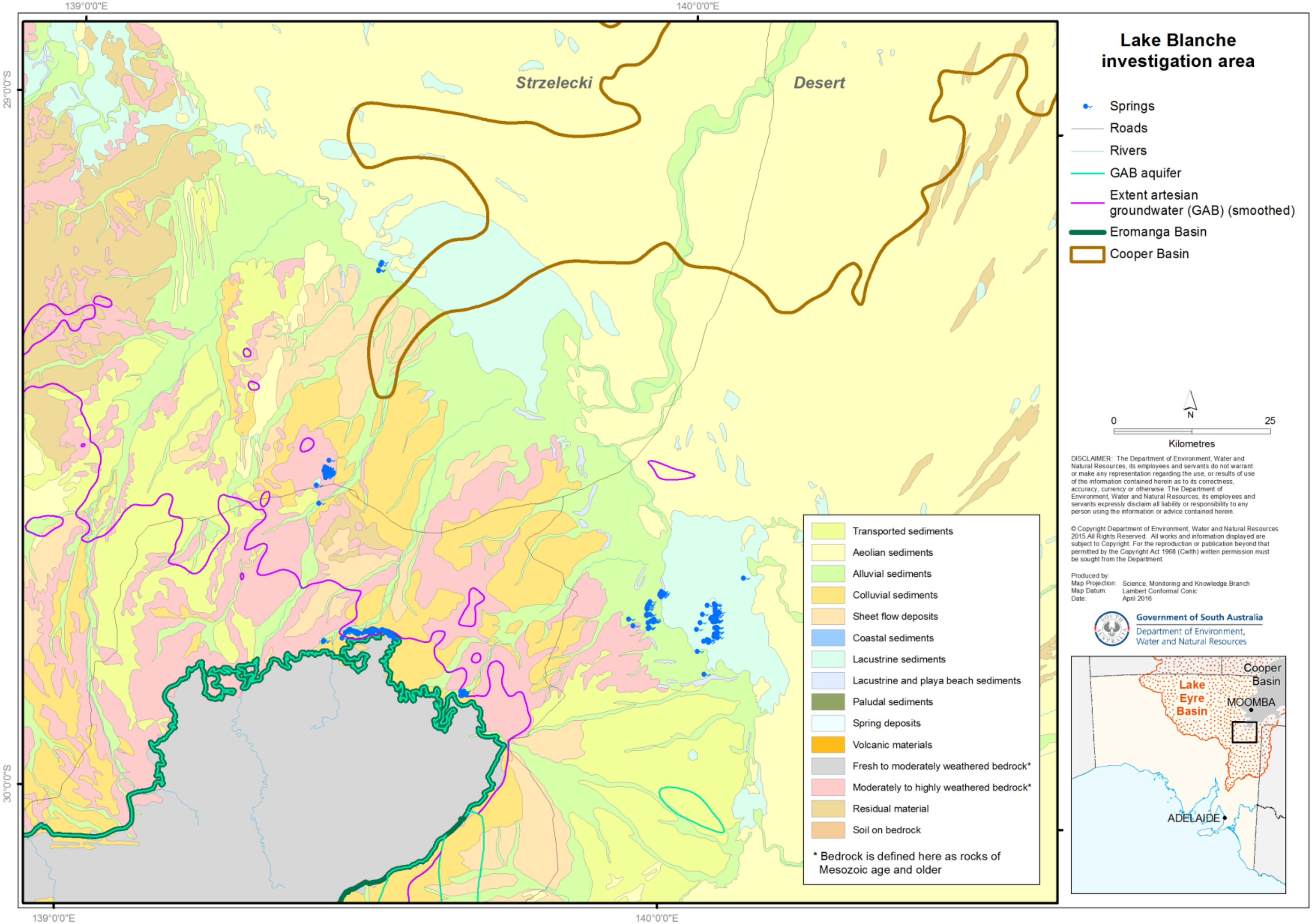


Figure 2-5: Regolith geology of the investigation area

2.2.7 Coal and hydrocarbon deposits

The Cooper Basin contains extensive and economically important petroleum resources, and is the largest known inland hydrocarbon resource in Australia. The basin contains approximately 190 productive gas fields and 115 productive oil fields. These fields are currently being exploited via approximately 820 gas-production wells and more than 400 oil-production wells that feed two production facilities at Moomba, South Australia, and Ballera, Queensland (Santos 2015).

The majority of oil and gas production from the Cooper Basin has been from conventional oil and gas targets. Unconventional oil and gas plays in the Cooper Basin include shale gas, tight gas, basin-centred gas systems and CSG. Potential targets for CSG include deep coal seams in the Gidgealpa Group and shallow coal seams in the overlying Eromanga Basin. Deep CSG targets in the Patchawarra Formation have been identified, hosted in thick, laterally extensive coal seams. DMITRE (2012) states that the base of the Patchawarra Formation is sufficiently mature for gas to be generated from coal seams over much of the Cooper Basin. Additionally, coal seams contain significant meso-porosity that counteracts cleat closure and permeability reduction because of burial depth in the range of 2000 m, which is normally considered detrimental to CSG production (DMITRE 2012).

Strike Energy is actively exploring for CSG in the Weena Trough in the northern part of the study area. Here, net coal beds in the Patchawarra Formation can reach more than 100 m in thickness, with one coal seam 35 m thick. Sustained gas flows to the surface were achieved after a series of flow tests using both fracture stimulation (i.e. fracking) and non-stimulation completions (Strike Energy 2015). Additionally, although Beach Energy is not actively exploring for CSG, it is actively exploring for other forms of unconventional gas that involve fracking activities, such as shale gas and basin-centred gas systems. Beach Energy’s unconventional gas exploration and development activities in South Australia are largely centred on a tenement located approximately 20 km north-west of Moomba (Beach Energy 2016; RPS-Aquaterra 2012).

2.3 Hydrogeology

2.3.1 Crystalline basement

Crystalline metasediment and igneous units of the Proterozoic and Archean basement sequences primarily outcrop in the North Flinders Ranges within the investigation area. A fractured rock aquifer is interpreted to occur within crystalline Precambrian basement rocks. Groundwater is recharged either by direct infiltration of rainwater or via drainage channels. Groundwater yields within fractured rock aquifers are 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. Groundwater from crystalline basement fractured rock aquifers in the North Flinders Ranges, based on historical and current water quality results, is typically fresh to brackish, being between 1,000 mg/L and 6,000 mg/L total dissolved solids. Wohling et al. (2013) 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 near the Peake and Denison Inlier, located approximately 380 km west of the investigation area (Figure 1–1).

2.3.2 Cooper Basin

Sedimentary rocks in the Cooper Basin are not typically exploited for groundwater resources and therefore knowledge of this basin as a hydrogeological entity is limited. Available knowledge about the groundwater in the Cooper Basin comes from work during the exploration for, and development of, energy resources. Youngs (1971) studied groundwater within the Gidgealpa Group in some detail as a means of identifying the potential for hydrocarbon productivity. Findings included a marked difference in salinities between areas, with areas of low salinity interpreted as being at least partially flushed with groundwater from the overlying GAB. This was particularly evident in the southern half where the lack of a Triassic cap rock has allowed interconnectivity between the GAB and underlying aquifers. Salinities ranged between 2,000 and 15,000 mg/L and generally increased with depth towards the centre of the basin. Youngs (1971) observed, on the basis of very limited pressure data, that the Upper Gidgealpa Member of the western central Cooper Basin had a very undulating potentiometric surface – a feature thought to be caused by considerable infiltration of groundwater via connectivity with other aquifers. Conversely, the potentiometric surface of the Lower Middle Gidgealpa Member had a general flow to the south-west. Following on from this initial work, Dubsky and McPhail (2001) compiled groundwater pressure and salinity data in the central western portion of the Cooper Basin for the Toolache–Daralingi, Epsilon, Patchawarra, and Tirrawarra–Merrimelia Pre-Permian formations and formation groupings. Groundwater salinities for Cooper Basin groundwater samples varied from 2,500 mg/L to 20,000 mg/L, and displayed a general tendency of increasing with depth. Groundwater flow for most of these formations and formation groupings was radial, flowing away from the Nappamerri Trough, located near the centre of the basin. Dubsky and Macphail's (2001) study also supported Youngs (1971) in finding evidence for groundwater connectivity between aquifers in the Eromanga and Cooper basins, particularly over the southern portion of the Cooper Basin.

Similarly, Altmann and Gordon (2004) discussed the interaction between groundwater from the GAB and connate groundwater from the Patchawarra Formation. Intermixing of these groundwaters was interpreted to lead to a decrease in salinity within Patchawarra Formation groundwaters, which are typically around 14,000 mg/L.

2.3.3 Great Artesian Basin

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

The GAB is one of the largest groundwater basins in the world, underlying approximately 1.7 million km^2, or 22% of the Australian continent (Audibert 1976; 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, and civil and cultural communities in Australia (Ah Chee 2002; Leek 2002).

Near the investigation area, the aquifer units of primary importance are the Algebuckina Sandstone, the Cadna-owie Formation and lateral equivalents (collectively referred to as the J-K aquifer in South Australia), because they form the major aquifer in this part of the basin. The most important confining layers include the Bulldog Shale, the Oodnadatta Formation and lateral equivalents within the Rolling Downs Group. In the study area, yields higher than 20 L/sec. were estimated from New Toonketchen Bore (Figure 2-6). Groundwater flow in the J-K aquifer within the investigation area is interpreted to flow away from areas of higher elevation near the margins of the basin, as well as from areas further to the east and north (Figure 2-6).

In addition to the J-K aquifer, confined, subartesian and artesian groundwater is found in a number of other units, including the Coorikiana Sandstone, the Winton Formation and the Mackunda Formation (Habermehl 1980), as well as minor groundwater occurrences within the predominantly aquitard sequences of the Bulldog Shale in the wider basin (Smith 1976). Historically, groundwater extraction from the Winton and Mackunda formations is known from the central portions of the GAB, although water quality is generally of poor quality (Habermehl 1980). A review of drilling logs and hydrogeological data for the Coorikiana Sandstone (?) aquifer during this investigation indicates that the aquifer is potentially important within the investigation area (Figure 2-7). Reported yields from this aquifer within the investigation area vary from 0.36 to 10 L/sec., and salinity is typically above 8,000 mg/L. Although there are very few points from which to make an assessment, groundwater appears to flow from areas of high elevation near the North Flinders Ranges to areas further north. Further discussion of the Coorikiana Sandstone (?) aquifer is in Section 5.1.

2.3.4 Cenozoic

The most recent phases of sedimentation may provide local 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. A number of stock bores using groundwater from the Cenozoic aquifers are in the investigation area (Figure 2-7). Shepherd (1978) reported salinities to vary from 1,000 mg/L to more than 100,000 mg/L, while inferred transmissivities were 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 of approximately 8,000 mg/L, with yields from 5 to 12.6 L/sec. Within the investigation area, salinities have been recorded between 4,810 mg/L (New Lignum Bore) and 7,020 mg/L (Happy Thoughts Bore). Groundwater elevations in Cenozoic aquifers are highly variable; however, a rough flow from areas of higher elevation near the North Flinders Ranges towards the north and east can be determined (Figure 2-7). Cenozoic aquifers are important to spring and other groundwater-dependent ecosystems (see Section 5).

2.3.5 Comparison of head data

A comparison of water levels from the J-K aquifer, the Coorikiana Sandstone (?) aquifer and the Cenozoic aquifers indicates that groundwater throughout the majority of the investigation area generally has an upward pressure gradient. Head data from wells completed in the J-K aquifer are generally higher than both the Coorikiana Sandstone and Cenozoic aquifers, whereas groundwater from the Cenozoic aquifers generally appears to have the lowest pressure head (Figure 2-7). Groundwater in the Coorikiana Sandstone aquifer in generally lower than in the J-K aquifer, but higher than groundwater in the Cenozoic aquifers; however, there are only four data points in the investigation area. In general, groundwater from these three aquifers appears to be flowing from the margins of the North Flinders Ranges towards Lake Blanche and Lake Callabonna to the north and east. The uncorrected potentiometric surface for the J-K aquifer also indicates that groundwater flows south towards Lake Frome and the Frome embayment (Figure 2-6).

2.3.6 Springs

The springs in the study area are part of the Lake Frome Supergroup. In this area, there are 5 spring complexes containing 16 spring groups (Figure 2–1). Mulligan Springs, which is part of the Lake Callabonna complex, consists of a cluster of three spring groups on the western edge of Lake Callabonna, and is treated as a separate entity in this study because of significant variation in water chemistry and its isolation. The spatial hierarchy of springs is explained in detail in Gotch et al. (2016). Most of the springs in the Lake Frome Supergroup have low diversity of endemic crustaceans and molluscs relative to the Lake Eyre and Dalhousie supergroups. Floristically, the springs are superficially similar to springs within the Lake Eyre Supergroup; however, *Phragmites australis* (common reed) is less dominant. Several plant species found in these springs are not common or not found in other South Australian spring supergroups, including *Fimbristylis ferruginea* (fringe rush) and *Wilsonia backhousei* (narrow-leaf wilsonia). Most of the springs are low-flow springs and, as will be discussed in Section 5, a number may source some or all of their water from sources other than the J-K aquifer. Carbonate mounds and terraces are rare in the springs in this area.

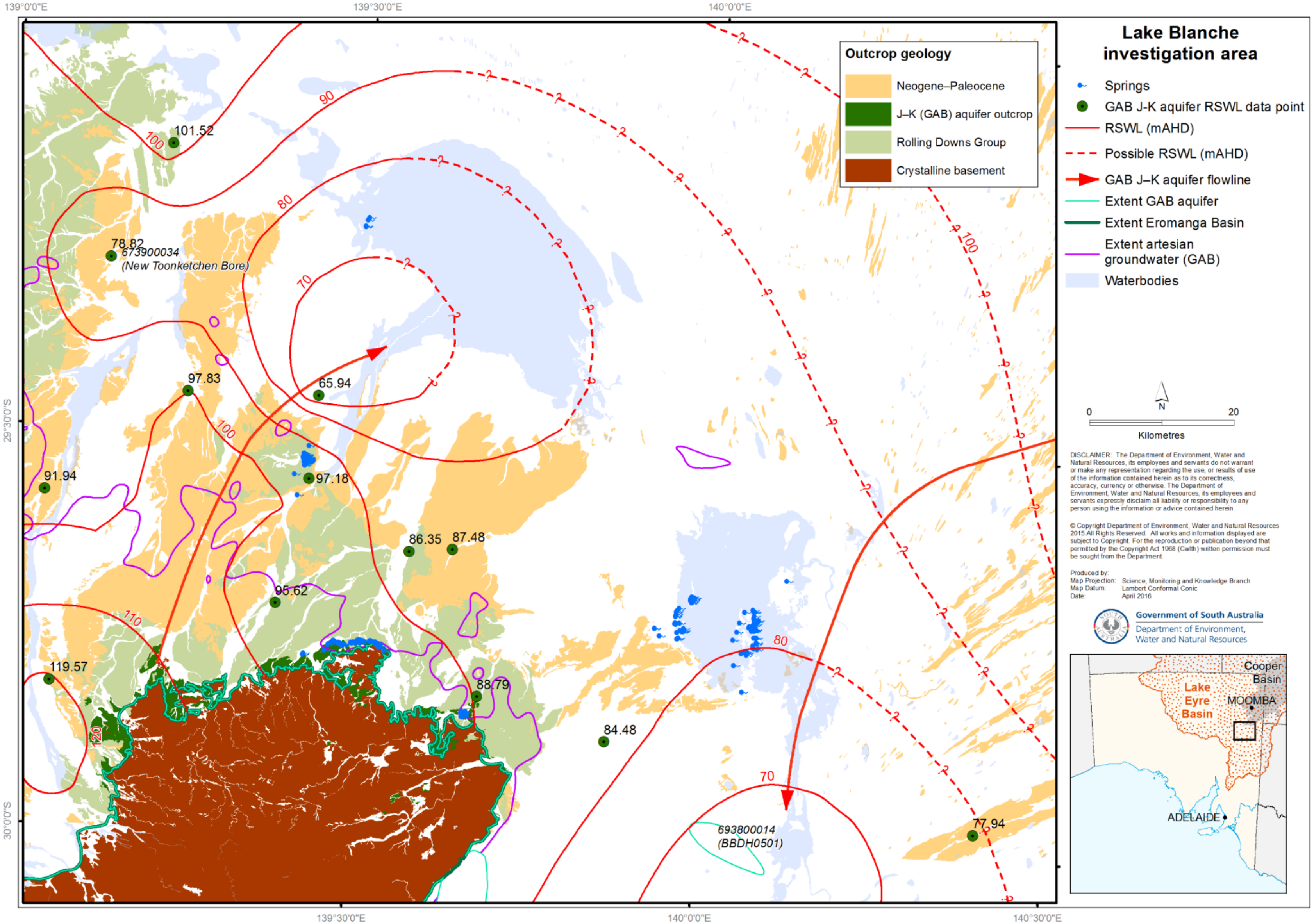


Figure 2-6: Hydrogeology of the investigation area – J-K aquifer relative standing water level (RSWL) contours

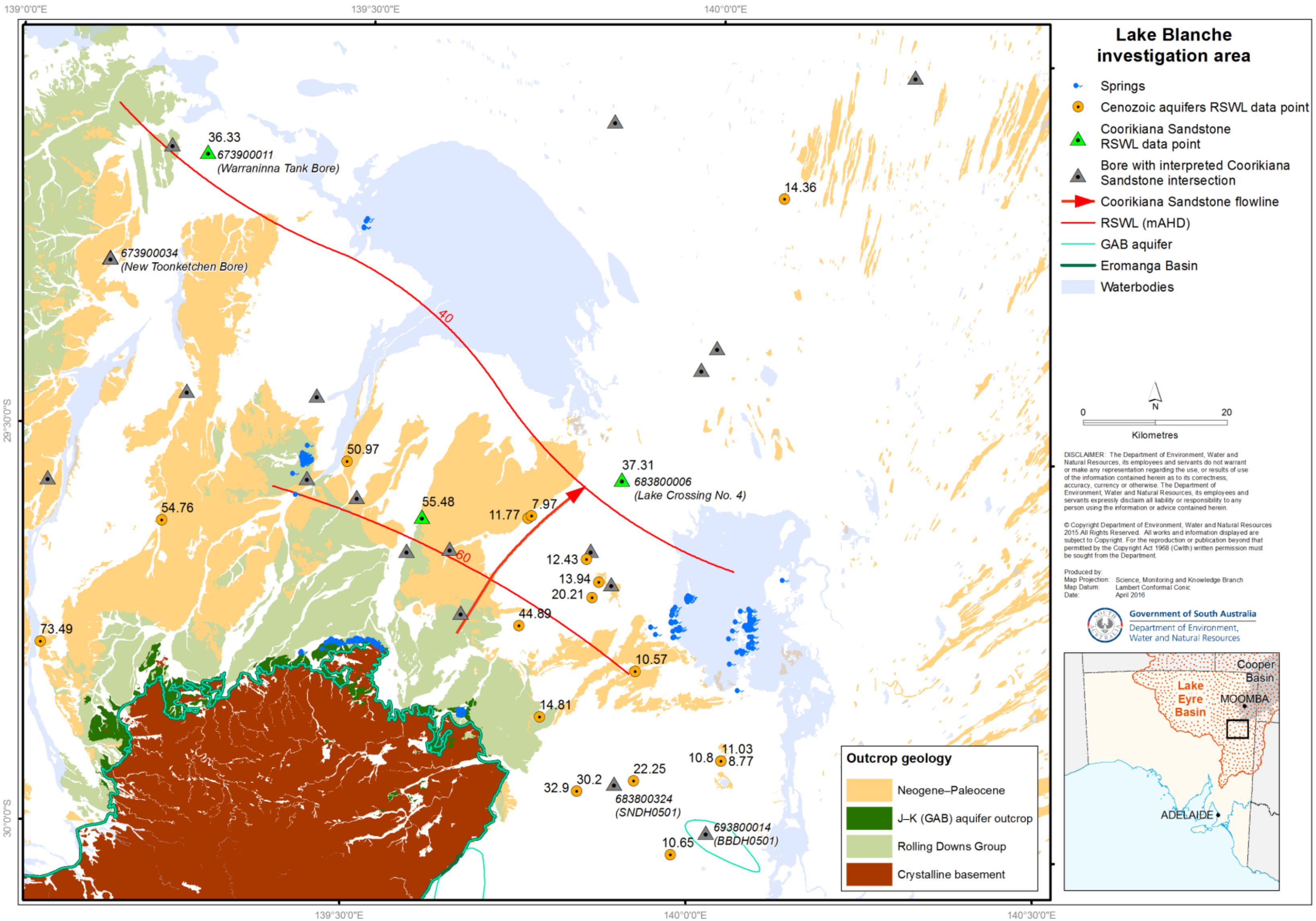


Figure 2-7: Hydrogeology of the investigation area – Coorikiana Sandstone (?) relative standing water level (RSWL) contours and Cenozoic aquifers

3 Methodology

3.1 Geological architecture

The location of springs was considered with respect to a number of structure surfaces and isopachs developed for major stratigraphic horizons rocks in the region (Jensen-Schmidt 1997; Sampson and Jensen-Schmidt 2013) to determine whether a spatial relationship between spring location and regional structure exists.

The interpreted basin architecture was based on isopachs and surface elevations developed for the J-K aquifer units (Great Artesian Basin), determination of the top of Permian and top of basement using archival seismic and borehole data, and spatial coverage of 1:100,000-mapped surface geology. The geoscientific mapping, modelling and data management software Petrosys dbMap® was used to determine the basin architecture. Data were obtained from publicly available reports and data files accessed through the SARIG online database, and from the SA Geodata database. Once the top of basement (Base Permian) and the formation elevation thicknesses described by each isopach were resolved against borehole data, three-dimensional subsurface datasets were developed to describe the top and extent of each formation, as well as the base of the Permian sequence. Basement for this study are all rocks older than the Permo-Carboniferous of the Cooper Basin.

Spring locations were compared, based on the occurrence and magnitude of structures identified in the developed cross-sections. In particular, the occurrence and position of regional-scale fault structures, identified using available seismic data and the thickness of confining layers near springs, were of interest for identifying the possible reasons for spring formation at a given location.

3.2 Hydrochemistry and environmental isotopes

Hydrochemistry data from 14 springs and 17 wells were collected between 5 and 11 June 2015, and 25 and 28 August 2015. A description of the sampled springs and wells is provided in Appendix A, and locations are presented in Figure 3–1. Results from laboratory analysis are provided in Appendices B–E.

Wells were sufficiently purged before sampling. Ideally, at least three well volumes were removed; if this was not possible, sufficient water volume was removed to achieve stable water quality. Before sampling, regular measurements were taken for pH, electrical conductivity, dissolved oxygen, redox potential and temperature using a YSI© multiparameter meter, to ensure that water quality was stable. At the time of sampling, final field measurements for these parameters, as well as for alkalinity (as $CaCO_3$, using a Hach© titration kit) were taken. One sample per analysis was collected from each sampling site. The details of sampling, field preparation and laboratory techniques for each chemical and isotopic species are summarised in Table 3-1.

Analytes measured during this investigation include:

- the major ions chloride (Cl^-), sulfate (SO_4^{2-}), sodium (Na^+), potassium (K^+), calcium (Ca^{2+}), magnesium (Mg^{2+}) and carbonate ($CaCO_3$), measured as alkalinity. Nitrate (NO_3^{2-}), fluoride (F^-), bromine (Br^-), silica (Si^{4+}) and strontium (Sr^{2+}) were also analysed
- the ratios of stable isotopes deuterium (δ^2H), oxygen-18 ($\delta^{18}O$) and strontium ($^{87}Sr/^{86}Sr$)
- the radioisotopes radiocarbon or percent modern carbon (pMC), and chlorine-36 ($^{36}Cl/Cl^-$).

3.2.1 Data analysis

3.2.1.1 Major ion data

Major ion hydrochemistry sampling was primarily designed to fill gaps in the coverage of the region to enable a more complete hydrochemical characterisation of groundwater from wells and springs. Scatter plots and Piper diagrams were used to determine broad hydrochemical characteristics of the groundwater and interpret important hydrochemical processes.

3.2.1.2 *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. Results were rejected if charge balances for major ions were ±5% or greater. Previous data were extracted from Radke et al. (2000), Crossey et al. (2013) or the South Australian Government–maintained online database SA Geodata, which provides a compilation of geological, hydrogeological and hydrochemical data from multiple government and nongovernment sources.

3.2.1.3 *Stable isotopes of water*

The ratios of stable isotopes hydrogen (δ^2H) and oxygen-18 ($\delta^{18}O$) were compared with 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. The LMWL is derived from precipitation collected from a single site or set of 'local' sites (USGS 2004). Groundwater that has evaporated or mixed with evaporated water typically plots below the LMWL, along lines that intersect the LMWL at the location of the original unevaporated composition of the water (Craig 1961; USGS 2004).

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).

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, 45 µm 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, 45 µm	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	125	Filtered, 45 µm	Adelaide Research and Innovation, University of Adelaide	Finnegan Mat 262 thermal ionisation mass spectrometer
Radiocarbon	HDPE bottle	250	Unfiltered	Rafter Scientific, New Zealand	Accelerator mass spectrometry (AMS)
Chlorine-36	HDPE bottle	250	Unfiltered	Australian National University	Accelerator mass spectrometry (AMS)
Archive	HDPE bottle	1,000	Filtered, 45 µm		

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

Shand et al. (2009) states that strontium is a divalent ion that shows similar geochemical characteristics to calcium (Ca), while noting that the isotopic abundance in rocks may vary due to the formation of ^{87}Sr by the decay of naturally occurring rubidium-87 (^{87}Rb). Consequently, the mineralogy and age (to allow for the decay of ^{87}Rb) of rocks in an aquifer are important controls on the variation of ^{87}Sr and ^{86}Sr. By extension, Shand et al. (2009) and Aberg et al. (1989) described differences in the variations in the ratio of ^{87}Sr to ^{86}Sr in groundwater as a sum of atmospheric inputs, mineralogy along the flow path, mineral dissolution, ion exchange characteristics and residence time, and therefore make the ratio of ^{87}Sr to ^{86}Sr useful for the study of groundwater mixing or exchange between different sources. 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, is to plot ^{87}Sr and ^{86}Sr data against the reciprocal of Sr^{2+} (Shand et al. 2009). Such a method allows end-member groundwaters to be identified, mixing trends as well as the influence of mineral precipitation or evaporation.

3.2.1.5 Radioisotopes (carbon-14 and chlorine-36)

The radioisotopes carbon-14 (radiocarbon) and chlorine-36 ($^{36}Cl/Cl$) were analysed to estimate the age of the groundwater. These radioisotopes will decay at a predictable rate into more stable isotopic forms, and the rate of decay can be used to estimate the age of groundwater as long as the initial value of the radioisotope in groundwater (the value at the point of recharge) can be reasonably estimated.

As well as the basic mathematical methods used to calculate an age, methods are available to correct results for other influences – such as water–rock interaction and paleo-environmental influences – on the radioisotopic value of a given sample beyond the initial input value and the decay rate (for comprehensive reviews on the subject, refer to Phillips 2013; Plummer and Glynn 2013). However, for this report, no age determination or correction calculations have been applied to the radioisotopic results to calculate an age. Instead, the raw pMC and $^{36}Cl/Cl$ results are used to provide a relative indication of age differences between samples and to identify possible mixing. By only analysing raw results, hydrochemical processes that would be reasonably interpreted to effect such values have not been accounted for and thus provide a potential source of error. However, without knowing for certain the hydrochemical history of the groundwater from such a complex system, there is a risk that correction may be introducing further error. For example, previous pMC and $^{36}Cl/Cl$ results from groundwater collected from the south-eastern margin of the Arckaringa Basin presented by Keppel et al. (2015a) indicated that apparent groundwater age using corrected $^{36}Cl/Cl$ results were much older than equivalent results provided by pMC. It has been recognised that sampling of groundwater across large sections of an aquifer may provide water samples with varying origins and recharge history while dispersion and mixing in heterogeneous aquifers can lead to a large distribution of apparent groundwater age, even from wells screened across short intervals (Weismann et al., 2002; Jurgens et al., 2012). Furthermore, with respect to pMC, Aggarwal et al. (2014) argues that age determination for results ≤5 ‰ is too difficult to undertake with any certainty. Consequently, without sufficient knowledge concerning the hydrochemical history of this region, a conservative approach of using uncorrected pMC and $^{36}Cl/Cl$ data was employed. Further work could involve evaluating the groundwater age distributions from the environmental tracer data using lumped parameter models (LPMs). LPMs provide a mathematical evaluation of transport based on simplified aquifer geometry and flow configurations taking into account hydrodynamic dispersion and mixing (Jurgens et al., 2012).

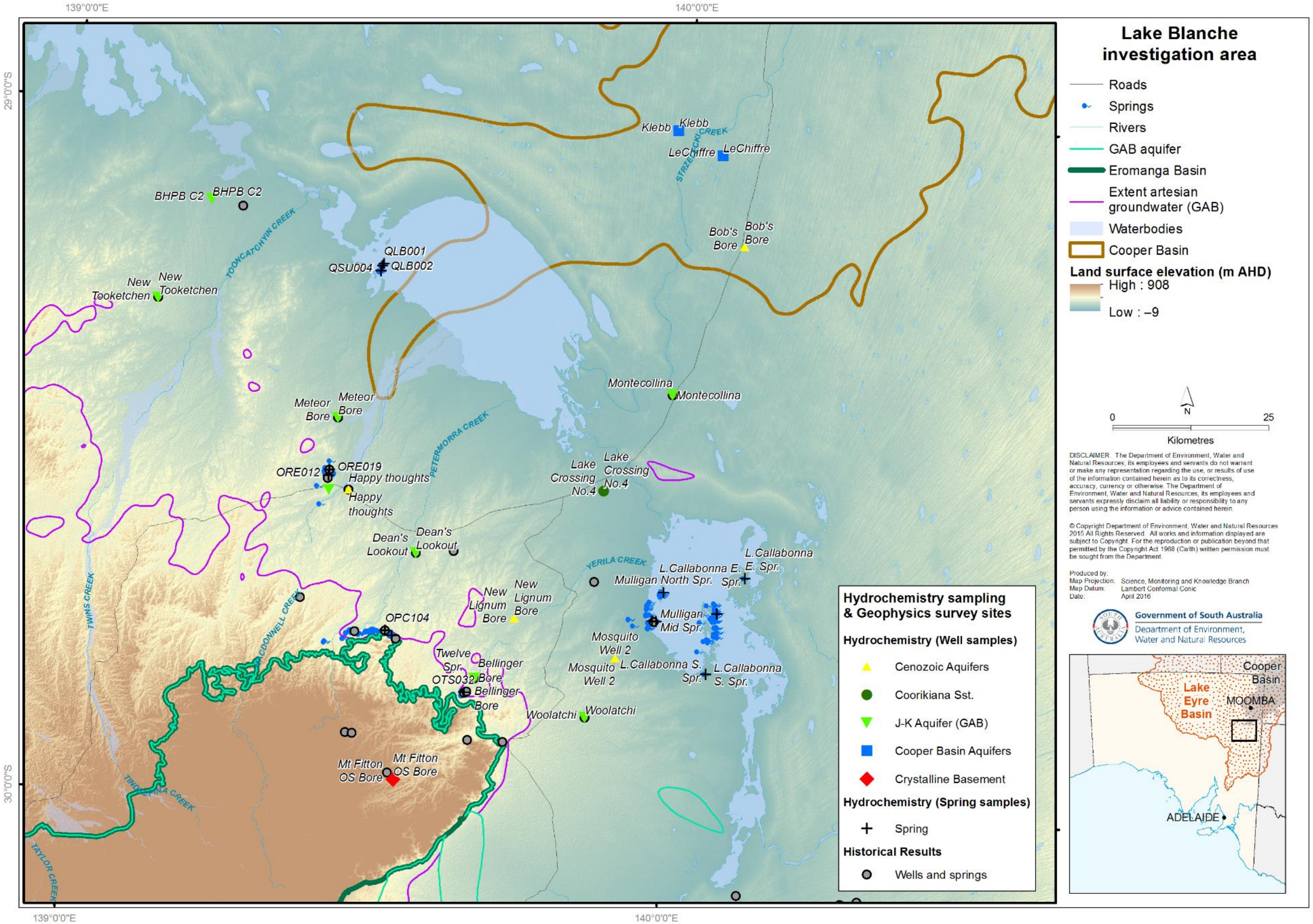


Figure 3-1: Hydrochemistry sampling sites

3.3 Geophysics

Two spring vent sites were chosen for ground-based geophysical surveys: Reedy Springs (ORE) and Lake Blanche Spring (QLB001) (Figure 3-2). These sites were chosen because they provided good variation in the near-surface geology, were sites that did not have any existing geophysics information, are proximal to the Cooper Basin and were reasonably accessible.

The techniques used were self-potential (SP), time-domain electromagnetic surveying (e.g. NanoTEM) and natural-source audio-magnetotellurics (AMT).

3.3.1 Self-potential

Surface SP surveys measure the amplitude and spatial distribution of static electrical potentials in the earth. Such potentials are affected by the flow of water (the electrokinetic effect) and the groundwater chemistry (Revil et al. 2012). The technique has been used for many years to delineate electrically conductive sulfide and graphite mineralisation (Corry 1985). The electrokinetic effect is caused by the flow of fluid through a porous medium. Because electrical double layer forms on mineral grain surfaces, the flow of water carries a net electrical charge, which constitutes an advective electrical current. The magnitude and polarity of the current is determined by the streaming current coupling coefficient, which depends on a variety of petrophysical and fluid properties, including the salinity, temperature and pH of the pore fluid. For most common earth materials, the current coupling coefficient is negative and generally in the range -10^{-6} to -10^{-7} V/Pa; certain types of clay minerals can modify the value slightly. Calcite and volcanic rocks can affect the coefficient more significantly, causing it to become positive (and therefore reverse the sign of the current). These rocks were not encountered, so the coupling coefficient is assumed to remain negative. Because of the uncertainties in these variables, only a qualitative interpretation of the SP is attempted here.

Measured anomalies in the SP (voltage) can be caused by sources or sinks of fluid flow underground, parallel gradients in coupling coefficient and hydraulic pressure, or gradients in hydraulic conductivity (Hamman et al. 1997). In these areas, because the coupling coefficient is assumed to be negative and constant (Jouniaux et al. 2009), the primary interpretation is that where there is an source of flow underground, there is an associated increase in voltage in the same direction, and vice versa for sinks of flow. For example, a spring with water flowing vertically upwards underneath the vent will result in a symmetric peak in voltage measured over the vent. Lateral flow of water underground will result in a steady increase in voltage in the direction of flow.

The SP surveys used two Pb-$PbCl_2$ surface electrodes to measure the voltage field caused by underground currents at the surface (Corry et al. 1983). One electrode was stationary and the other was moved along the survey line to sample the voltage at 10-m station intervals. At Reedy Springs, one 300-m survey line was collected using variable station intervals (1 m to 10 m), while at Lake Blanche Springs, two 200-m survey lines were collected using a 10-m to 20-m station interval. In each case, while the roving electrode returned to the base, one or two repeat measurements were made to validate the data. In all cases the repeat measurements closely corresponded to the original data point, confirming the validity of the measurements.

The depth of investigation of the technique depends on the survey geometry (i.e. the length of the survey line). For example, flow at a depth of 50 m will result in signals in the SP survey along the ground surface with a half-wavelength of approximately 100 m. Therefore, the surveys in this study contain information pertinent to a depth of 100–150 m.

3.3.2 Time-domain electromagnetic induction

Time-domain electromagnetic induction techniques use an artificial electromagnetic (EM) signal to induce electrical currents in the subsurface and measure the ground's resistivity. The primary EM field diffuses and dissipates into the ground and induces a faint secondary field in a receiving loop. In the time-domain surveying technique used here, the secondary field is sampled and recorded digitally and the field's decay is recorded as a function of time. The rate of decay is related to the ground's electrical resistivity (McNeill 1980; Nabighian and Macnae 1991). In this work, a 20-m square central in-loop configuration was used, resulting in a site being measured every 20 m along a profile, and at a depth of approximately 40 m below the ground surface.

For interpretation, the decay curve was used to model the ground's resistivity as it varies with depth, using the AarhusInv modelling/inversion package (AarhusInv 2015). These models were then placed alongside each other to show a cross-section of the ground's resistivity along the surveyed profile. Variations in resistivity within the model can be due to:

- changes in fluid properties (e.g. more saline fluids are more conductive)
- changes in fluid content (e.g. porosity and saturation – fluids are generally more conductive than minerals, and air is highly resistive)
- changes in lithology.

Although these effects can be modelled with empirical methods such as Archie's Law, this approach requires laboratory analysis of field samples to determine parameters suitable for the field site and to validate the modelling results. This work uses qualitative interpretation of the resistivity models in terms of likely changes in salinity, porosity/saturation and lithology, and discusses the effect each of these may have on the interpretation

3.3.3 Natural-source audio-magnetotellurics

This technique uses naturally occurring global EM fields caused by lightning strikes and solar activity that diffuse into Earth's upper crust to determine the resistivity in the top 3 km of the crust (Chave and Jones 2012). The inducing field is measured using two induction coil magnetometers laid on the ground surface, while the induced potential in the earth is measured with two 15-m-long electrical dipoles with Pb–$PbCl_2$ electrodes installed in the ground. The equipment recorded data for several hours to ensure reasonable data quality. An estimate was then made of the strength of the fields at different frequencies, using a robust statistical technique (Chave and Thomson 2004).

The electric and magnetic fields were measured in a north–south and an east–west orientation. The ratio of the orthogonal measurement was then interpreted in terms of the apparent resistivity of the ground, while the relationship of the two modes of induction (e.g. the phase tensor of Caldwell et al. 2004) was also used to determine the dimensionality of the electrical structure of the ground, which relates to how the resistivity varies – for example, does it vary only with depth, as in a horizontally layered stratigraphy (1D), are there flat layers that are folded or tilted with a particular strike direction (2D), or does it vary in a more complicated way (3D). The phase tensor can also provide information on structural anisotropy, which may be caused by deformation or fault zones.

Because the way in which EM energy diffuses into the subsurface, it is not straightforward to assign a depth to an estimate of resistivity from the measured fields without using resistivity inversions. We have estimated the depth of penetration using the common Bostick–Niblett method (Chave and Thomson 2004).

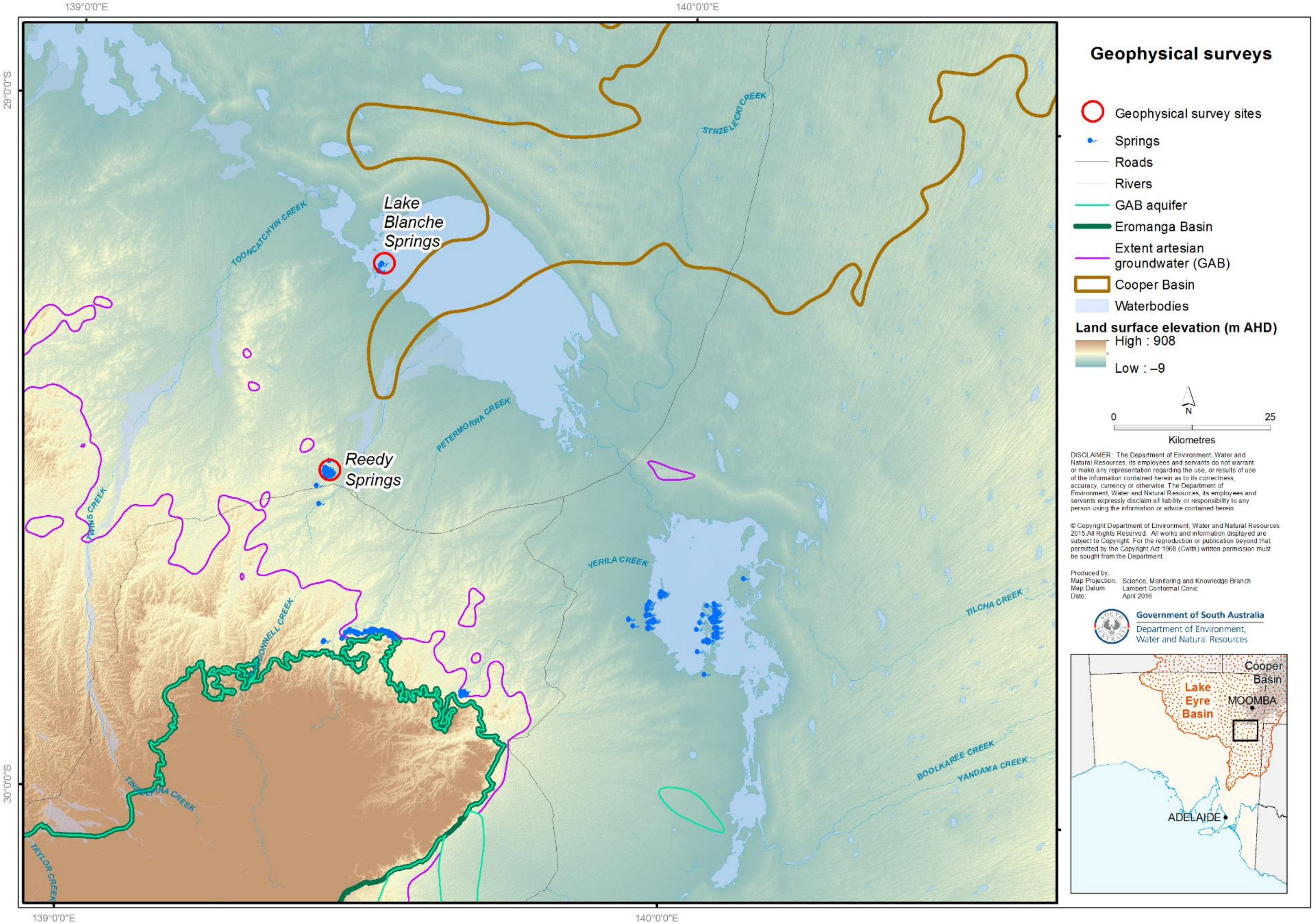


Figure 3-2: Geophysical survey sites

3.4 Ecological assessment

Collected data for the springs can be broadly defined into four categories: spatial, morphological, biological and hydrogeological. The methodology used in this assessment follows that used by Gotch et al. (2016), except where specified. Data sheet templates are included in Appendix G of Gotch et al. (2016).

3.4.1 Spatial

Spring vent locations for Lake Blanche, Reedy, Petermorra and Twelve springs complexes were originally surveyed in 2004 by Gotch and in 2005 by WMC Pty Ltd. New spring locations and other spatial data required for the geophysics work was surveyed using a Trimble® R8 real-time kinematic differential GPS (RTK dGPS), using the methods described in Gotch (2013). RTK dGPS spring vent locations and elevations were not surveyed for Mulligan and Lake Callabonna springs; temporary positions were collected using a handheld Garmin® eTrex, and RTK dGPS positions will be surveyed at a later date. Other site-specific field data were recorded using a handheld Garmin® E-Trex GPS. Photographs were taken with handheld digital cameras.

The dGPS survey data were post-processed using a control point network created by Gotch (2013), which is based on static observations derived from zero-order horizontal and third-order vertical survey benchmarks supplied by the Office of the Surveyor General of South Australia.

Data collected during the field program were entered into various corporate databases (hydrological, hydrochemical and geomorphological data predominantly into SA Geodata, and biological data and photographs into the Biological Databases of South Australia). The data will be made available to the Australian and Queensland governments, and to the public, except if the site is culturally or ecologically sensitive

3.4.2 Morphological

The general geomorphological setting – including overall land form and land system, topography, connectivity to surface water drainage systems, and context in the broader landscape – was recorded. Individual springs were described by mound shape, size (length, width and height, where relevant), ascribed a type based on the identification of key characterising features collected in a detailed site description, and examined for surface expression of water (Fatchen and Fatchen 1993; Gotch 2013). The presence of sulfur crystals were noted, together with a description of the size and location of the sulfation zone. Disturbance factors were noted, including grazing, pugging (trampling of wet clayey soils by cattle; Fatchen and Fatchen 1993) and excavation (e.g. bore casings, fencing, tracks) (Gotch 2013), using the categories on the data sheet (Gotch et al. 2016). Photographs of each vent were collected and are to be stored in SA Geodata.

3.4.3 Biological

The presence of spring flora and fauna was recorded at each spring vent and grouped up to the spring complex level. Plants were distinguished as native or introduced species, and estimates were taken of cover and abundance (Fatchen and Fatchen 1993). Presence or inferred presence (e.g. through the observation of indirect evidence such as tracks, scats and other traces) was recorded for all native and introduced animal species. Species presence for flora and fauna was measured by taking continuous observations down the wetland of the spring (of various lengths, depending on spring size) – from the vent to the end of the spring tail. Fauna groups recorded included birds, fish, crustaceans, molluscs, arachnids, insects and microbial mats (oncoids, stromatolites and thrombolites).

Voucher specimens of several faunal groups likely to be short-range endemic species, including hydrobiid snails, isopods, amphipods and ostracods, were collected for future DNA analysis (beyond the scope of this study). Voucher specimens of any other unusual flora or fauna species were also collected.

Species were classified for their significance to the system – that is, either endemic spring biota, locally rare species or species that are disjunct from their normal habitat. Examples of the latter include *Gahnia trifida* (cutting grass) and *Baumea juncea* (bare twig-rush), which are common in coastal areas or in southern swamp and wetlands but are typically absent in the arid zone, except on springs. Genetic studies of several of these species have shown very little gene flow between the different spring populations or with more distant populations (Clarke et al. 2013). Essentially, the populations are isolated and dependent on the long-term stability of the springs for their local survival.

3.4.4 Hydrogeology

Detailed hydrogeological assessment methods are detailed in the preceding sections, but for springs where no detailed hydrogeological investigations were made, the basic parameters recorded were pH, electrical conductivity and temperature (where sufficient water depth occurred for measurement to take place). A qualitative flow assessment was made for all spring vents using the method described by Gotch (2013).

Detailed data analysis was not part of this project. However, the new data has enabled detailed conceptual hydrogeological and ecohydrological models to be developed and/or refined (Gotch et al. 2016), as well as supporting evidence base tables (refer to Appendix E) describing each spring or type of groundwater-dependent ecosystem commonly associated with spring complexes in the South Australian portion of the Great Artesian Basin.

4 Results

This chapter presents data obtained from the interpretation of cross-sections, groundwater hydrochemistry sampling, geophysics and ecological classification fieldworks. The data are then used to:

a) distinguish the structural setting of spring complexes to determine the likelihood of structural connectivity between the springs and deep groundwater sources

b) characterise the groundwater hydrochemistry from each known aquifer in the investigation area so that comparisons can be made with spring water chemistry and therefore an interpretation made of likely groundwater sources to each spring

c) establish the ecological significance of each spring complex to help in risk assessment.

4.1 Structural setting of spring formation

The following structural model interpretation is based on and extends work previously presented by Keppel et al. (2015b), who developed five structural models to describe spring occurrences near the Neales River catchment and Lake Cadibarrawirracanna. These models are:

- 1a – basin margin, structure (fracture zone)
- 1b – basin margin, structure (fault zone). Displacement deformation caused by faulting clearly evident using regional seismic or other data
- 2 – basin margin, sediment thinning
- 3 – basin margin, structure / sediment thinning combination
- 4 – astrobleme.

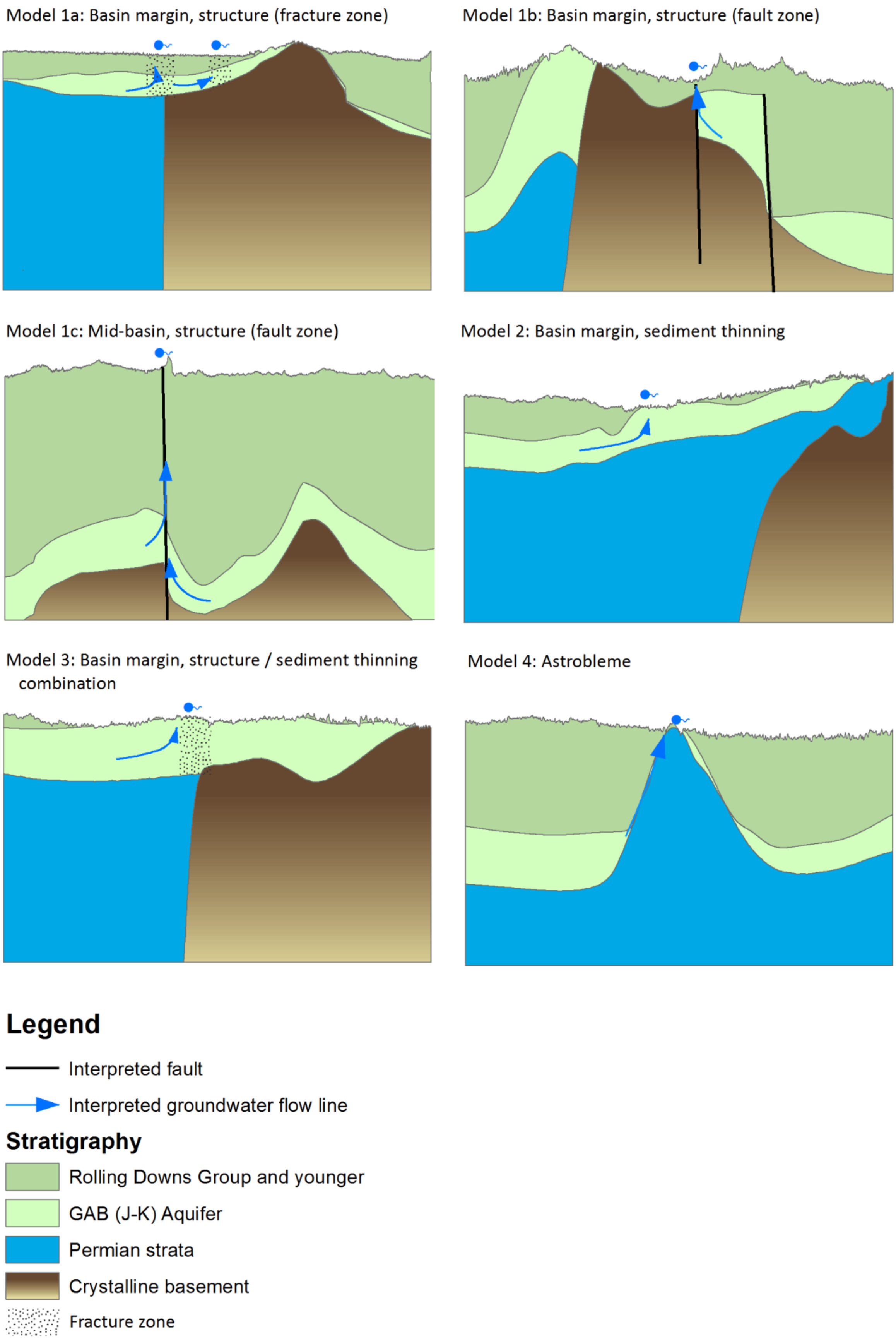
The difference in interpretation between models 1a and 1b is related either to the form of deformation responsible for conduit formation or the scale of the fault structure. Since interpretation was largely based on regional-scale seismic data, springs associated with fault zones that are regional are more likely to be classified as 1b, unless finer-scale data are available. Springs classified as 1a may also be related to faulting; however, existing data may preclude a definitive interpretation and so other forms of deformation, such as tensional jointing or drape structures need to be considered. Typically, if a spring classified as 1a is fault related, such faulting is probably more localised in scale than faults associated with the 1b classification.

Schematic diagrams of these models are presented in Figure 4-1. In this work, spring complexes were placed in these existing structural models where possible; however, a new model type – structural model 1c – Mid-basin, structure (fault zone) – has been developed to describe certain spring complexes in the investigation area. It should also be noted that no examples of structural model type 4 – astrobleme was encountered during this study, although an example is presented in Keppel et al. (2015b).

4.1.1 Structural model 1c – Mid-basin, structure (fault zone)

Structural model 1c appears to be most applicable for the Reedy, Rocky, Lake Blanche and potentially Lake Callabonna spring complexes (Figure 4-1). In this model, a fully developed fault zone has displaced basin sediments from the basement to the surface. Tensile secondary fault structures that form within the wider fault zone provide the basis for conduit formation (Karlstrom et al. 2013; Keppel 2013; Keppel et al. 2013).

Mapping of structure surfaces at the top of the J-K aquifer and the base of the Mesozoic (top of the crystalline basement) suggests that a couple of faults with notable vertical displacement occur close to the Reedy Spring and Lake Blanche Springs complexes. The faults have a north–south and a south-west–north-east strike, and are interpreted to intersect near Reedy Springs. Additionally, the north–south faults have been mapped from the northern margin of the Flinders Ranges towards Lake Blanche (Figure 2-3).



Source: Modified from Keppel et al. (2015b)

Figure 4-1: Schematic diagrams of various structural models

Vertical displacement by faulting of up to several hundred metres of Great Artesian Basin (GAB) sedimentary rocks has been noted previously by Senior and Habermehl (1980), Radke et al. (2000) and Moya et al. (2014). Smerdon and Ransley (2012) provide a discussion summarising fault displacement affecting basin architecture in the central Eromanga Basin region, suggesting that fault displacement of Eromanga Basin strata can range from 10s to 100s of metres, with one example of over 400 m of vertical displacement (Canaway and Cork Faults) observed. Radke et al. (2000) suggested that such vertical displacement was sufficient to completely disrupt groundwater flow in the J-K aquifers, while Karlstrom et al. (2013) suggested that such vertical displacement may also partition aquifers into subbasin areas and connect vertically stacked aquifer units.

Conceptual models 1a, 1b and 1c are similar in that they represent large changes in the depth of basinal sediments and large changes in basin architecture; however, the primary difference is the degree and maturity of active fault movement emanating from the basement structure causing conduit formation. Faulting in models 1b and 1c is thought to be sufficiently mature to have caused major displacement of basinal aquifer and confining layer units, potentially leading to a complex hydrogeology, including the development of impermeable or leaky barriers to lateral groundwater flow, and secondary faulting and fracture development that may have different porosity and permeability characteristics compared with the primary structure. Such deformation is potentially important in causing aquifer partitioning, influencing groundwater flow paths and allowing vertical transfer and mixing of fluids (Karlstrom et al. 2013; Keppel 2013).

At this point in time, we are uncertain about the true significance of the difference between models 1b and 1c, given they both involve regional-scale faulting. However, given the potential effects that faulting has on regional groundwater flow, active faulting that transects hydrogeological basins supplying springs has been distinguished here from faulting that may only define the edge of a basin on the basis that such differences may influence regional hydrogeology differently.

It is possible that the springs at Lake Callabonna may be a result of faulting, although no significant faulting has been mapped in the vicinity. The lack of mapped structure may be a consequence of inadequate data, given that the area is not easily accessible and that Lake Callabonna is within a fossil reserve. In contrast, the thick confining layer sequences that are reasonably interpolated to occur in this region suggest a similar setting as the Lake Blanche Springs, which are approximately 70 km to the north-west.

4.1.2 Structural model 2 – Basin margin, sediment thinning

As previously discussed in Keppel et al. (2015b), a common feature of many springs is their location on the margins of confining layer outcrop or in areas of aquifer unit outcrop. However, in a number of cases, location of a spring does not appear to be related to any major linear deformation structures (such as basin margins or regional-scale faulting). Rather, such springs occur in the general vicinity of mountain block structures, 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.

One such spring group sampled during this study is Petermorra Springs (Figure 2-1,

Figure 4-2A). Petermorra Springs is near the margin of the Rolling Downs Group, which suggests that their occurrence is primarily controlled by removal of the confining layer and development of a shallow spring conduit. Further, it is interpreted that discrete spring vents may be formed from minor fracture development within outcropping aquifer material, or local variations in weathering and regolith processes. 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 4-2B). 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 the surface, either as free-flow or as diffuse discharge.

Figure 4-2: (A) Spring OPC000B on the margin of a crystalline basement outcrop and (B) a local reverse fault north of Petermorra Springs displacing Bulldog Shale (dark layer) and overlying Quaternary sediments by ~0.5 m

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

In the case of Twelve Springs and some springs in the Petermorra Springs Group, a combination of models 1 and 2 may be appropriate (Source: Modified from Keppel et al. (2015b)

Figure 4-1). Interpretation of structure surfaces in this region suggest that J-K aquifer sediments have been deposited near a basement high and/or have since been elevated, evidenced by a relatively steep depositional repose of sediments compared with surrounding regions. However, this has also led to the preferential stripping of confining units within the Rolling Downs Group at this location. Consequently, although the position of springs is highly indicative of a conceptual model 2 scenario, the influence of structures on conduit formation as described in model 1 may also be a factor.

In particular, springs at a distance from the margin of the basement outcrop associated with the Flinders Ranges may be best described using this model. In such areas, there is a notable thickness of confining layer units; however, local-scale faulting as observed in outcrop exposed in creek channels provides the means for spring formation. Such faulting is interpreted to also be quite recent, given that displacement of Quaternary sediments is also evident (

Figure 4-2B). Given the interpreted role faulting has in spring conduit formation, as well as effects to the broad underlying hydrogeological regime, the timing and nature of faulting should be addressed in the future to add to the existing knowledge.

4.2 Hydrochemistry

4.2.1 Major ions, stable isotopes, ^{87}Sr:^{86}Sr of groundwater

Considerable variability was observed in major ion concentration from different aquifers from the investigation area when their proportional distribution relative to one another is examined using a Piper diagram and scatter plots. Ratios of stable isotopes of hydrogen (δ^2H‰) and oxygen-18 ($\delta^{18}O$‰) and isotopic strontium ratios (^{87}Sr:^{86}Sr) were also useful for defining different groundwater groupings based on aquifer type in the investigation area.

Five hydrochemical classifications for groundwater were identified, based on trends observed in, and the interpretation of, hydrochemical data. These classifications coincide with the aquifer from which groundwater is sourced:

- crystalline basement (fractured rock) aquifer

- Patchawarra Formation (Cooper Basin) aquifer
- J-K aquifer
- Coorikiana Sandstone (shallow GAB) aquifer
- Cenozoic aquifer.

4.2.1.1 Crystalline basement fractured rock aquifer

Groundwater from crystalline basement fractured rock aquifers in the investigation area are typically fresh to brackish, although all samples were collected from shallow wells in the North Flinders Ranges and are therefore interpreted to be close to areas of potential recharge. Total dissolved solids varied between 1,557 mg/L (673800080, Bore A, historical result) and 2,931 mg/L (683800049?, Mt Fitton OS Bore). Proportional major ion hydrochemistry of the fractured rock aquifer groundwater can be described as Na^{+} + (Ca^{2+} + Mg^{2+}) + Cl^{-} + SO_4^{2-} dominant (Figure 4-3). There appears to be a trend towards proportionally higher concentrations of Na^{+}+ K^{+}, although it is not clear whether this is being caused by an increase in dissolved halite in solution or from evapotranspiration.

Of note are the high concentrations of Mg^{2+} and, to a lesser extent, SO_4^{2-} and Ca^{2+} in samples from this groundwater type compared with other groundwaters (Figure 4-4A, Figure 4-4B, Figure 4-4C). This is particularly evident when the ratio of these major ions and Cl^{-} are compared with Cl^{-} (Figure 4-4D, Figure 4-5A, Figure 4-5B). Concentrations of Mg^{2+} (Figure 4-4A), Ca^{2+} (Figure 4-4B), K^{+} (Figure 4-5C) and HCO_3^{-} (Figure 4-5D) appear to be independent of salinity, in contrast to concentrations of SO_4^{2-} (Figure 4-4C) and Na^{+} (Figure 4-6A). It is interpreted that elevated Mg^{2+} and Ca^{2+} concentrations are related to the interpreted dolomite bedrock into which the wells in question have been completed. SO_4^{2-} may be coming from sulfides in basement rocks, whereas Na^{+} appears to come from a marine aerosol source. A comparison of Na^{+} to Cl^{-} concentrations (Figure 4-6A) and ratios of Br^{-} to Cl^{-} (Figure 4-6B) suggest that salinity is largely derived from marine-derived aerosols, although in the case of ratios of Br^{-} to Cl, this interpretation is based on only a single result and so is not considered definitive.

The single stable isotope sample indicates that the crystalline basement groundwater is similar to ratios obtained from the J-K aquifer (Figure 4-7). Ratios from Mount Fitton OS Bore are –7.06‰ for $\delta^{18}O$ and –47.0‰ for $\delta^{2}H$. Compared with other groundwater types, this is relatively depleted except when compared with groundwater from the Patchawarra Formation aquifer. These results plot very closely to both the local mean water line (LMWL) and the global mean water line (GMWL), indicating that no evaporative influence is evident.

The isotopic strontium ratio of 0.7194 from Mt Fitton OS Bore is the most enriched when compared with other hydrostratigraphic groundwater types (Figure 4-8). This ratio is most similar to those returned from Cooper Basin groundwater.

4.2.1.2 Patchawarra Formation aquifer

Groundwater from the Patchawarra Formation aquifer is brackish and generally more saline than the majority of groundwater samples from the J-K aquifer (Appendix B). Total dissolved solids varied between 3,120 mg/L (Klebb-1) and 4,452 mg/L (LeChiffre-1). When collected, groundwater was noted to be gaseous and tinted yellow. Despite the difference in salinity, proportional major ion hydrochemistry of the Patchawarra Formation aquifer is similar to groundwater from the J-K aquifer, and can be described as predominantly Na^{+}+Cl^{-}(+ HCO_3^{-}) dominant (Figure 4-3), with the proportions of Ca^{2+} + Mg^{2+} typically at less than 10%. The proportional concentrations of HCO_3^{-} also appear variable, ranging between 30% and 60%. Furthermore, relative concentrations of SO_4^{2-} are very low compared with groundwater from other aquifers, being typically less than 5%.

Of note are the high concentrations of K^{+} compared with Cl^{-} concentrations in the aquifer, compared with groundwater from other aquifers (Figure 4-5C). Cooper Basin groundwater appears to have more than twice the concentration of K^{+} compared with other groundwater types, although as a proportion of total major ion content, concentrations of K^{+} are still minor. Elevated K^{+} concentrations from groundwater collected either from or near coal were also noted from groundwater samples collected near the Lake Phillipson coal deposit (Keppel et al. 2015c). However, elevated K^{+} may also be a function of remnant drilling muds. A comparison of Na^{+} with Cl^{-} concentrations (Figure 4-6A) and Br^{-} to Cl^{-} ratios (Figure 4-6B) suggest that salinity is largely derived from marine-derived aerosols.

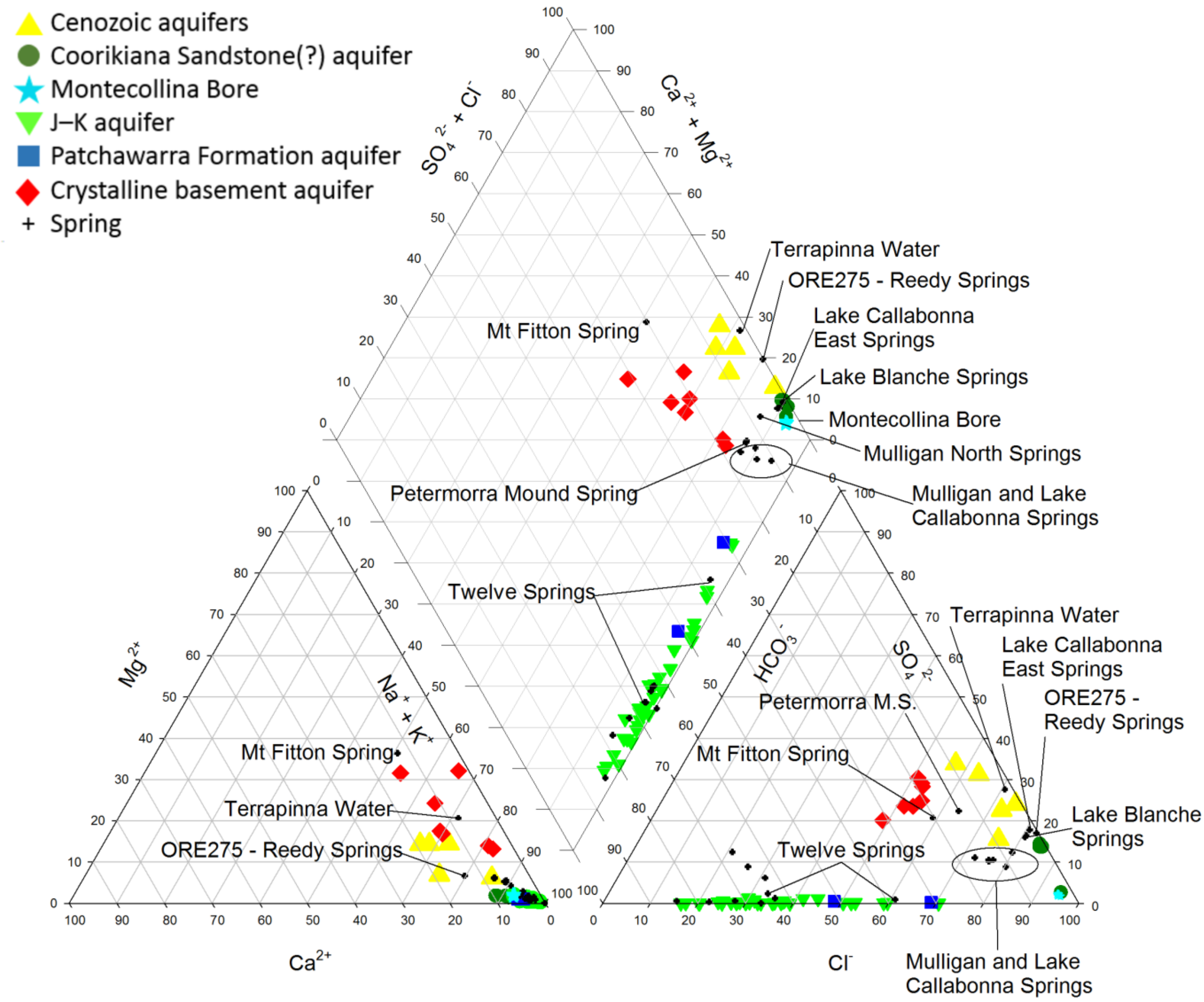


Figure 4-3: Piper diagram displaying major ion results from the investigation area

From the two stable isotope measurements obtained, Cooper Basin groundwater ratios are depleted in both $\delta^{18}O$ and δ^2H compared with all other groundwater types, with $\delta^{18}O$ less than –8.0‰ and δ^2H less than –48.5‰ (Figure 4-7). Results for the Patchawarra Formation groundwater plot very closely to both the LMWL and the GMWL, indicating that there is no evaporative influence, as is the case for the crystalline basement fractured rock aquifer, J-K aquifer and Coorikiana Sandstone (?) aquifer water types.

Ratios of ^{87}Sr to ^{86}Sr are greater than 0.716, which is relatively enriched compared with groundwater from other aquifers within the investigation area, although this is within the upper range of ratios from the J-K aquifer (Figure 4-8).

4.2.1.3 J-K aquifer

Groundwater from the J-K aquifer is fresh to brackish. Total dissolved solids varied between 1,092 mg/L (673900016, BHP C2) and 2,158 mg/L (683800003, Dean's Lookout Bore). Montecollina Bore, which is completed in the J-K aquifer, has a higher salinity than Dean's Lookout Bore (7,884.5 mg/L), and we infer (Section 4.2.1.4 and Appendix G) that a significant proportion of groundwater from this well is from the Coorikiana Sandstone. Proportional major ion hydrochemistry of J-K aquifer groundwater samples are predominantly Na^++ HCO_3^- + (Cl^-) dominant (Figure 4-3), with typically less than 10% of Ca^{2+} + Mg^{2+} by mass. The proportional concentrations of HCO_3^- also appear variable, ranging between 30% and 90%, although they are typically greater than 50%. Additionally, relative concentrations of SO_4^{2-} are very low compared with groundwater from other aquifers, and are typically less than 5%. This description fits that provided by Jack (1923) and Habermehl (1980) of groundwater being predominantly sourced from the eastern portion of the GAB.

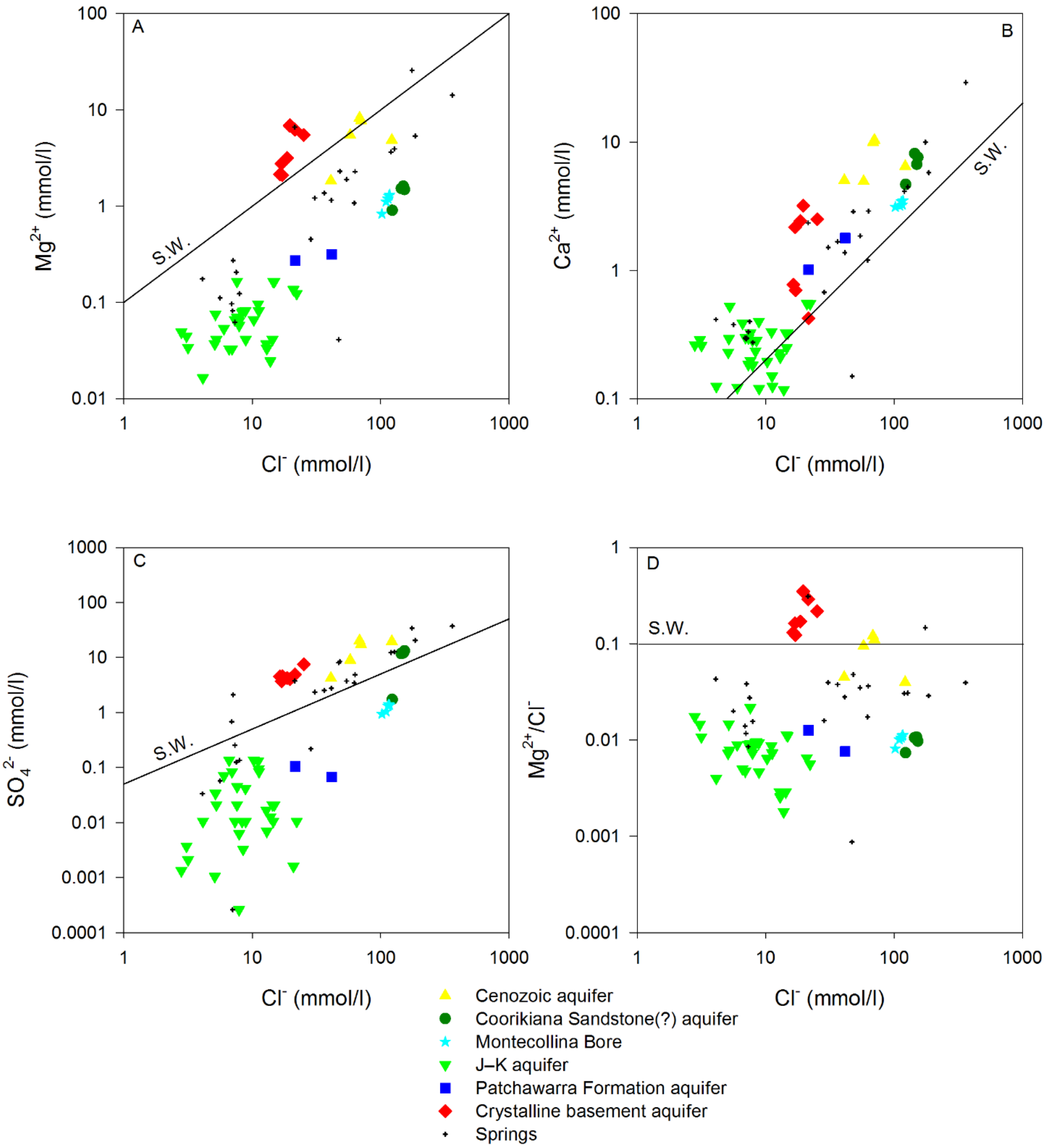


Figure 4-4: Scatter plots of (A) log Mg^{2+} versus log Cl^{-}, (B) log Ca^{2+} versus log Cl^{-}, (C) log SO_4^{2-} versus log Cl^{-} and (D) log Mg^{2+}/Cl^{-} versus log Cl^{-}

Using Cl^{-} concentration as a proxy for salinity, J-K aquifer groundwater can be described as largely less saline than groundwater from other aquifers when Cl^{-} is compared with other major ions (Figure 4-4A, Figure 4-4B, Figure 4-4C, Figure 4-5C, Figure 4-5D, Figure 4-6A). Increases in concentration of SO_4^{2-}, Ca^{2+} and K^{+} all appear to be independent of salinity as defined by Cl^{-} (Figure 4-4B, Figure 4-4C, Figure 4-5C), whereas Mg^{2+} appears to be only weakly correlated with salinity (Figure 4-4A). The ratio of Na^{+} to Cl^{-} is larger than what might be expected from a source dominated by marine aerosols, as is the case with groundwater from other aquifers (Figure 4-6A). To explain the excess Na^{+}, the proportional relationship between HCO_3^{-} and Na^{+} was examined. There is a 1:1 relationship between Na^{+} and HCO_3^{-}, which is particularly evident when the ratios Na^{+}: Cl^{-} and HCO_3^{-}: Cl^{-} are compared (Figure 4-6C, Figure 4-6D). This implies that the Na^{+} concentrations in low salinity J-K aquifer groundwater is predominantly sourced from water–rock interactions that involve the release of sodium bicarbonate ($NaHCO_3$), with the proportion of Na^+ from NaCl sources increasing as salinity increases. Herczeg et al. (1991) used mass-balance and equilibrium hydrochemistry models to describe the likely water–rock interactions responsible for the predominance of $NaHCO_3$ hydrochemistry in J-K aquifer groundwater: (a) dissolution of Na-bearing minerals (e.g. plagioclase and orthoclase), (b) cation exchange that releases Na^+ for Ca^{2+}–Mg^{2+} and (c) conversion of Na-smectite to kaolinite. In particular, the incongruent dissolution of albite will release both Na^+ and HCO_3^- at a ratio of 1:1, which is the same ratio displayed between Na^+ and HCO_3^- from J-K aquifer groundwater samples in Figure 4-6C and Figure 4-6D.

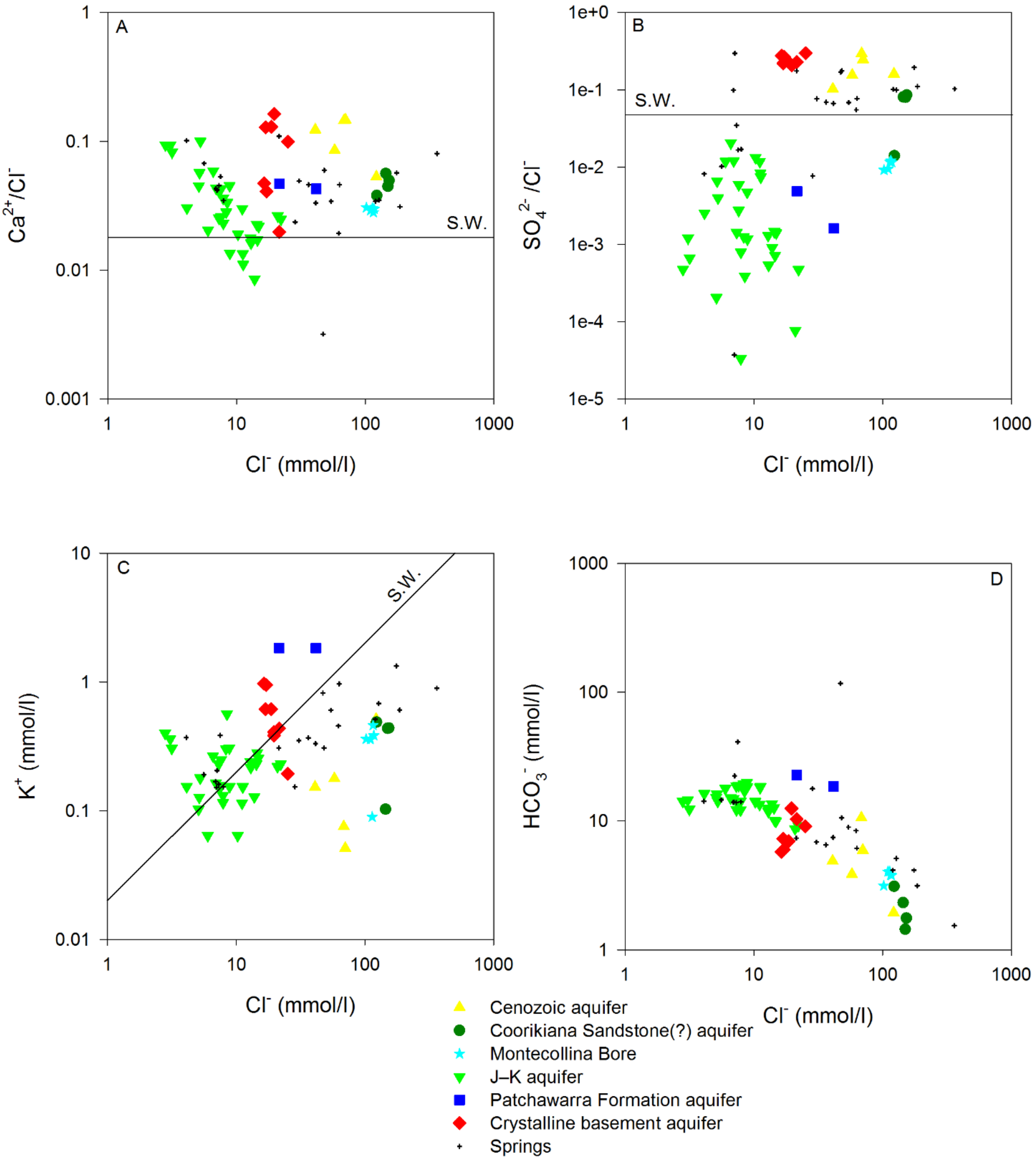


Figure 4-5: Scatter plots of (A) Ca^{2+}/Cl^- versus Cl^-, (B) log SO_4^{2-}/log Cl^- versus log Cl^-, (C) log K^+ versus log Cl^- and (D) log HCO_3^- versus log Cl^-

Relatedly, F^- in J-K aquifer groundwater samples appears slightly elevated in comparison with most other aquifer types, although F^- in Bellinger bore (10.3 mg/L) and Woolatchi bore (9.0 mg/L) is notably elevated compared with other samples (Figure 4-9). Edmunds and Smedley (2013) indicate that F^- is more stable in solution if Ca^{2+} is absent, because of the relative insolubility of fluorite (CaF_2) and the affinity of Ca^{2+} to react with F^- at temperatures typically found in groundwater. Therefore, in keeping with the findings of Herczeg et al. (1991), ion exchange that results in the removal of Ca^{2+} from solution may also be responsible for the relative stability and relatively high concentrations of F^- in J-K aquifer groundwater.

With respect to sources of salinity, Br^-/Cl^- is generally lower than expected for a seawater source, but not so low as to suggest that the primary source of salinity is halite dissolution (Figure 4-6B). That being said, these ratios suggest that mineral dissolution is at least partially contributing to salinity. In the central and western portions of the investigation area, samples from the four most eastern wells (Fortville 3, WK2, WK3 and Yandama Bore) are those with a Br^- to Cl^- ratio closest to seawater (Figure 3-1).

Stable isotope ratios of water for the J-K aquifer are relatively depleted compared with other groundwater types, except when compared with groundwater from the Patchawarra Formation aquifer (Figure 4-7). $\delta^{18}O$ ratios are between –7.17‰ (Dean's Lookout) and –7.61‰ (Petermorra), and $\delta^{2}H$ ratios are between –46.2‰ (Dean's Lookout) and –48.4‰ (Fortville 3). Also, similar to the results from the crystalline basement, the Patchawarra Formation aquifer and the Coorikiana Sandstone (?) aquifers, these results plot very closely to both the LMWL and the GMWL, indicating that there is no evaporative influence.

Ratios of ^{87}Sr to ^{86}Sr are typically between 0.706 and 0.7195, with only Montecollina Bore (0.7059) outside this general range (Figure 4-8). Importantly, isotopic strontium has a very narrow range compared with other groundwater types, varying between 0.285 mg/L (Meteor Bore) and 0.81 mg/L (Deans Lookout). However, when strontium results are presented as a reciprocal (Figure 4-8), the spread of results between 1.2 (Deans Lookout) and 3.5 (Meteor bore) is indicative of strontium loss via mineral precipitation, using the proposition presented by Shand et al. (2009). This subtle change in concentration is also indicated when the ratio of Ca^{2+} to Cl^- is compared with Cl^- (Figure 4-5A), where an inversely proportional relationship is noted in results from the J-K aquifer. As Sr^{2+} has similar physical and chemical properties to calcium, it is likely that these two plots are suggesting Sr^{2+} and Ca^{2+} loss via mineral precipitation with increasing salinity; a similar inversely proportional trend in HCO_3^- concentration when compared with Cl^- (Figure 4-5D) indicates that calcite is the primary mineral being precipitated. In the case of Montecollina Bore, the documented degradation of well construction over time may have resulted in leakage of Coorikiana Sandstone (?) aquifer groundwater into this well (Section 5.1 and Appendix G). This leakage may be evidenced from increases in salinity over time, as well as the hydrochemical similarity between groundwater from this well and Lake Crossing No. 4.

4.2.1.4 Coorikiana Sandstone

Groundwater from the interpreted Coorikiana Sandstone (?) aquifer is saline, particularly when compared with all other groundwater types. Total dissolved solids varied between 8,533 mg/L (673900011, Warraninna Tank Bore, historical result) and 11,102 mg/L (683800006, Lake Crossing No. 4). Proportional major ion hydrochemistry is predominantly Na^++ Cl^-, with typically less than 10% of Ca^{2+} + Mg^{2+} (Figure 4-3). Relative concentrations of HCO_3^- are very low, being typically less than 5%, whereas relative concentrations of SO_4^{2-} are less than 20%. Low concentrations of HCO_3^-,in absolute terms and as a proportion of total salinity compared with other groundwater types are particularly notable when HCO_3^- concentrations are compared with Cl^- (Figure 4-5D). Concentrations of HCO_3^- also appear to have an inverse relationship to salinity, as described by Cl^-.

The J-K aquifer groundwater from Montecollina Bore has a proportional major ion hydrochemistry very similar to Coorikiana Sandstone (?) aquifer groundwater. It is interpreted that groundwater from the Coorikiana Sandstone (?) aquifer is leaking into this bore. This is discussed further in Section 5.1.

Similar to the J-K aquifer, ratios of Br^- to Cl^- are generally lower than might be expected for a seawater source, but not so low as to suggest that the primary source of salinity is halite dissolution. That being said, these ratios suggest that mineral dissolution is at least partially contributing to salinity (Figure 4-6B).

Stable isotope ratios for Coorikiana Sandstone (?) aquifer groundwater appear more enriched than groundwater from deeper aquifers such as the Patchawarra Formation (Cooper Basin), the crystalline basement and the J-K aquifer, but more depleted compared with the shallower Cenozoic aquifers (Figure 4-7). Stable isotope ratios for Lake Crossing No.4 are –6.27‰ for $\delta^{18}O$ and -40.9‰ and –42.08‰ for $\delta^{2}H$. Stable isotope ratios from Montecollina Bore more closely resemble the results from Lake Crossing No.4 than those from other wells completed in the J-K aquifer, with a $\delta^{18}O$ ratio of –6.66‰ and a $\delta^{2}H$ ratio of -43.1‰.

However, like results from the crystalline basement, the Patchawarra Formation aquifer and the J-K aquifer, these results plot very closely to both the LMWL and the GMWL, indicating that there is no evaporative influence.

Ratios of ^{87}Sr to ^{86}Sr from Lake Crossing No.4 and Montecollina Bores are depleted compared with groundwater samples from the J-K, Cenozoic and Patchawarra Formation aquifers and are slightly lower or similar to the modern seawater Sr isotope ratio (N. Harrington, IGS, pers. comm., 28th August 2015) (Figure 4-8). Ratios are typically less than 0.706. Ionic strontium is generally more concentrated in the Coorikiana Sandstone (?) aquifer groundwater than in groundwater found in the J-K, Patchawarra Formation or crystalline basement fractured rock aquifers. The ionic strontium concentrations of between 3.6 and 8.5 mg/L are similar to concentrations returned from groundwater samples from the Cenozoic aquifers.

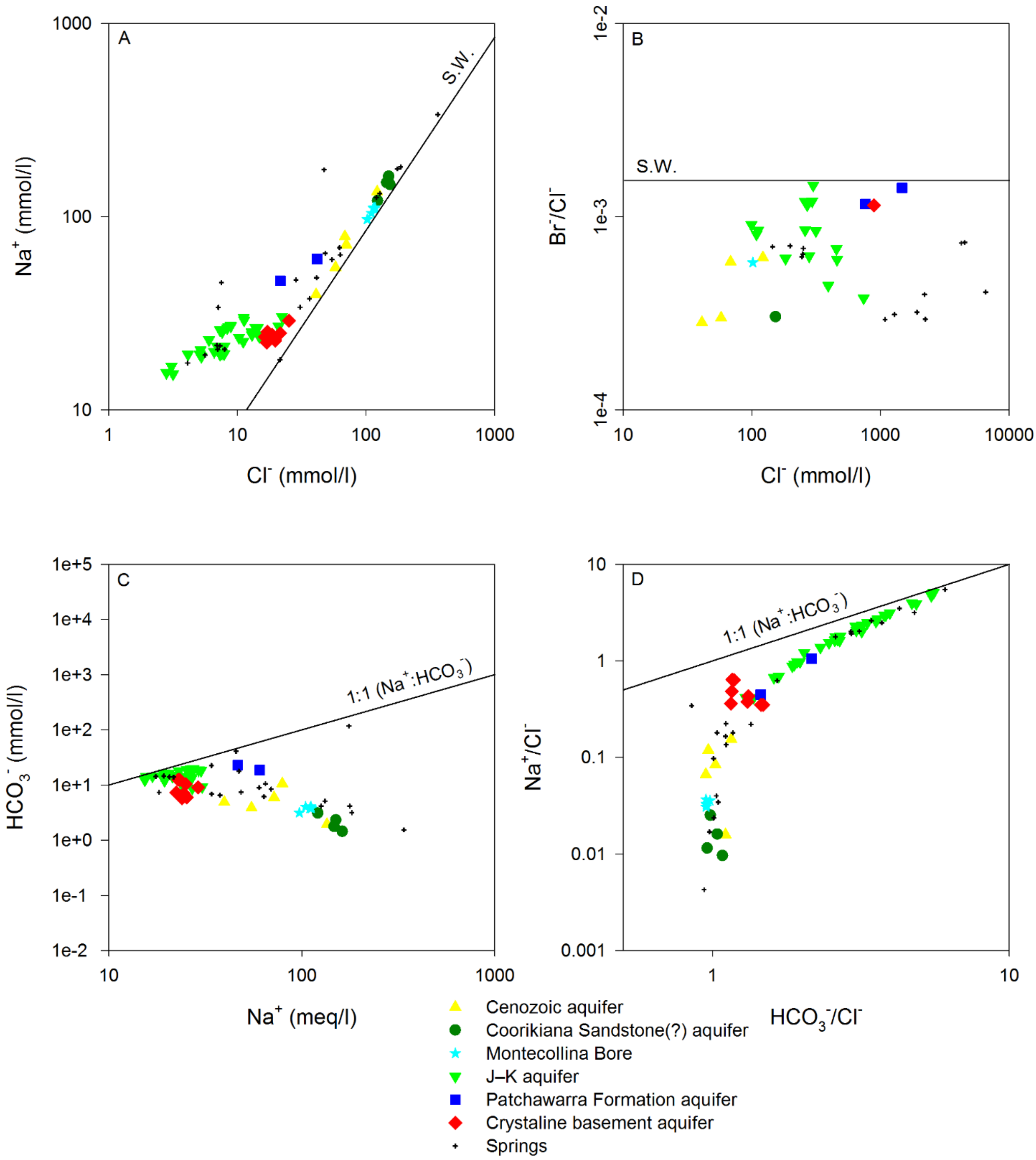


Figure 4-6: Scatter plots of (A) log Na^+ versus log Cl^-, (B) log Br^-/Cl^- versus log Cl^-, (C) log HCO_3^- versus log Na^+ and (D) log HCO_3^-/Cl^- versus log Na^+/Cl^-

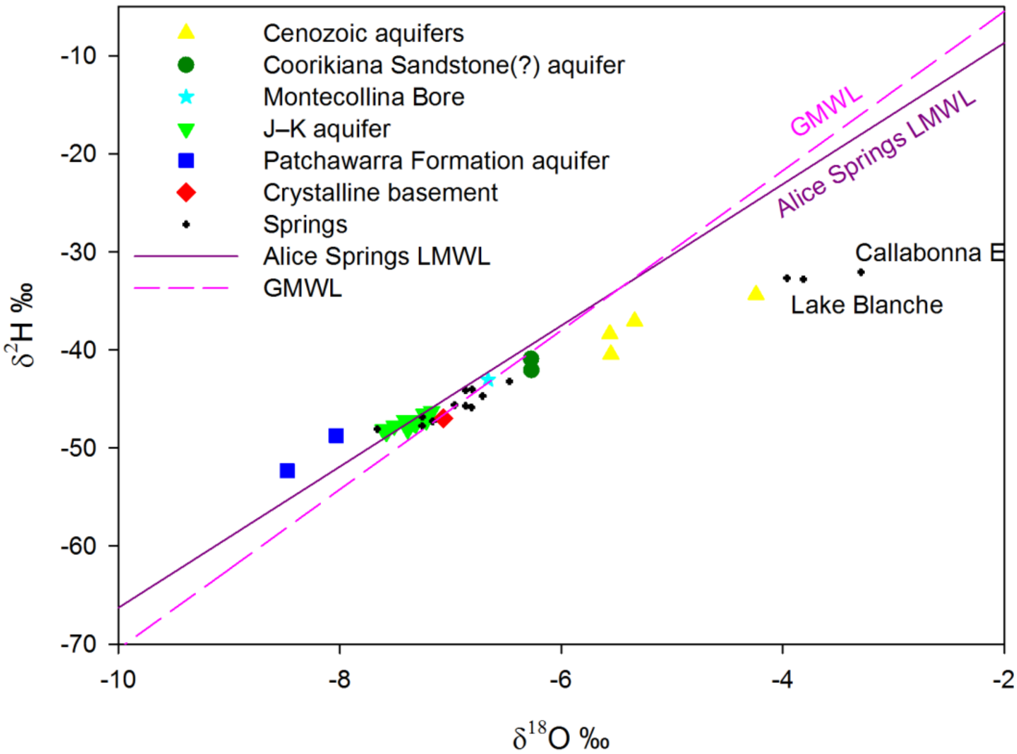


Figure 4-7: δ² versus δ¹⁸O ratios of groundwater in the investigation area

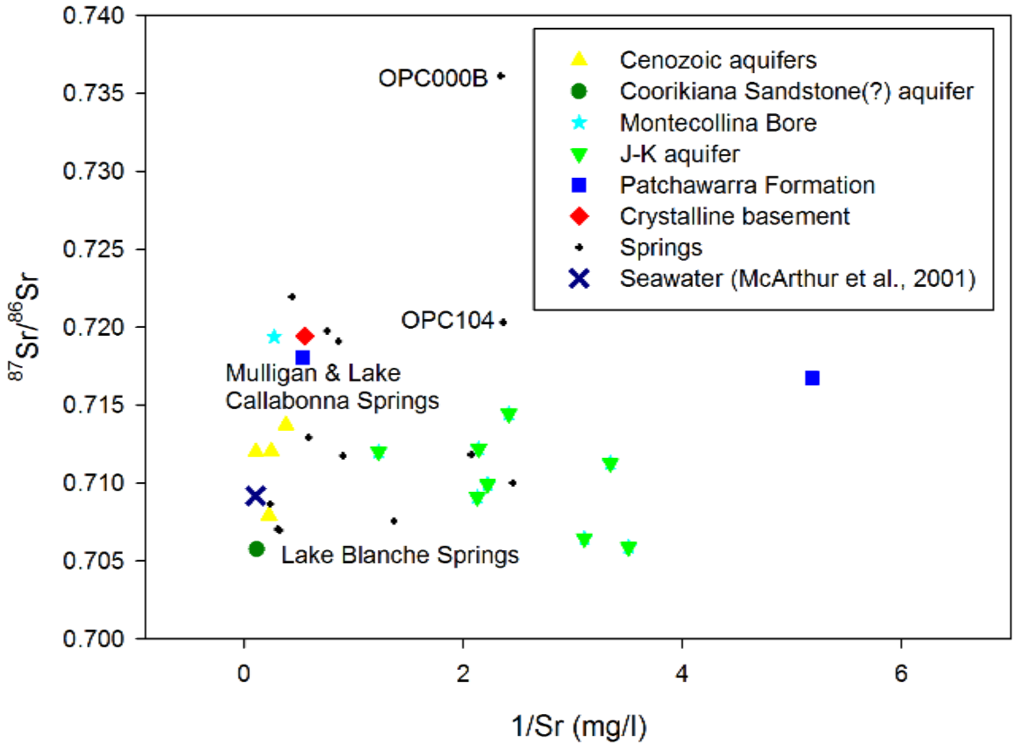


Figure 4-8: $^{87}Sr/^{86}Sr$ versus 1/Sr. Modern seawater value

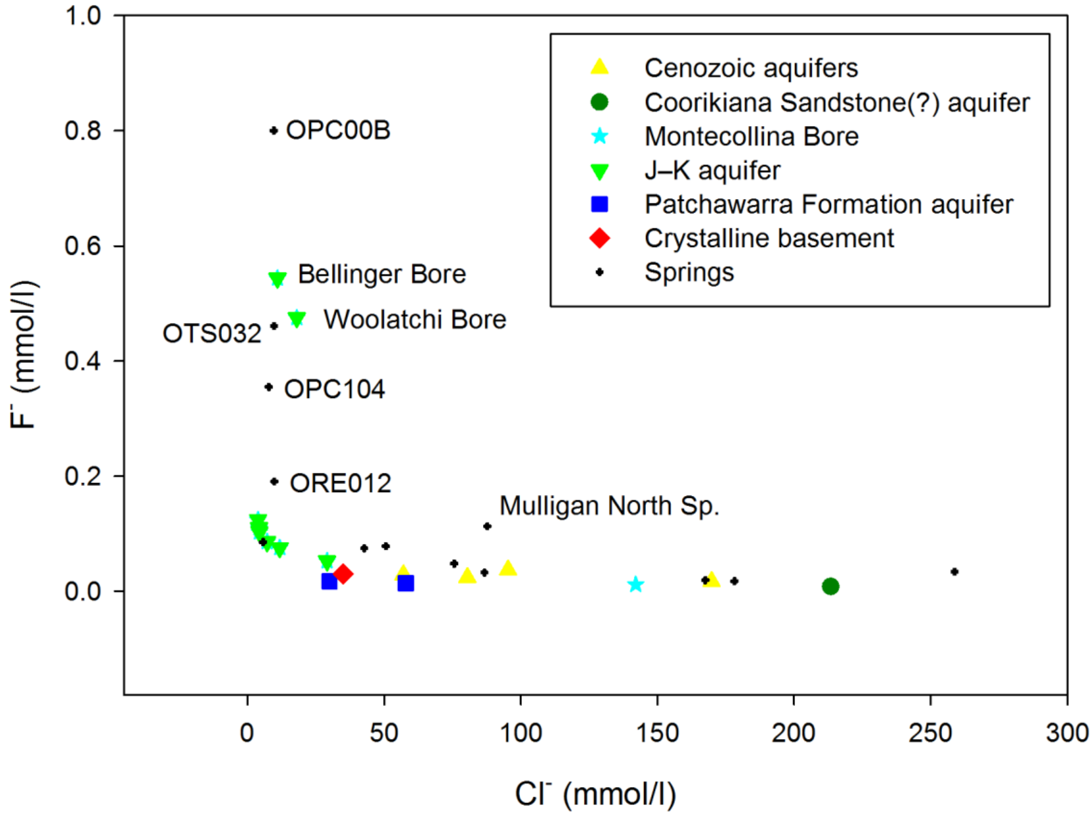


Figure 4-9: F^- versus Cl^-

4.2.1.5 Cenozoic aquifers

Groundwater from the Namba and Eyre formation aquifers is brackish to saline. Total dissolved solids vary between 3,776.5 mg/L (683800048, Mosquito Well 2) and 10,530 mg/L (693900015, Bob's Bore). Proportional major ion hydrochemistry is Na^+ + Cl^- + SO_4^{2-} dominant (Figure 4-3). Relative concentrations of SO_4^{2-} vary and are typically between 20% and 40%, whereas HCO_3^- relative concentrations are typically less than 10%. SO_4^{2-} concentrations as a percentage of salinity appear to be slightly higher than other groundwater types (Figure 4-4C). Additionally, and similar to an observation concerning the Coorikiana Sandstone (?) aquifer groundwater, concentrations of HCO_3^- also appear to have an inverse relationship to salinity as described by Cl^- (Figure 4-5D), which is in contrast to other major ions that appear to increase proportionally to increasing salinity (Figure 4-4 and Figure 4-5). There appears to be a trend towards Na^++ Cl^- dominance when data are displayed using a Piper diagram (Figure 4-3), which is interpreted to be predominantly derived from marine aerosols (Figure 4-6A). This is interpreted to be related to either the dissolution of halite or evapotranspiration based on Br^-: Cl^- ratios, which are comparable to those from the Coorikiana Sandstone and J-K aquifer groundwater types (Figure 4-6B).

Stable isotope ratios for the Cenozoic aquifer groundwater samples appear more enriched than samples from all other groundwater types (Figure 4-7). $\delta^{18}O$‰ ratios are between –4.24‰ (Bob's Bore) and –5.56‰ (Mosquito Well 2), and δ^2H‰ ratios are between –34.4‰ (Bob's Bore) and –40.4‰ (New Lignum Bore). Stable isotope results depart from the trend predicted for local and global mean water lines for rainwater, indicating an important evaporation influence on data. The relative enrichment of stable isotope found in Cenozoic aquifer groundwater samples compared with others is interpreted to be a consequence of recharge occurring in the local arid environment.

$^{87}Sr/^{86}Sr$ ratios are similar to those found from the J-K aquifer, but are slightly enriched compared with ratios from the Coorikiana Sandstone (?) aquifer, depleted compared with the ratios from the Patchawarra Formation aquifer, and slightly higher or comparable to the ratio in seawater (N. Harrington, IGS, pers. comm., 28 August 2015) (Figure 4-8). $^{87}Sr/^{86}Sr$ results for Cenozoic aquifer groundwater samples are between 0.705 and 0.715. Strontium is generally more concentrated in Cenozoic groundwater than in J-K, Cooper Basin or crystalline basement fractured rock aquifer groundwater. The ionic strontium concentrations of 2.6–9.4 mg/L are somewhat equivalent to concentrations found within the Coorikiana Sandstone (?) aquifer groundwater.

4.2.1.6 Major ion, stable isotope and $^{87}Sr/^{86}Sr$ hydrochemistry of springs

Although many spring water samples using historical and current hydrochemistry results can be compared favourably to the J-K aquifer, results from a number of spring waters are more like other groundwater types, and therefore suggest that these springs are supplied by groundwater from aquifers other than the J-K aquifer (Figure 4-3).

Springwater from the Sunday and Lake Blanche Springs are most similar to groundwater from the Coorikiana Sandstone or the Cenozoic aquifers (Figure 4-3). Springwater samples from Mt Fitton Spring, Reedy Springs spring number ORE0275, Petermorra Mound Spring, Terrapinna Waters spring, Lake Callabonna Springs and Mulligan Springs more closely match groundwater results from the Cenozoic, crystalline basement and/or Coorikiana Sandstone (?) aquifers than the J-K aquifer.

In the case of Mt Fitton Spring and Petermorra Mound Spring, the closest comparison can be made to the crystalline basement aquifer and, given these springs location near the margin of the GAB and the North Flinders Ranges, or within the North Flinders Ranges, a crystalline basement aquifer source therefore seems reasonable.

In contrast, although the proportional major ion concentrations for Mulligan Springs and Lake Callabonna Springs are comparable to Petermorra Mound Spring, it is more likely that the source of groundwater is a mix of groundwaters from the Cenozoic aquifer and the Coorikiana Sandstone (?) aquifer, with the J-K aquifer also a possible contributor. In the case of Lake Callabonna Springs in particular, there was a small but notable difference between the hydrochemistry of ZCS001, ZCM001 and ZCE001. Although the hydrochemistry of ZCS001 and ZCM001 may be suggestive of a mixed groundwater, as described above, the water quality and hydrochemistry of ZCE001 points more definitively to the Coorikiana Sandstone (?) aquifer being the primary source.

Elevated F^- in springwater samples from OPC000B, OTS032, OPC104 and ORE012 is most likely related to a primary source of water being the J-K aquifer. Slightly elevated F^- from OMN001 may be suggestive of a contribution from J-K aquifer groundwater, but, on the weight of other evidence, may also suggest the impact of localised groundwater conditions.

Finally, Reedy Springs vent ORE0275 and Terrapinna Waters spring are most like Cenozoic aquifer groundwater, although Terrapinna Waters spring may be better described as a waterhole.

4.2.2 Radioisotopes and $^{36}Cl/Cl^-$

As stated in Section 3.2.1.5, for this report, no age determination or correction calculations have been applied to the radioisotopic results to calculate an age. Instead, the raw percent modern carbon (pMC) and $^{36}Cl/Cl^-$ results are presented to provide a relative indication of age between samples.

Similar to major ions, stable isotopes and $^{87}Sr/^{86}Sr$, it also possible to discriminate between groundwater from different hydrostratigraphic origins on the basis of radioisotope values. However, it appears that only some of the spring groups can be linked to a particular groundwater source, with others better described as having a mixed source.

4.2.2.1 Crystalline basement fractured rock aquifer

The radiocarbon and $^{36}Cl/Cl^-$ values of groundwater from the crystalline basement fractured rock aquifer is represented by one sample (Mt Fitton OS Bore); therefore, some limitations to extrapolating interpretations based on these results should be considered. However, pMC and $^{36}Cl/Cl^-$ values suggest that groundwater from this aquifer is relatively young compared with other groundwater types within the investigation area (Figure 4-10, Figure 4-11). The $^{36}Cl/Cl^-$ value of 86.6×10^{-15} and pMC value of 29.9% are most comparable to values from the Cenozoic aquifer groundwater, and are significantly elevated when compared with groundwater from the J-K and Patchawarra Formation aquifers. The shallow total depth of the bore (37 metres below top of casing (mbtoc)) and depth to groundwater (4.32 mbtoc) suggests that the groundwater collected. This is likely to be a zone of local 'mountain front' groundwater recharge (Wilson and Guan 2004), at least to the crystalline basement fractured rock aquifer within the investigation area.

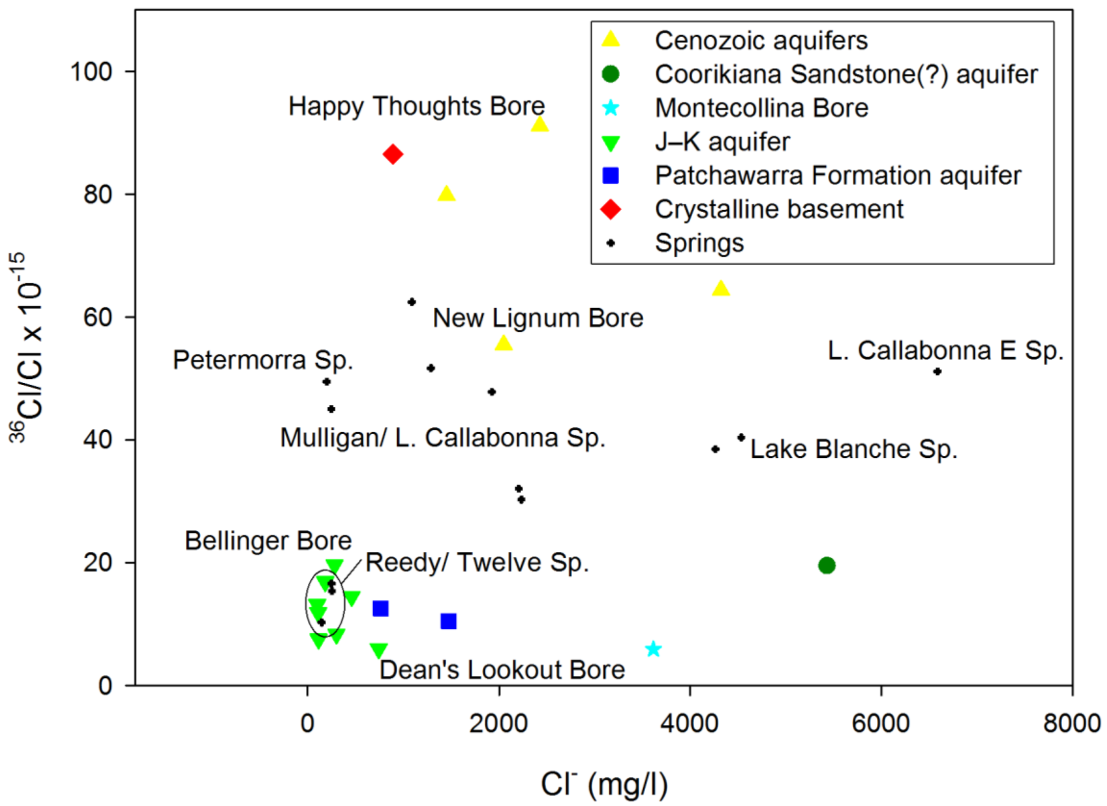


Figure 4-10: $^{36}Cl/Cl^{-} \times 10^{-15}$ versus Cl^{-} (mg/L)

4.2.2.2 Patchawarra Formation aquifer

The pMC and $^{36}Cl/Cl^{-}$ values for the two samples collected from the Patchawarra Formation aquifer are relatively old compared with most other groundwater types, but are most similar to results obtained from J-K aquifer groundwater samples (Figure 4-10, Figure 4-11). Results from both samples were similar: $^{36}Cl/Cl^{-}$ values of 12.6 (Klebb-1) and 10.5 (LeChiffre-1), and pMC values of 0.7% (Klebb-1) and 2.7% (LeChiffre-1) were obtained (Figure 4-11). Based on Aggarwal et al. (2014), age of groundwater based on pMC is likely to be more than 30,000 years. Likewise, based on an interpreted initial $^{36}Cl/Cl$ ratio input from groundwater of $125 \pm 10 \times 10^{-15}$ from Love et al. (2000), groundwater from the Patchawarra Formation and J-K aquifers would appear to be very old. The similarity of these results to those obtained from J-K aquifer samples supports the assertion obtained from major ion, stable isotope and $^{87}Sr/^{86}Sr$ results that the groundwater hydrochemistry of these two groundwater types is similar.

4.2.2.3 J-K aquifer

As discussed in Section 4.2.2.2, pMC and $^{36}Cl/Cl^{-}$ values from J-K aquifer from the investigation area suggest that this groundwater type is relatively old compared with other groundwater types, with the closest comparison to groundwater from the Cooper Basin (Figure 4-10, Figure 4-11). Results reveal that this is likely to be the oldest groundwater within the investigation area: $^{36}Cl/Cl^{-}$ values range between 6 (Deans Lookout) and 19.7 (Bellinger Bore), and pMC values range between 0.3% (Bellinger Bore) and 2% (BHP C4), with most results less than 0.7%.

Additionally, pMC (1.6%) and $^{36}Cl/Cl^{-}$ (5.9) values from Montecollina Bore most resemble those from J-K aquifer groundwater, despite the use of major ion, stable isotope and $^{87}Sr/^{86}Sr$ values suggesting a greater similarity to groundwater from the Coorikiana Sandstone (?) aquifer (Figure 4-10, Figure 4-11). The differences in interpretation between the various hydrochemical analytes suggest that groundwater abstracted from this bore is most likely representative of a mix between the J-K and Coorikiana Sandstone (?) aquifer groundwater types, as a consequence of a compromised well construction (Appendix G).

4.2.2.4 Coorikiana Sandstone

Similar to crystalline basement fractured rock aquifer, the radiocarbon and $^{36}Cl/Cl^{-}$ values of groundwater from the Coorikiana Sandstone (?) aquifer are represented by only one sample (Lake Crossing No. 4), and therefore some limitations to extrapolating interpretations based on these results should be considered. However, pMC and $^{36}Cl/Cl^{-}$ values suggest that groundwater from this aquifer is likely to be younger than groundwater from the J-K and Patchawarra Formation aquifers, but is likely to be older than Cenozoic or crystalline basement fractured rock aquifer groundwater within the investigation area (Figure 4-10, Figure 4-11). The $^{36}Cl/Cl^{-}$ value of 19.5×10^{-15} is most comparable to the more enriched end members of the J-K aquifer values, whereas the pMC value of 17.2% is most comparable to the more depleted end members from the Cenozoic aquifer groundwater.

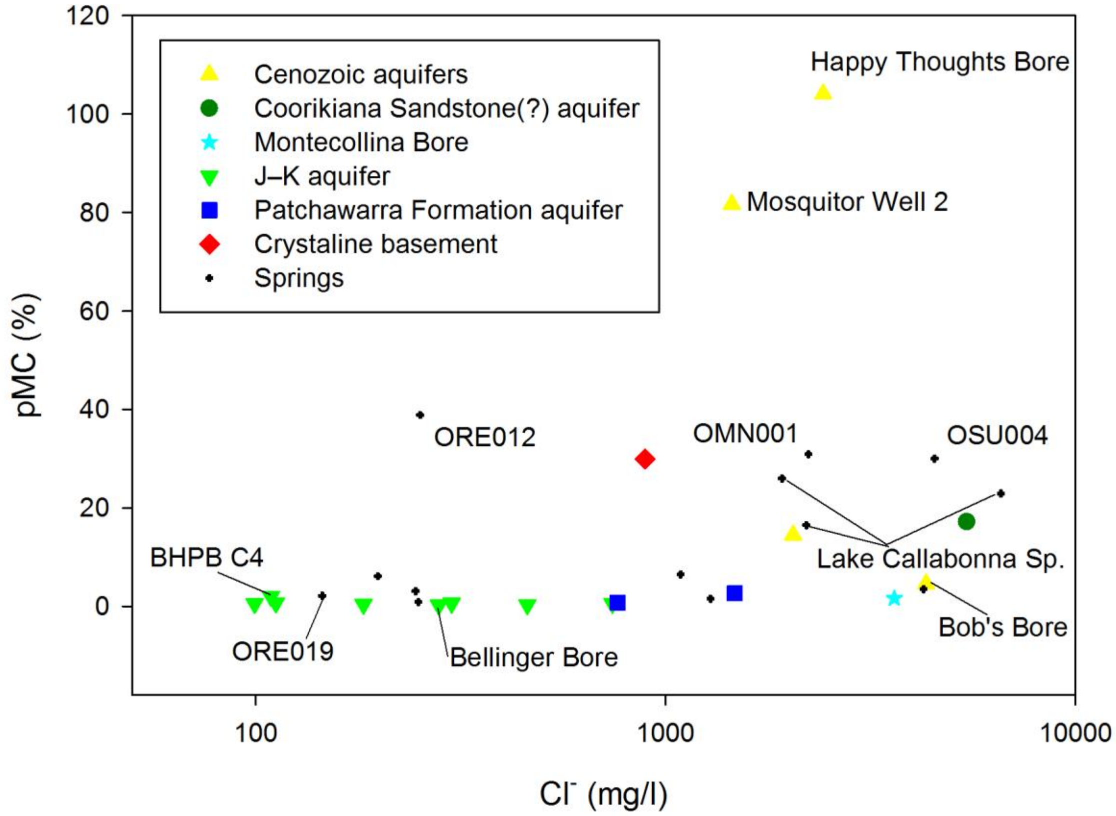


Figure 4-11: pMC % versus Cl⁻ (mg/L)

4.2.2.5 Cenozoic aquifers

The pMC and $^{36}Cl/Cl^-$ values for the two samples collected from the Cenozoic aquifers are relatively young in comparison to most other groundwater types (Figure 4-10, Figure 4-11). Results for $^{36}Cl/Cl^-$ varied between 55.5 $^{36}Cl/Cl^-$ (New Lignum) and 91.1 $^{36}Cl/Cl^-$ (Happy Thoughts), and pMC values varied between 4.6% (Bob's Bore) and 104.1% (Happy Thoughts). There is a wide range in apparent age within the Cenozoic aquifer groundwater sample grouping, as defined by radiocarbon and $^{36}Cl/Cl^-$ results, especially when compared with values from other groundwater types. This may reflect the occurrence of a number of localised groundwater recharge zones to the Cenozoic aquifer across the investigation area. It is noted that Mosquito Well 2 and Happy Thoughts, which provided groundwater with the youngest apparent ages, are located close to ephemeral creeks, suggesting that the surface drainage across the investigation area may be providing at least one potential source of recharge to the Cenozoic aquifers.

4.2.2.6 Radioisotope and $^{36}Cl/Cl^-$ hydrochemistry of springs

Springs within the investigation area may be divided into two broad groups based on pMC and $^{36}Cl/Cl^-$ values. The first group, which primarily comprises groundwater from Twelve Springs and Reedy Springs (ORE019), returned pMC and $^{36}Cl/Cl^-$ results most comparable to those obtained from J-K aquifer groundwater, suggesting strongly that the likely source of groundwater to these springs is the J-K aquifer. The second group, which primarily comprises groundwater from the Mulligan, Callabonna and Lake Blanche Springs Groups and complexes, returned pMC and $^{36}Cl/Cl^-$ values that suggest notably younger groundwater than that from the J-K and Patchawarra Formation aquifers, but either similar to or older than values returned from the Cenozoic or Coorikiana Sandstone (?) aquifers, suggesting a likely groundwater source of either one of these two aquifers, or a mix between these aquifers and groundwater that is older (Figure 4-10, Figure 4-11).

Viewed using a log scale, pMC and $^{36}Cl/Cl^-$ results display a broad correlation, suggesting that the overall trends in age between the groundwater types as described above are reliable (Figure 4-12). However, important differences in apparent age using pMC and $^{36}Cl/Cl^-$ were found in values obtained from the Petermorra Spring complex, Reedy Spring ORE012 and Lake Blanche Spring QLB001 (Figure 4-10, Figure 4-11, Figure 4-12). In the case of the Petermorra Spring complex and QLB001, although $^{36}Cl/Cl^-$ suggested groundwater was significantly younger than the J-K aquifer, pMC values suggested either a good comparison in the case of Petermorra Springs, or at least a much smaller difference in the case of QLB001. In contrast, pMC values from ORE012 suggested a groundwater source younger than J-K aquifer groundwater, but $^{36}Cl/Cl^-$ values suggested a good comparison. Such differences may suggest that groundwater supply to these particular springs may be a mix of groundwater types. Alternatively, the difference may also be due to environmental factors attributable to each particular spring site that may be skewing at least one set of results, as these results have not been corrected to calculate an apparent age.

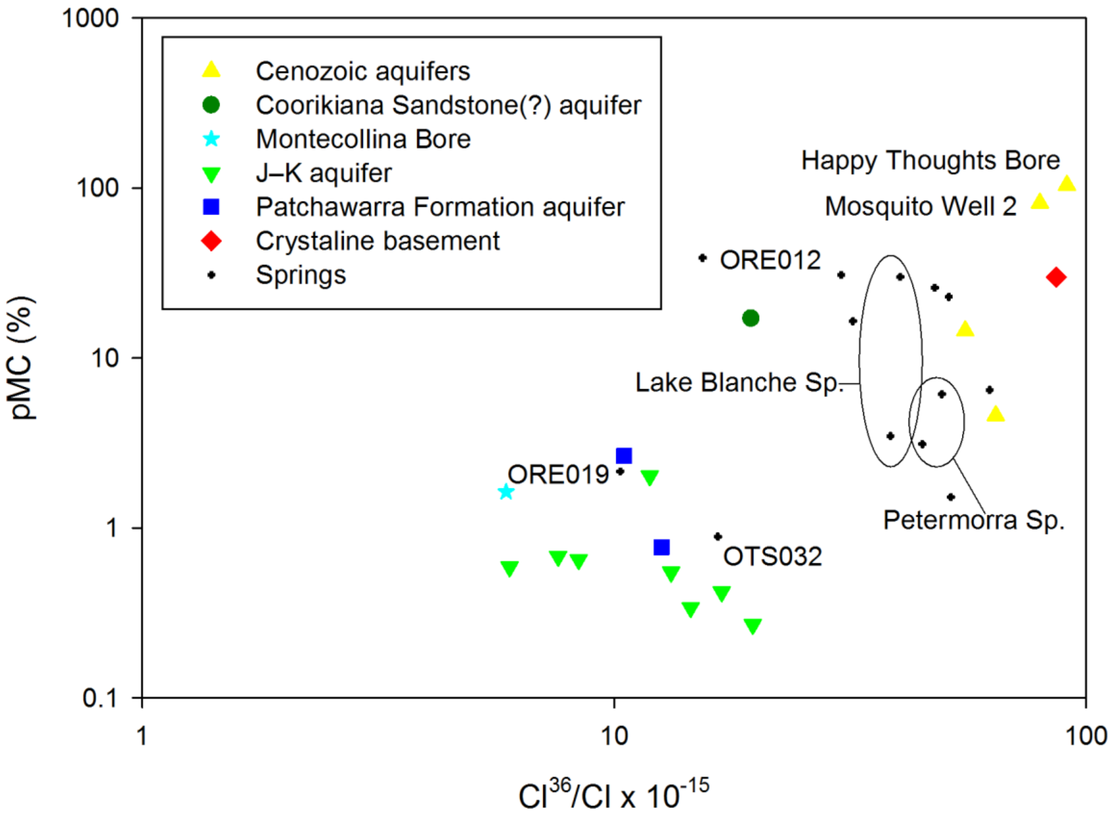


Figure 4-12: $^{36}Cl/Cl^-$ × 10^{-15} ratios versus pMC

4.2.3 Summary of hydrochemical characteristics

A summary of hydrogeological characteristics from each interpreted groundwater type is provided in Table 4-1.

Table 4-1: Summary of hydrogeological characteristics for the investigation area

Hydrogeological group	Major ions	Stable isotopes	$^{87}Sr/^{86}Sr$	Radiocarbon and $^{36}Cl/Cl^{-}$
Crystalline basement	Na+ + (Ca^{2+} + Mg^{2+}) + Cl^{-} + SO_4^{2-}	Depleted compared with Cenozoic and Coorikiana Sandstone (?) aquifers. Comparable with J-K aquifer	Enriched compared with other types	Relatively young age indicated. Comparable to Cenozoic aquifer groundwater
Patchawarra Formation aquifer	Na^{+} + Cl^{-} (+ HCO_3^{-}) Elevated K^{+} compared with other aquifer types	Depleted compared with all other groundwater types	Relatively enriched compared with J-K and Cenozoic aquifers	Relatively old age indicated. Comparable to J-K aquifer
J-K aquifer	Na^{+} + HCO_3^{-} + (Cl^{-})	Depleted compared with Cenozoic and Coorikiana Sandstone (?) aquifers. Comparable to crystalline basement aquifer	Large range from 0.706 to 0.7195. Isotopic Sr range very narrow	Oldest ages indicated compared with all other groundwater types
Coorikiana Sandstone (?) aquifer	Na^{+} + Cl^{-}	Enriched compared with J-K, Patchawarra Formation and crystalline basement aquifers. Depleted compared with Cenozoic aquifers	Depleted compared with J-K, Cenozoic and Patchawarra Formation aquifers. Comparable to seawater	Younger age indicated compared with J-K and Patchawarra Formation aquifers but older than Cenozoic or crystalline basement aquifer
Cenozoic aquifer	Na^{+} + Cl^{-} + SO_4^{2-}	Enriched compared with all other groundwater types	Comparable with results found from J-K aquifer	Youngest ages indicated compared with all other groundwater types

With respect to spring water supply, Table 4-2 summarises the most likely source of groundwater to each spring system within the investigation area.

Table 4-2: Summary of possible sources of spring water based on hydrochemistry

Spring complex	Possible supplying aquifer
Lake Blanche	Coorikiana Sandstone/Cenozoic
Reedy	J-K aquifer and Cenozoic
Petermorra	J-K aquifer and crystalline basement
Twelve	J-K aquifer
Lake Callabonna (Mulligan Group)	Cenozoic, Coorikiana Sandstone and J-K aquifer (?) (mix)
Lake Callabonna (Callabonna Group)	Cenozoic, Coorikiana Sandstone and J-K aquifer (?) (mix)

4.3 Geophysics

As stated in Section 3.3, two spring vent sites were chosen for ground-based geophysical surveys: Reedy Springs and Lake Blanche Spring (QLB001) (Figure 3-2). The techniques used were self-potential (SP), time-domain electromagnetic induction (NanoTEM) and natural-source audio-magnetotellurics (AMT).

SP surveys measure the amplitude and spatial distribution of static electrical potentials in the earth. Such potentials are affected by the flow of water (the electrokinetic effect) and the groundwater chemistry (Revil et al. 2012). The magnitude and polarity of the current is determined by the streaming current coupling coefficient, which depends on a variety of petrophysical and fluid properties, including the salinity and pH of the pore fluid.

NanoTEM techniques use an artificial electromagnetic (EM) signal to induce electrical currents in the subsurface and measure the ground's resistivity. The primary EM field diffuses and dissipates into the ground, and induces a faint secondary field in a receiving loop. In time-domain surveying such as NanoTEM, this secondary field is sampled and recorded digitally, and the field's decay recorded as a function of time. The rate of decay is related to the ground's electrical resistivity (McNeill 1980; Nabighian and Macnae 1991) that is affected by changes in fluid properties, fluid content and lithology.

The AMT technique uses naturally occurring global EM fields (caused by lightning strikes and solar activity, which diffuse into Earth's upper crust) to determine the resistivity structure in the top 0–3 km of the crust (Chave and Jones 2012). The electric and magnetic fields are measured in both north–south and east–west orientations. The ratio of the orthogonal measurement is then interpreted in terms of the apparent resistivity of the ground, and the relationship of the two modes of induction (e.g. the phase tensor of Caldwell et al. 2004) is used to determine the dimensionality of the electrical structure of the ground, which relates to how the resistivity varies.

4.3.1 Reedy Springs

4.3.1.1 Shallow structures

NanoTEM and SP surveys were run at Reedy Springs over the southern margin of the main spring mound, which was covered in sedge grass. NanoTEM sites were collected at 20 m intervals over a 1.1 km line (Figure 4-13) and inverted for a resistivity model (Figure 4-14). SP sites were collected at intervals of 1–10 m on a profile across the northern part of the mound (Figure 4-15).

A resistivity model derived from a smooth-model inversion of NanoTEM data collected on an east–west profile at Reedy Springs is shown in Figure 4-14. The model contains a distinct difference on either side of the creek that runs past the springs (at station 1280). On the western side of this creek is a highly conductive layer (~ 0.6 to 1 Ωm) about 10 m below the surface, underlain by what is still the relatively conductive sediments of the Rolling Downs Group (10 Ωm). This is the typical shallow structure found at other mound springs located on outcropping/subcropping Rolling Down Groups, both in the investigation area (e.g. Lake Blanche) and at other locations in the Lake Eyre Basin (Keppel et al. 2015c; Inverarity 2014).

On the eastern side of the creek, there is no shallow conductor; instead, there is a moderately to highly resistive layer to a depth of 10–12 m, varying between 12 Ωm and 60 Ωm. This is beneath the entire spring mound area (containing active vents and sedge grasses). Underlying this is a homogeneously conductive area of about 3–4 Ωm extending to more than 40 m (beyond which the model is not necessarily accurate).

The existence of the resistive layer compared with surrounding sediments strongly suggests that less saline water (compared with pore water in surrounding sediments) discharging from the spring is broadly distributed underneath the spring mound; and/or there is a significant change in lithology underneath the spring mound (e.g. clay/shale Rolling Downs Groups sediment compared with aeolian sand and spring carbonates on the mound).

The contrast in resistivity (1 Ωm vs 12–60 Ωm) is uncharacteristically large for mound springs, and is probably caused by both factors.

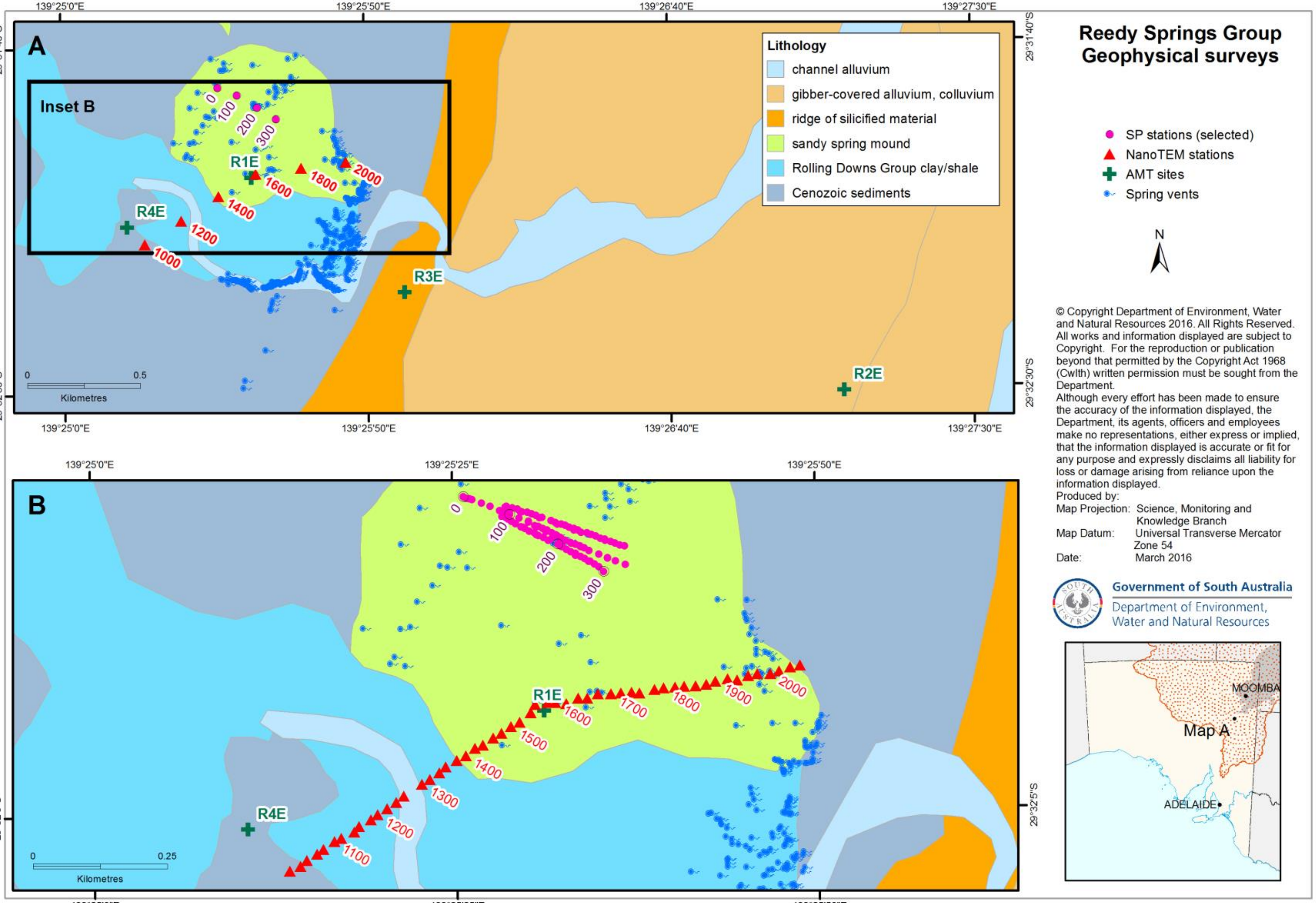


Figure 4-13: Location of geophysical survey sites at Reedy Springs: (A) AMT sites and (B) detail of area around spring vents

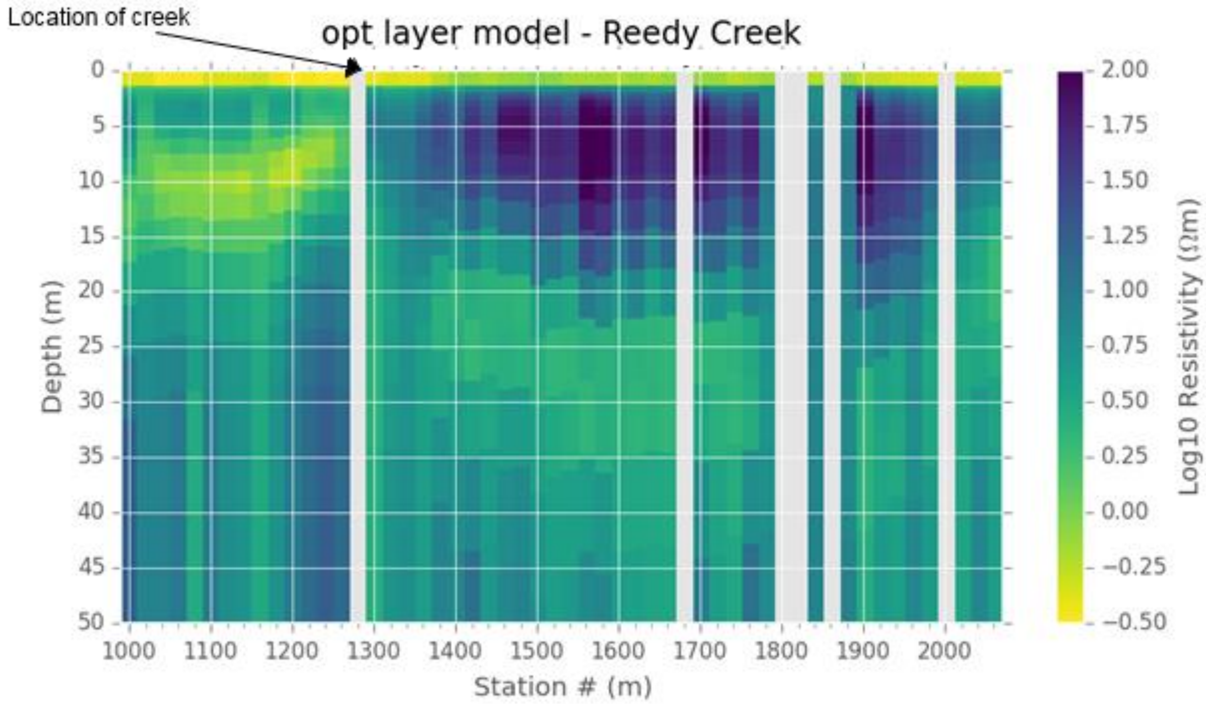


Figure 4-14: Resistivity model from inversion of NanoTEM data at Reedy Springs

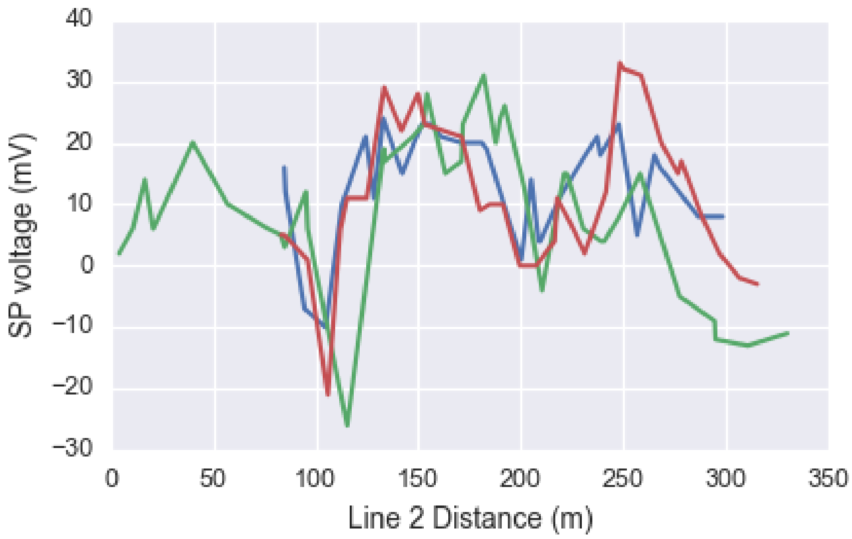


Figure 4-15: Self-potential data from Reedy Springs, showing three closely-spaced parallel profiles

Water was visibly discharging from the flanks of the slightly elevated sandy grassed spring mound in the early morning, but these areas were dry later in the afternoon. If these flank waters were related to the water discharging on top of the mound, as seems likely, then the broadly distributed resistive area supports the idea that the entire mound is hydraulically connected as a single spring, and contains comparatively resistive water.

However, the contrast in resistivity (1 Ωm vs 12–60 Ωm) cannot be explained only by fresher (more resistive) water in the spring mound, because the resistivity of water sampled from the mound at ORE019 is 5.2 Ωm. It is very likely that the presence of carbonate deposits and a reduction in clay content also contribute to the higher resistivity.

This interpretation is supported by the SP data collected slightly further north on the same sandy mound covered by sedge grasses (Figure 4-15). Three parallel SP profiles showed no significant long-wavelength gradients or anomalies that would indicate lateral differences in vertical groundwater flow in the top 50 m.

The main features of the SP data are differences in voltage caused by variation in the cross-coupling coefficient where the profile crossed from a thin cap of carbonate on the surface to saturated sandy soil. However, some features were interpreted to be related to groundwater flow via the electrokinetic effect. Within the spring mound area (i.e. where water was discharging in vents), there were internal topographic features best described as large, slightly elevated areas. There was a consistent drop of 15–20 mV when traversing down the flank of one of these areas (260–280 m on Line 2 in Figure 4-15). This is probably caused by upwards vertical flow of groundwater underneath the elevated area, in the area below ground surface to a depth of about 20 m.

4.3.1.2 Deep structures

AMT data were collected at four sites, spread across an east–west section about 3.5 km long. From west to east, the sites were:

- R4E, on the alluvial/sheetwash/colluvial sediments that overlie the subcropping Rolling Downs Group in the area
- R1E, in the centre of the spring mound area
- R3E, adjacent to an elevated ridge running north-north-east–south-south-west (silicified Neogene sediments)
- R2E, on gibber-covered plains several kilometres east of the Reedy Spring complex.

The data collected were of reasonable quality, with responses calculated in the range 1–200 Hz. Apparent resistivities across this bandwidth varied between 1 Ωm and 30 Ωm, with significant variation between the two orthogonal modes. Figure 4-16 shows the geoelectric strike (specifically, the electric field direction for the transverse electric induction mode) derived from phase tensor analysis of the responses. The high-frequency responses at the top of Figure 4-16 (e.g. 200 Hz) relate to a penetration depth of approximately 100–140 m, and the lowest frequency responses (e.g. 1 Hz) correspond to approximately 2–3 km penetration depth. The strike varies from north-north-east on the western end of the line (R4E) to north-north-west on the elevated ridge on the eastern side of the spring complex (R3E).

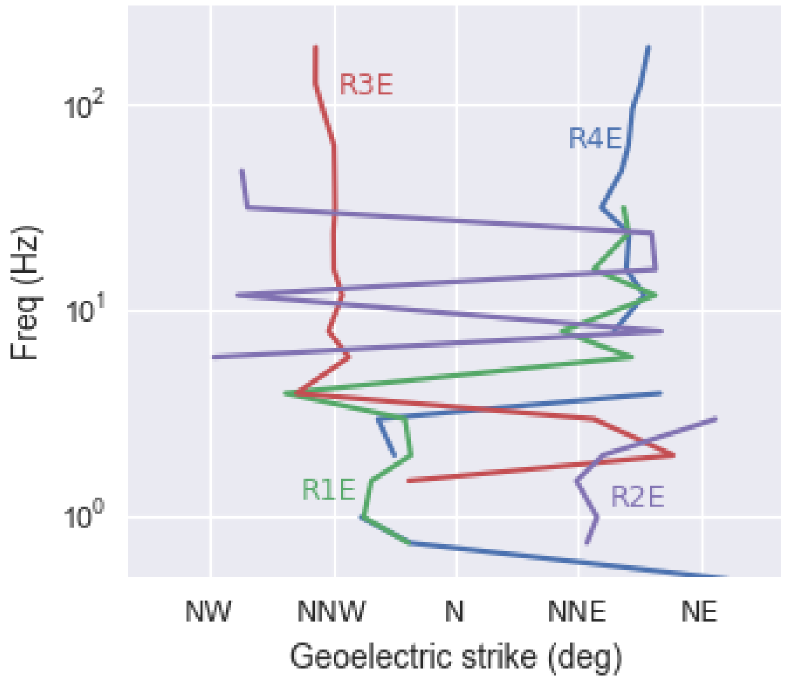


Figure 4-16: Geoelectric strike direction from AMT phase tensor data at Reedy Springs

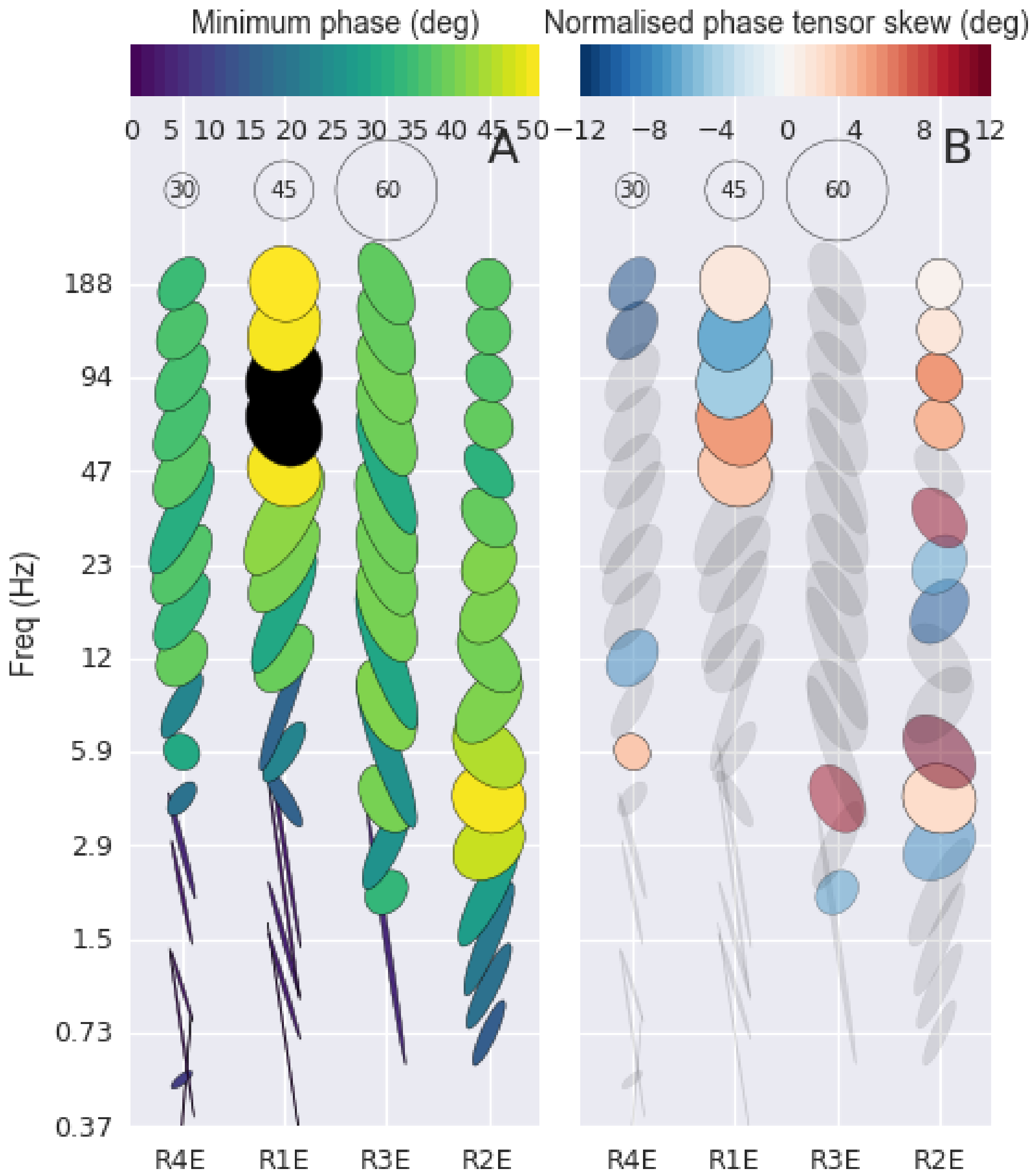


Figure 4-17: Phase tensor ellipse pseudosections from AMT data at Reedy Springs, coloured by the phase tensor; (A) minimum phase and (B) skew

The full dimensionality of the response is shown in Figure 4-17, where the long axis of the ellipse points towards the geoelectric strike and the minimum phase indicates the extent to which induction varies between the orthogonal phases. The skew indicates the extent to which resistivity variation in the earth can be described by a single strike direction (i.e. 2D) or whether it is more complex (i.e. 3D, such as buried blocks with different resistivities, plunging folds or multiple generations of faulting). Grey shaded ellipses have 3D skews, and it is apparent that, apart from the site on the gibber plains to the east (R2E), the Reedy Springs Group has a complex underground electrical structure, even in the shallow subsurface near the elevated ridge separating the spring complex from the gibber plains in the east and north-east. This is strongly suggestive of faulting and fold-related deformation in this area, possibly related to the structural offset noted in Mesozoic sediments at depths of 500 m or more (Figure 6–3).

The complexity of the responses, sparsity of data sites, noisy instrument/logger conditions and lack of resources prevented 2D or 3D modelling of the AMT data.

4.3.2 Lake Blanche Springs (QLB001)

4.3.2.1 Shallow structures

Both NanoTEM and SP surveys were run across the QLB001 vent at the Lake Blanche Springs Group. A single east–west oriented NanoTEM line was recorded at 20 m station intervals, and two SP lines were recorded across the QLB001 vent: one north–south and another east–west (Figure 4-18 inset).

The NanoTEM data were inverted for resistivity models using the 1D AarhusInv (AarhusInv 2015) EM inversion software package. A number of inversion setups were used with varying numbers of layers, and also a smooth model, and then the best-fitting models were stitched together into the resistivity cross-section shown in Figure 4-19. Overall, the model shows only minimal variation in resistivity and is very conductive (0.2–3 Ωm) compared with the model at Reedy Springs (1–70 Ωm), as expected given its location in the bed of Lake Blanche, where it is subject to infiltration by saline surface water.

A conductive layer (0.5 Ωm) occurs about 5 m below the lake bed, which is underlain by a homogeneous layer of around 2–3 Ωm, which extends to the penetration depth of the survey (~ 40 m). This conductive layer is more conductive than water sampled from the QLB001 spring vent (12,949 µS/cm or 0.77 Ωm), supporting the idea that lakebed evaporation and infiltration has likely resulted in the pore fluid of the sediments surrounding the spring vent being significantly more conductive than the spring water.

The spring vent is located at station 1000. The model shows a resistive structure underneath the vent and on several stations either side. This structure contains a deepening (to about 15 m) of the shallow conductive layer, which is not quite so conductive underneath the vent. A structure extending the full surveyed depth immediately below the vent is comparatively conductive (1.2 Ωm) compared with the surrounding layers (2–3 Ωm) and consistent with a simple petrophysical model of a permeable but conductive fracture zone around 30 m to 60 m wide (i.e. one containing clay gouge).

There is also a significantly more resistive structure immediately below the vent (4 Ωm, 0–5 m depth), which is very likely to be caused by more resistive material in the vent, such as subsurface precipitation of carbonate (e.g. a calcrete). The presence of more resistive/fresher water in the vent may also be responsible for this, as the relatively conductive water discharging from the vent (0.77 Ωm) may be the result of mixing between conduit water and more saline water affected by surface infiltration.

The SP data contain a narrow positive voltage anomaly centred on the spring in both north–south and east–west orientations. This strongly supports a model of concentrated vertical upward flow of water directly underneath the vent, consistent with a fracture zone model. Although the data are somewhat sparse, there is no indication of any kind of structure connecting or sharing flow paths between QLB001 and the spring vent located approximately 400 m to the south-south-west (e.g. common fault zone). There is another asymmetric SP feature at station 940 (about 70 m west of QLB001), which is not related to any surface features, and is unlikely to be directly caused by a groundwater flow feature due its dipolar (asymmetric) nature. It is possibly related to a steeply dipping geological structure or contact, but, as nothing unusual occurs at the same location in the NanoTEM model, it is difficult to be certain.

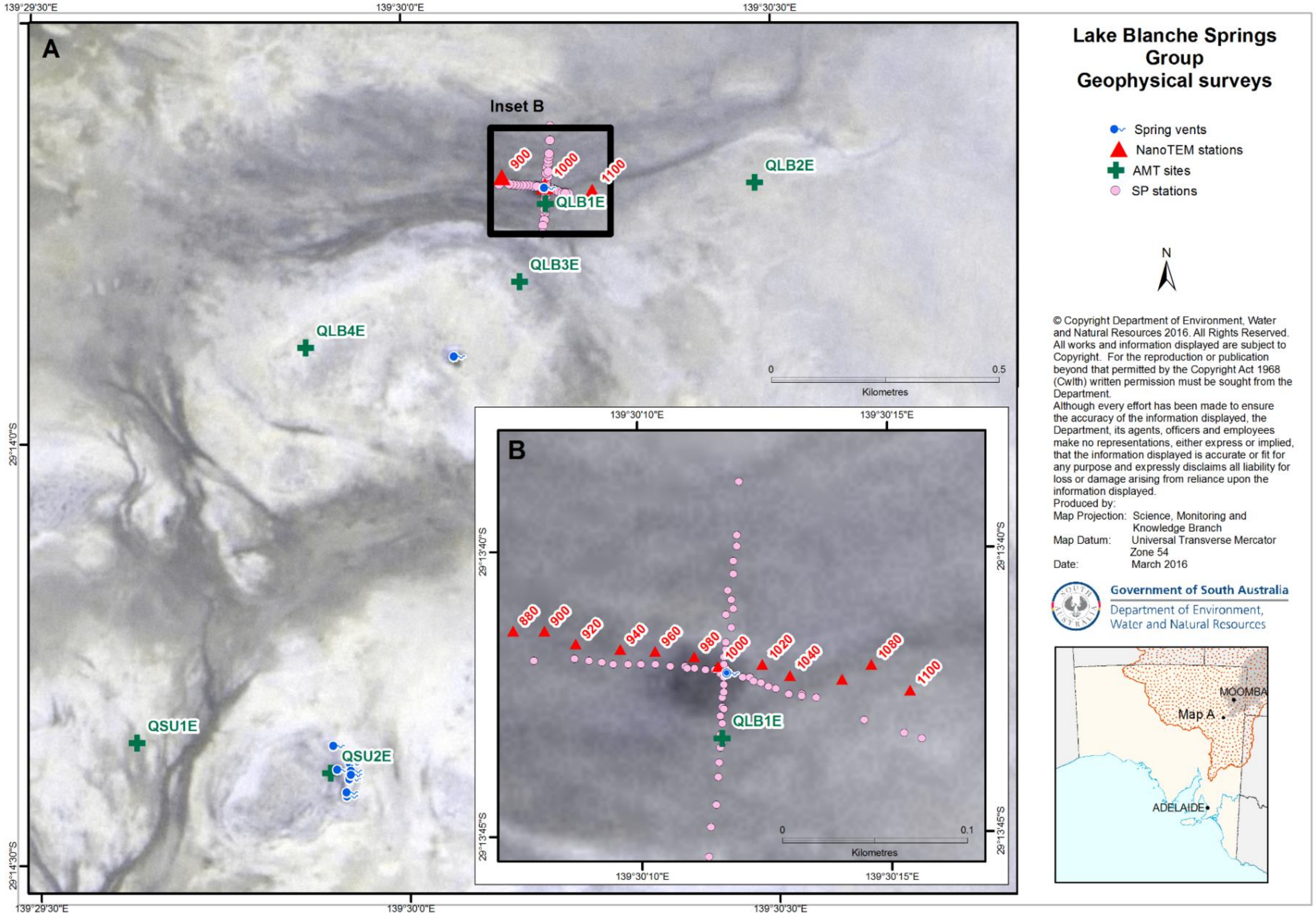


Figure 4-18: (A) Location of geophysical survey sites at Lake Blanche and Sunday Springs, and (B) detail of area around QLB001 vent

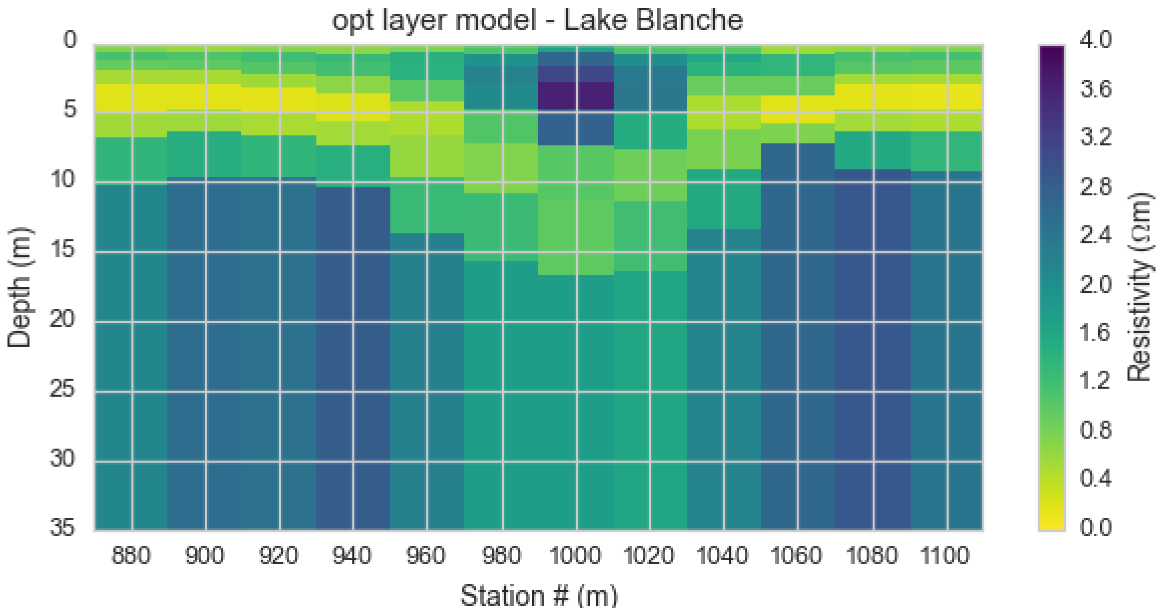


Figure 4-19: Resistivity model inverted from NanoTEM data at Lake Blanche (QLB001 vent)

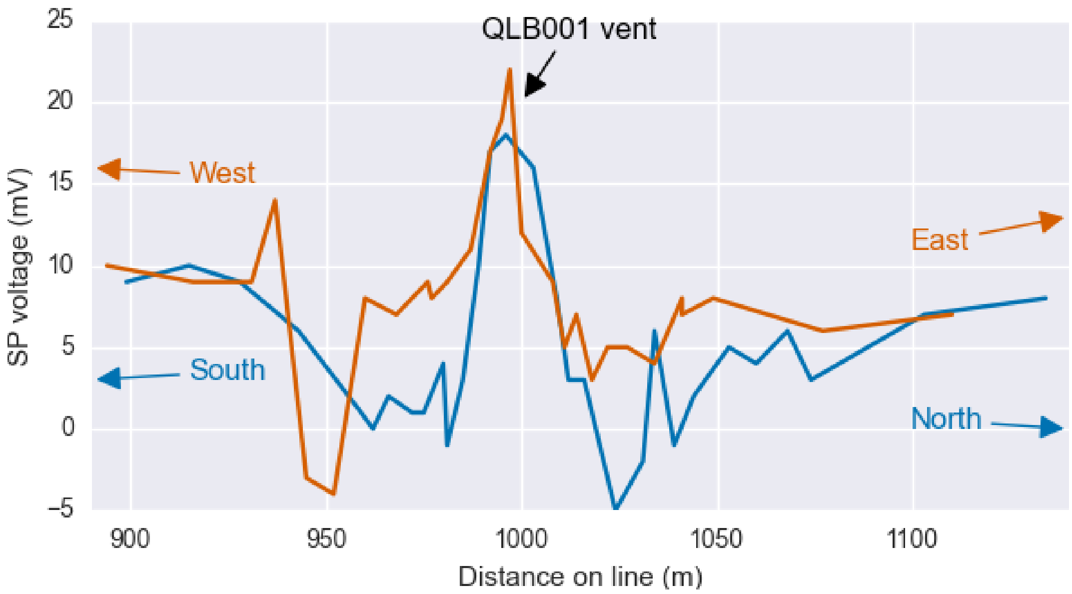


Figure 4-20: Self-potential data from orthogonal profiles crossing the QLB001 vent at Lake Blanche

4.3.2.2 Deep structures

AMT data were collected at four sites at the Lake Blanche Springs Group and two at Sunday Springs to the south-west. The Lake Blanche Group sites are:

- QLB4E, 300 m west of the southern Lake Blanche Springs Group vent (800 m south-west of QLB001)
- QLB3E, halfway between the two Lake Blanche Springs Group vents
- QLB1E, immediately south of QLB001

- QLB2E, more than 500 m to the east of the QLB001 vent.

The two Sunday Springs sites are:

- QSU1E, 500 m west of the springs
- QSU2E, within the Sunday Springs Group itself.

The data collected at both groups were of reasonable quality but had poor bandwidth coverage due to short instrument deployment times. Responses were calculated in the range 1–200 Hz. Apparent resistivities across this bandwidth varied between 1 Ωm and 100 Ωm, with significant variation between the two orthogonal modes. Figure 4-16 shows the geoelectric strike (i.e. the TE mode electric field direction) derived from phase tensor analysis of the responses. The high-frequency responses at the top of Figure 4-16 (e.g. 200 Hz) relate to a penetration depth of approximately 35–50 m, and the lowest frequency responses (e.g. 1 Hz) correspond to approximately 2–3 km penetration depth.

At the Lake Blanche Springs Group, the sites at the QLB001 vent (QLB1E) and off to the east (QLB2E) strike to the north-north-west at high frequencies (penetration depths of 35–160 m) but then move through a pseudo-1D at intermediate frequencies (depths of ~ 1 km) before indicating 3D structure with a dominant strike to the north-east at depths of more than 2 km.

Interestingly, the site between the two Lake Blanche Group vents (QLB3E) indicates 3D structure at all frequencies. It is oriented north-north-east throughout the bandwidth, indicating a dominant structure in this orientation, which is coincident with a line connecting the two vents. This strongly suggests that both vents are related to a single structure that is likely to be more complex than a single steeply dipping fault plane. Given that there are responses immediately to the north and east that are consistent with north-north-west–striking fault zones that are limited to shallow depths only, it is possible that a regional-scale 'deep' (i.e. >500–1,000 m) fault structure is present underneath the vents, which has formed in a transpressional or transtensional stress environment and led to the development of en-echelon fault planes closer to the surface in 'flower' structures (Aldam and Kuang 1988). These surface structures may not contain significant displacement, although, as noted below, there appears to be significant displacement of Mesozoic and Permo-Carboniferous sediments at depths of ~ 1,000 m beneath this spring group (Figure 6–4). It is possible that the asymmetric SP feature about 70 m west of QLB001 may be related to such a near-surface fault plane, although nothing appears at this location in the NanoTEM resistivity model.

The AMT sites at the Sunday Springs Group indicate 3D electrical structure at all but the deepest responses, which supports the interpretation above of multiple fault orientations in the top 500–1,000 m of the subsurface. The dominant skew-inclusive strike of both sites at Sunday Springs varies from north-north-west around to the north-west at greater depths, but the skew values indicate the response is 3D and that the structure is more complicated than a single strike direction represents.

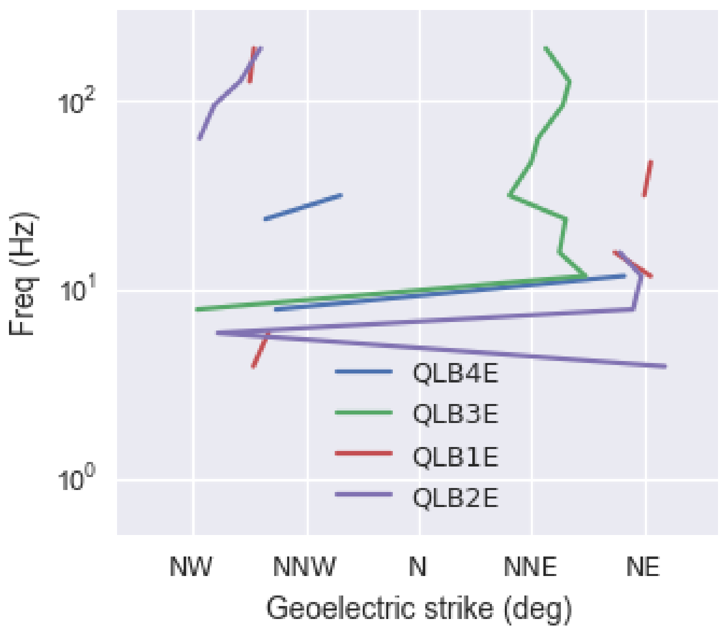


Figure 4-21: Geoelectric strike from AMT data at Lake Blanche Springs Group

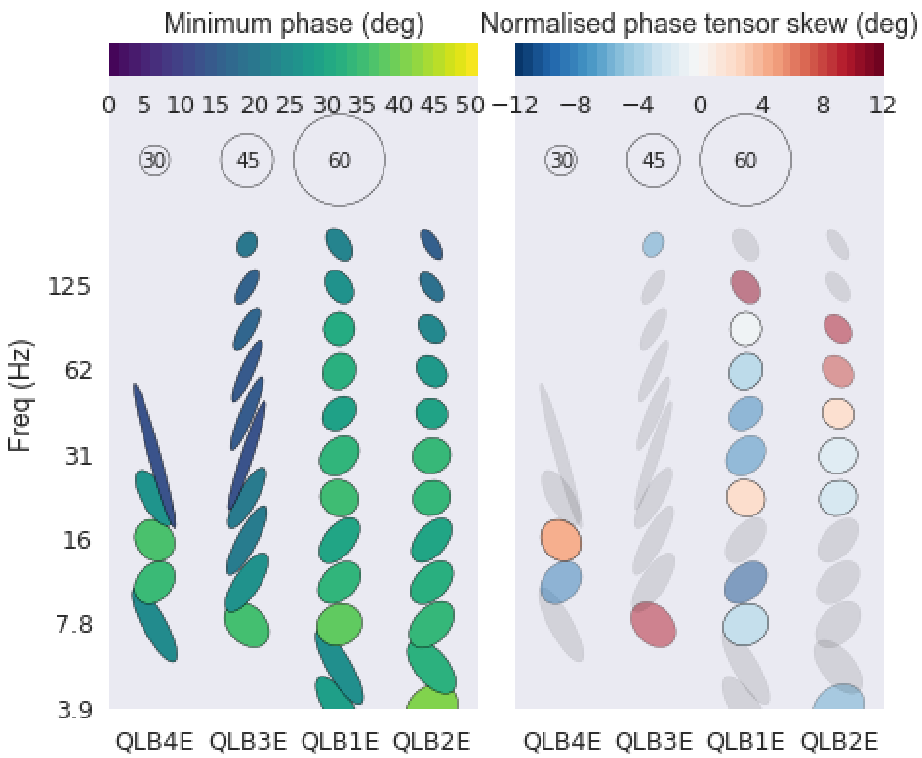


Figure 4-22: Phase tensor ellipse pseudosections from AMT sites at the Lake Blanche Springs Group

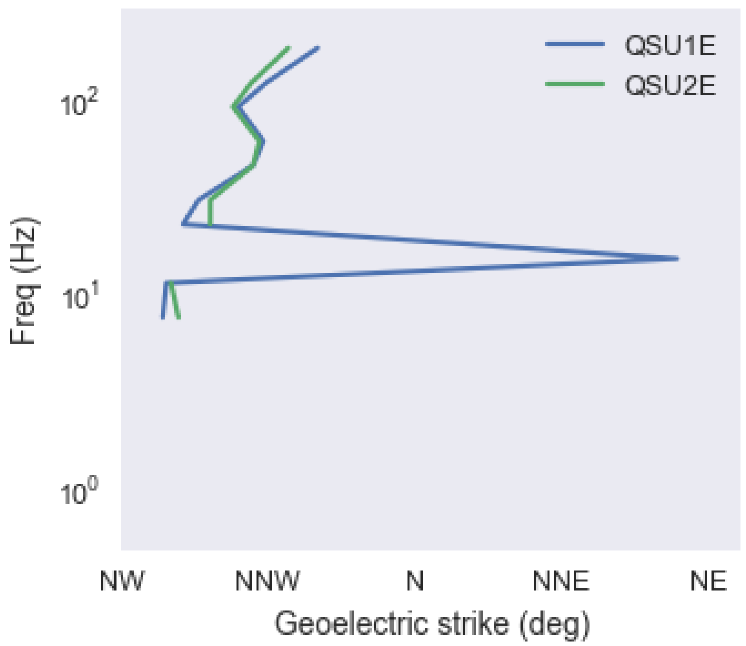


Figure 4-23: Geoelectric strike from AMT data at the Sunday Springs Group

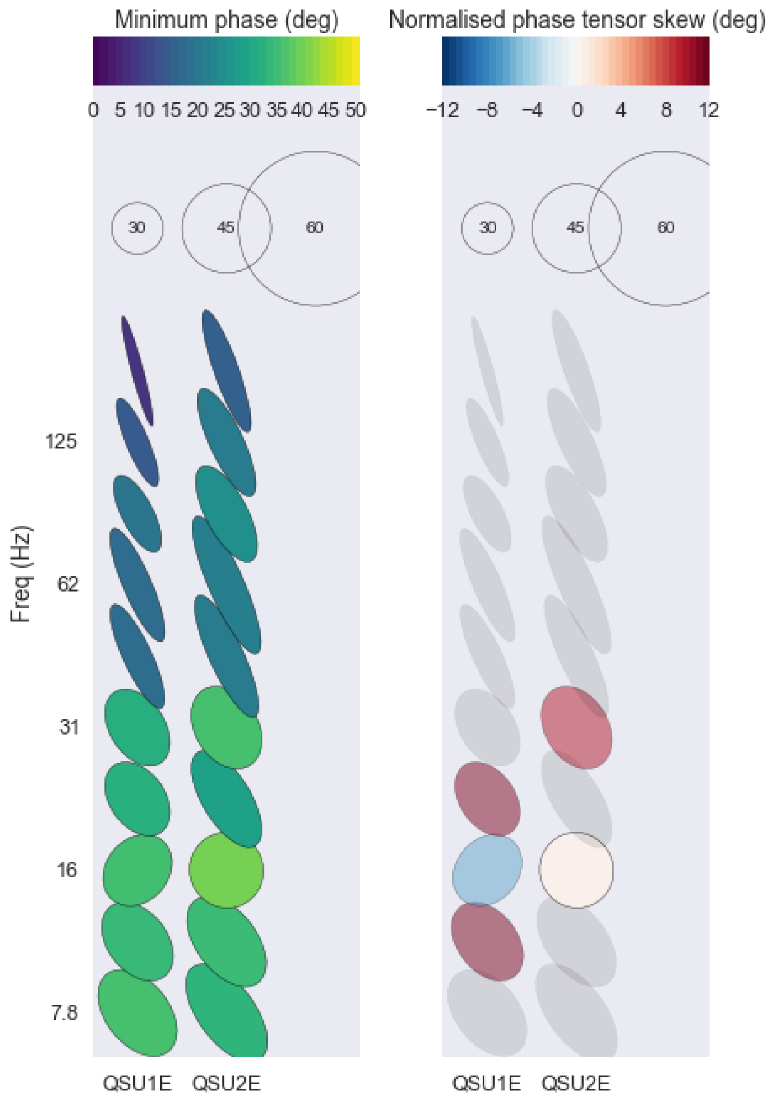


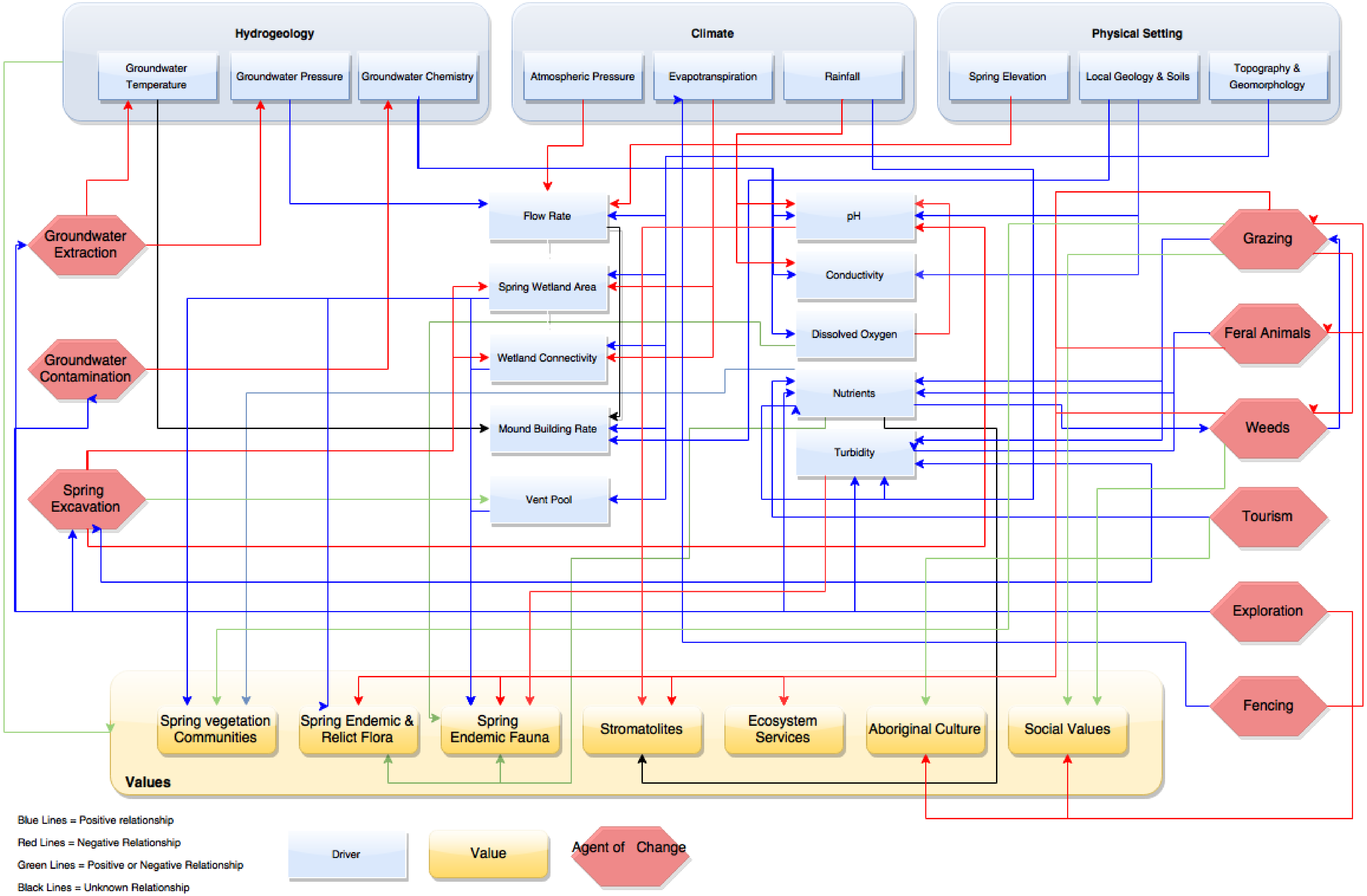
Figure 4-24: Phase tensor ellipse pseudosections from AMT sites at the Sunday Springs Group

4.4 Ecological assessment

4.4.1 Spring model

The generalised GAB spring box-line model Source: Gotch et al. (2016)

Figure 4-25) developed by Gotch et al. (2016) also applies to the springs in the Lake Blanche survey area. This ecohydrological model describes the relationships between the drivers and values of GAB springs and the agents of change that may affect the springs. For further detail and supporting evidence, see Gotch et al. (2016 Section 4.3).



Source: Gotch et al. (2016)

Figure 4-25: Generalised Great Artesian Basin spring model (box and line)

4.4.2 Spring types

The spring types observed in the Lake Blanche survey are shown in Table 4-3. Several of the types have already been described as part of the Lake Eyre Basin Springs Assessment (LEBSA) project and are explained in detail in Gotch et al. (2016). Three new spring types were observed during the survey. Conceptual models for two of these have been developed in detail here: Erosional Channel Springs (Figure 4-26) and Salt Lake Brine Density Springs (Figure 4-27). The third type is Mud Springs; these were only present at Lake Callabonna and represent the second known occurrence of these types of springs in South Australia. One Mud Spring is known to occur at Dalhousie that is significantly smaller than the Mud Springs at Lake Callabonna. At present, very little is known about these springs in South Australia; they are considered more frequent in Queensland and New South Wales. Until further studies of the South Australian Mud Springs are undertaken, it is recommended that the Queensland spring type developed as part of the broader LEBSA project be used.

The conceptual models (Figure 4–26, Figure 4–27) present an overview of the knowledge about these spring types, including the natural and human-induced drivers and their impacts, potential impacts of coalmining and coal seam gas activity. Connectivity is discussed in terms of the surface hydrological connectivity between spring vents. Critical chemistry and knowledge gaps are highlighted. Evidence-based tables have been developed for the new spring types (Appendix E).

Table 4-3: Surveyed spring complexes, spring groups and associated types

				Spring types											
Spring complex	**Spring group**	**Visited**	**Surveyed**	**Travertine Mounds**	**Rocky Seeps Terraces**	**Sand Mounds**	**Flat Depressions**	**Abutment Springs**	**Erosional Channel**	**Salt Lake Springs**	**Mud**	**Diffuse Discharge (scald)**	**EPBC-listed species[1] species**	**NPWSA-listed species[1] species**	**Notes**
Lake Blanche (2 spring groups)	Lake Blanche	✓	✓				✓			✓		✓			
	Sunday	✓	✓				✓			✓		✓			
Reedy (2 spring groups)	Reedy	✓	✓			✓			✓			✓		1	
	Rocky (extinct)	✓	✓	✓								✓			Survey completed by Western Mining Corporation
Petermorra (4 groups)	Petermorra	✓	✓		✓			✓				✓	1	1	Survey unfinished due to weather and time constraints
	Public House			✓					✓				1	1	
	Chimney	✓			✓			✓				✓			
	Catt	✓	✓						✓			✓			
Twelve Springs (1 group)	Twelve	✓	✓		✓	✓							1	2	
Lake Callabonna (Mulligan – 3 groups)	Mulligan South	✓	✓	✓		✓	✓		✓						
	Mulligan Mid	✓	✓			✓			✓						
	Mulligan North	✓	✓			✓			✓		✓				
Lake Callabonna (Callabonna – 4 groups)	Callabonna South	✓	✓	✓	✓					✓					Partial survey due to time constraints
	Callabonna Mid	✓	✓							✓	✓				
	Callabonna East	✓	✓							✓					
	Callabonna Far North														

[1] EPBC- and NPWSA-listed species are the total number of rated flora and fauna species under each of these legislations (Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* [EPBC], and South Australian *National Parks and Wildlife Act 1972* [NPWSA]) recorded in the Biological Databases of South Australia within the area of each spring group polygon (data supplied by D. Thompson, DEWNR, 25 February 2016).

Erosional channel springs

Erosional channel springs occur when drainage systems erode through overlaying regolith and confining layers into the aquifer allowing discharge to occur. They tend to be younger and potentially transient, lack travertine and are influenced by local geomorphology and surface hydrology than other spring types. Typically the springs will be located in the bases of creeks or adjacent to the sides of the banks. Small clusters of these springs will occur in a disjunct band along the various branches of creeks draining out from the upper catchment areas, a result of this is that these springs are naturally very fragmented and species lost cannot readily recolonise back in from neighbouring springs outside the immediate cluster. The mounds that form tend to be made of sands and silts, contain little if any carbonate and are often soft and spongy. Vegetation from the springs help protect the soft mounds from erosion during flood events however the relatively frequent inundation by flood waters results in low frequencies of endemic crustaceans and molluscs. Significant examples of these springs include Petermorra, Public House and Reedy Springs in the Lake Frome Supergroup.

Erosional channel spring at Petermorra Springs

Erosional channel springs at Petermorra Springs

Natural drivers

- Groundwater pressure
- Groundwater chemistry
- Local geology and topography
- Low spring connectivity between clusters
- Surface hydrology and flooding frequency
- Evapotranspiration, atmospheric pressure and tidal influences

Human induced drivers

- Aquifer drawdown from current developments
- Grazing pressure, and trampling by domestic and feral animals
- Introduced weeds and pests
- Alteration of natural flow paths

Impacts

- Provides refugia habitats in the upper catchments of ephemeral river systems
- Maintains ecosystem integrity
- Connectivity between springs cotrolled by local topography and hydrology
- Flooding results in low endemic fauna freq.

Impacts

- Reduction and fragmentation of habitat
- Reduced biodiversity
- Reduction in veg cover increases erosion of the mound
- Damage to spring structure
- Change in flood frequency

Potential impacts of coal mining and unconventional gas activity

- Decrease in aquifer pressures, due to groundwater extraction
- Reduction in wetland area and increase in habitat fragmentation
- Increased acid sulfate hazard and spring mound erosion
- Increased risk of extinction of short-range endemics
- Contamination of groundwater
- Structural destabilisation of aquifers and aquitards amplifying drawdown impacts
- Reduced biological values

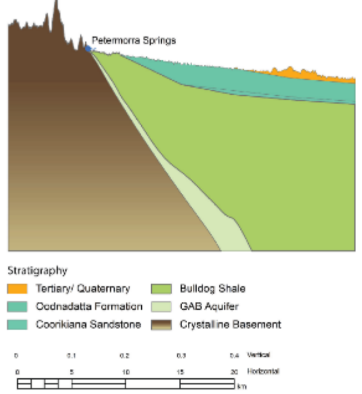
Connectivity

Relatively low connectivity between individual vents, although in some springs, such as the lower terraces of Freeling Springs, several vents can be permanently connected. Most vents are isolated from each other, except during periods of extremely low atmospheric pressure and large rain events. Exceptions occur in spring groups with high flows, outside the Preliminary Assessment Extent.

Critical chemistry

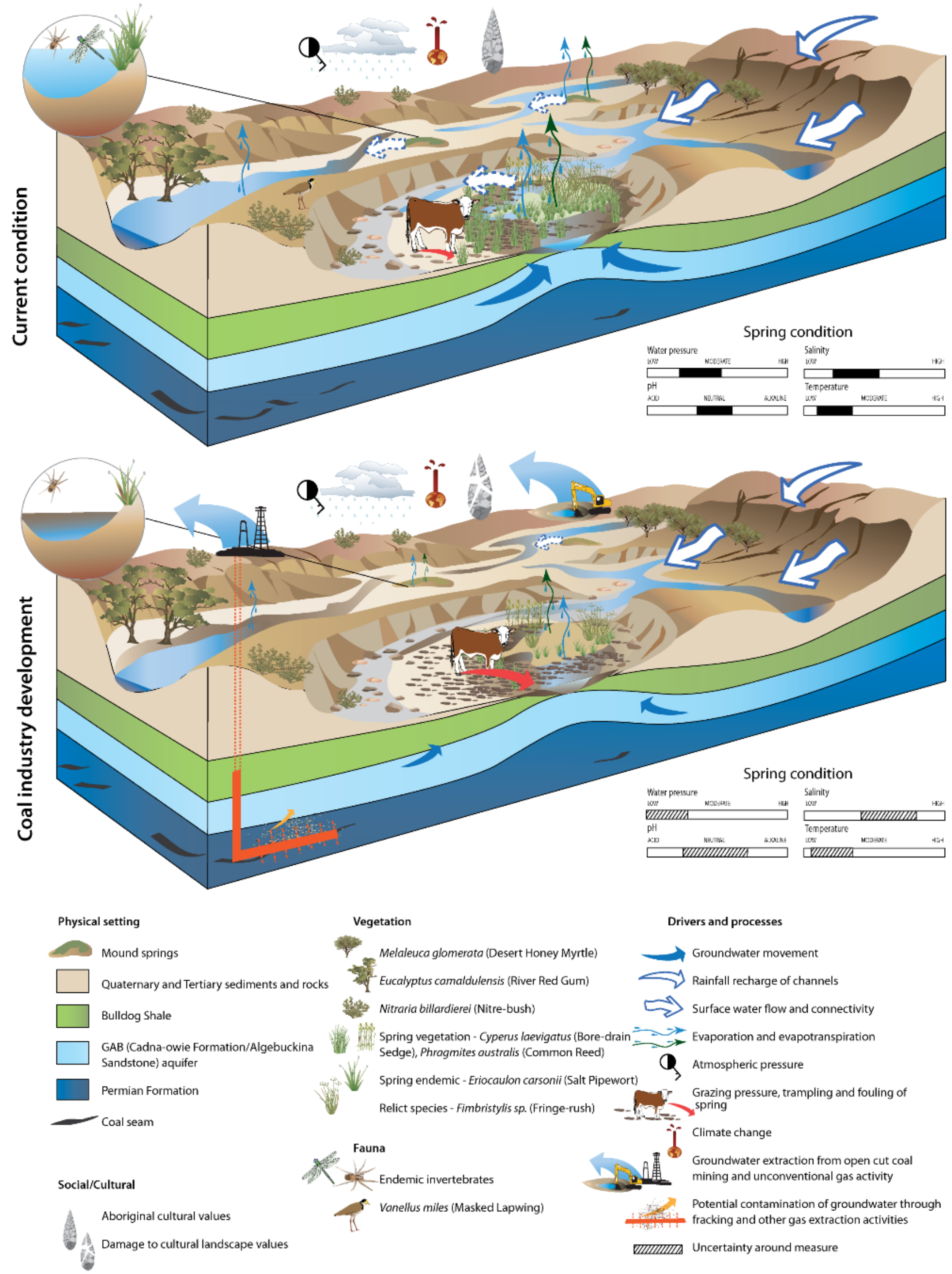
Sulfides, heavy metals and metalloids (e.g. Arsenic) accumulate in anoxic mounds. If spring flow decreases and deposits dry out, sulfides can oxidise into sulfates. If the mound rewets, as a result of pressure recovery or rainfall, the sulfates dissolve into the water creating sulfuric acid. Acidification can mobilise toxic metals into the water, impacting spring fauna.

Structural geology model for Petermorra Springs



Knowledge gaps

- Connectivity between aquifer and springs
- Sensitivity of springs to aquifer drawdown
- Limited species distribution information
- Sulfides, heavy metal and metalloid accumulation and mobilisation in springs
- Degree to which spring ecosystems have been affected by post-European disturbance

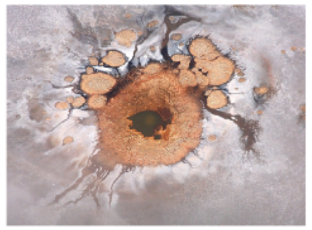


Government of South Australia
Department of Environment, Water and Natural Resources

Figure 4-26: Ecological conceptual model for Erosional Channel spring type

Salt lake brine springs

There are a number of different types of springs that occur on salt lakes. Some are conventional GAB springs and can be better classified as sand or travertine mounds. Others may be similar in appearance but source their water from non GAB Cenozoic aquifers, these can also be classified as sand or travertine mounds however depending on the connectivity of the overlying aquifers to the GAB they may or may not be impacted by water extraction from the GAB. Some of these springs may be discharging water from multiple sources including the GAB. A third type exits, Brine Density Springs, here dense hyper saline brines interact with and push less saline (and less dense) water to the surface. Examples of these can be seen on Lake Frome, Kati-Thanda Lake Eyre and Lake Torrens. These springs can be ecologically significant and are likely to be disconnected from any deep aquifers likely to be exploited by coal or unconventional gas activities. The information presented here deals mainly with brine density springs the other types potentially present on salt lakes are covered in Gotch *et al* (2015). We have grouped the other types here due to salt lakes importance as topographical features in this area.



Lake Eyre brine spring

Small salt precipitation brine spring at Lake Frome

Natural drivers
- Groundwater pressure
- Groundwater chemistry & conductivity
- Local geology
- Extremely low spring connectivity
- Influence of atmospheric pressure and lunar tidal cycle on spring flow
- Evapotranspiration

Human induced drivers
- Aquifer drawdown from current developments (e.g. pastoral bores, mining and town water supplies) only effects GAB and cenozoic springs
- Introduced weeds and pests

Impacts
- Maintains ecosystem integrity (spring flow, connectivity and biodiversity)
- Provides ecosystem services
- Source population for salt tolerant species ie Hardyheads

Impacts
For artesian springs
- Reduction and fragmentation of habitat
- Loss of resilience

For brine density springs
- reduced resiliance due to ferals

Potential impacts of coal mining and unconventional gas activity
- Low likelihood of impact from coal and unconventional gas activity especially for brine density springs
- uncertanty as to the source of the water will require detailed investigations to be carried out before determining they types of springs present

Connectivity
Almost zero conectivity during dry periods. During flood events springs are either totally inundated or are surrounded by lake water

Critical chemistry
For travertine and sand mounds the critical chemistry will be the same as for those types

Brine density springs will be strongly influenced by interactions between shallow groundwaters and evaporitic brines

Knowledge gaps
- Source aquifers if any
- Connectivity between aquifers and springs
- Sensitivity of springs to aquifer drawdown

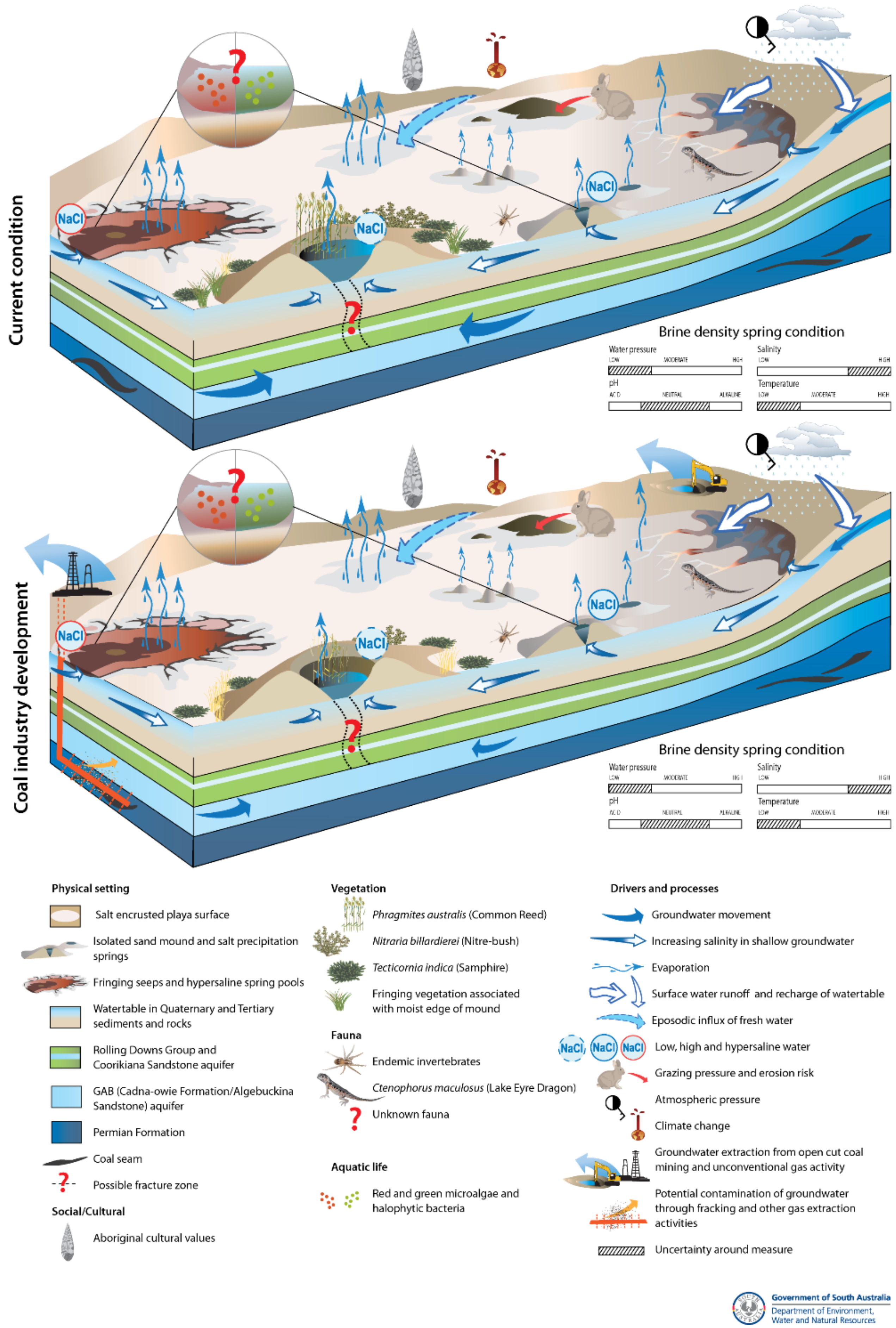


Figure 4-27: Ecological conceptual model for Salt Lake Brine Density spring type

4.4.3 Spring complex ecological characterisation

Detailed spatial, morphological, biological and hydrogeological data for Lake Blanche Springs is stored in SA Geodata and the Biological Databases of South Australia. The following provides a summary of the data and other knowledge for these springs.

4.4.3.1 Lake Blanche

Lake Blanche spring complex is located on the bed of Lake Blanche. The complex contains 10 vents in two groups: Lake Blanche (2 vents) and Sunday (8 vents). These springs are very isolated and presently well removed from the effects of cattle, although evidence exists of previous grazing impacts. Lake Blanche Spring Group consists of two vents surrounded by thick samphire. The Lake Blanche spring vent itself is heavily modified, with a concrete culvert driven into the spring to create a water trough. *Typha domingensis* (common bulrush) dominates this vent (Figure 4–28, top). The other spring is infested with *Polypogon monspeliensis* (annual beard grass). Sunday Springs are located on a small sand mound 1.3 km south of Lake Blanche Springs. These springs are also infested with *P. monspeliensis* (Figure 4–28 bottom) but are notable because the island supports a pelican breeding colony. The only species of note recorded here is *Mimulus repens* (creeping monkey-flower) which, although not rare, is uncommon in GAB springs.

The Lake Blanche Springs traditionally were in Pirlatapa country, but there are no Pirlatapa people remaining. Springs are cared for by the Dieri and Adnyamathanha people, who both had strong connections with the Pirlatapa (Hercus and Sutton 1985).

Very few ecological studies have occurred at these springs, and this study represents the most detailed assessment to date. The main vent in the Lake Blanche Spring Group was surveyed in 1984 (McLaren et al. 1985) and subsequently in 2005 by BHP Billiton (formerly Western Mining Corporation [WMC] Resources) as part of their third expansion pre-feasibility study (D. Niejalke, WMC, pers. comm., 2005). Neither of the earlier two surveys reported the presence of *T. domingensis*, but it was present in this survey at QLB001, indicating recent colonisation by this plant.

Spring types represented in this complex are predominantly Flat Depressions or Salt Lake (non–Brine Density type) springs described in Gotch et al. (2016).

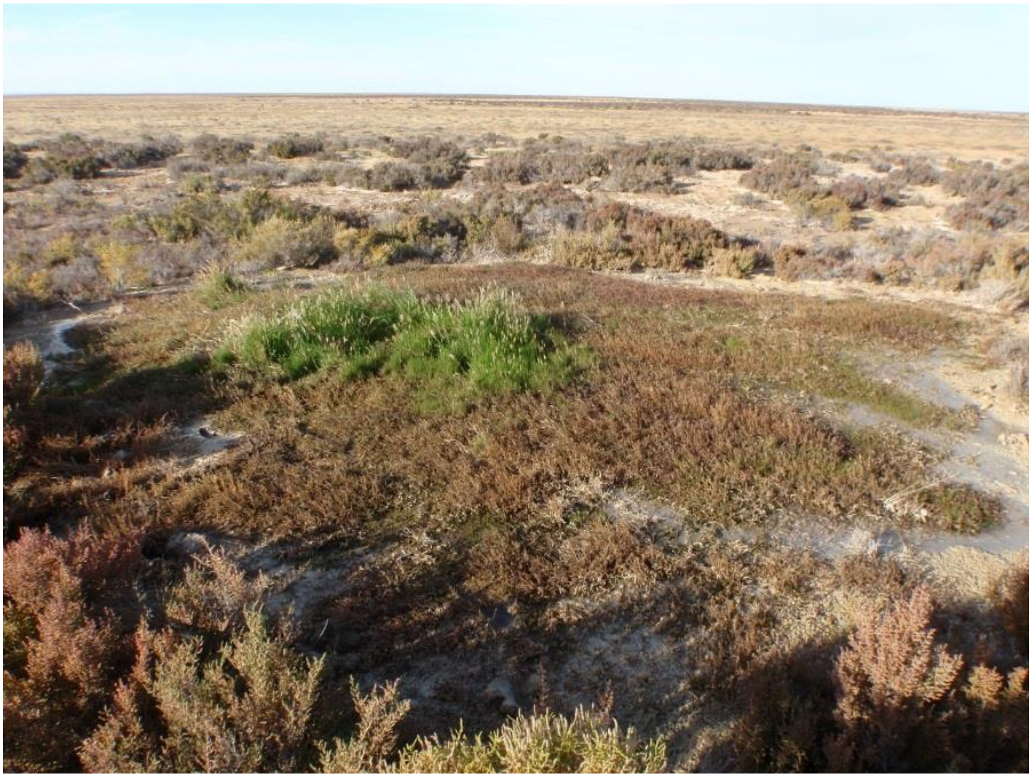


Figure 4–28: Lake Blanche Springs (top) and Sunday Springs (bottom)

4.4.3.2 Reedy

Reedy springs complex consists of two spring groups, Reedy (383 spring vents) and Rocky (one spring vent). Historically, the Heritage of the Mound Springs survey (McLaren et al. 1985) combined the Reedy, Petermorra and Twelve spring complexes into one large complex called the Mt Hopeless complex. This combination does not meet with the classification criteria for springs (Gotch 2013), and the complex has been split to better reflect the definition of a complex.

The springs are located in a slight depression in gibber country just north of the Strzelecki Track and north-west of Blanchewater Ruins. Rocky spring is extinct. In 1984, the spring was reported as inundated by floodwater and was not surveyed. It was visited by Gotch in 2002 and 2004, and was extinct on both occasions. Shells of the aquatic snail *Thiara* sp. were observed on both visits, but no live specimens were observed. Reedy Springs is a large spring group comprising two distinct sections. The main mound is several hundred metres across, and is mainly sand. It is eroded on its southern and north-eastern edges by a drainage channel that exposes the aquifer, creating the second spring zone in the group.

The springs are in poor condition due to excessive cattle grazing (Figure 4–29, top). The vent pools on the top part of the mound are particularly polluted (Figure 4–29, bottom). Macroinvertebrate diversity is low, and the only potential endemic group observed were wolf spiders. Floristically, the springs have limited diversity. A few vents had diverse vegetation communities, but the majority were vegetated only with *Cyperus laevigatus* (boredrain sedge). Two relict plant species have been found here, *Fimbristylis sieberiana* (fringe rush) and *Schoenoplectus subulatus* (clubrush); however, their distribution within the spring group is very restricted.

These springs are important cultural sites for the Pirlatapa; however, there are no Pirlatapa people remaining. Springs are cared for by the Dieri and Adnyamathanha people, who both had strong connections with the Pirlatapa (Hercus and Sutton 1985). The explorer Edward Eyre passed near here in his 1839–1841 expeditions, but did not report the presence of springs in the area.

These springs have been ecologically surveyed three times before this investigation. The first was McLaren et al. (1985). Gotch undertook an initial elevation survey in 2004 and, in 2005, BHP Billiton (formerly WMC) undertook a detailed study of the springs as part of their third expansion pre-feasibility study (D. Niejalke, BHP Billiton (formerly WMC), pers. comm., 2005).

The spring types in this complex are mainly Sand Mounds and Erosional Channel Springs. The one vent at Rocky is a very weathered Travertine Mound.

Figure 4–29: Reedy springs showing polluted top area (top) and springs in an Erosional Channel (bottom)

4.4.3.3 Petermorra

The Petermorra complex consists of four spring groups, Chimney Spring in the far east, Petermorra in the east, Public House in the main central part of the complex and Catt to the far west. There are 199 vents in total, with the majority in the Public House and Petermorra groups. As mentioned above, these spring groups were formerly classified part of the Mt Hopeless complex. The springs are located on the edge of the GAB adjacent to the Flinders Ranges. They are found abutting the ranges, in creek and drainage lines of the Petermorra Creek catchment, and on smaller carbonate terraces.

The springs receive some grazing by cattle but are mostly in good condition; pugging mainly occurs on the margins of larger flowing springs (Figure 4–30, top). The springs are difficult to access and adjacent to an area that is difficult to fence, so stocking rates are intentionally kept low for this area. Other impacts occur here from flooding, and at least one mound that was present in 2004 has been washed away.

The springs in this group have low macroinvertebrate diversity but very high floristic diversity. The Mound Spring–endemic *Eriocaulon carsonii* (salt pipewort) is abundant throughout these springs, and it is only one of two sites where the significant spring species, *Utricularia fenshamii* (mound spring bladderwort), is found in South Australia. Other significant flora include *F. sieberiana* and a species of *Glossostigma* (mud mat).

As with all of the springs in this study, the Petermorra complex is in Pirlatapa country. The stories that remain for these sites are looked after by the Adnyamathanha people (Hercus and Sutton 1985).

These springs have been ecologically surveyed three times before this investigation. The first was McLaren et al (1985). Gotch undertook an initial elevation survey in 2004 and, in 2005, BHP Billiton (WMC) undertook a detailed study of the springs as part of their third expansion pre-feasibility study (D. Niejalke, BHP Billiton (WMC), pers. comm., 2005).

The spring types in this complex vary, often by group. Chimney and Petermorra are predominantly Abutment springs, and springs in the Public House Group are predominantly Erosional Channel springs, with some Travertine Mounds to the western end of the group (Figure 4–30, bottom), including the named Catt Spring (an unmapped extinct spring to the east of OPH502, not to be confused with springs in the Catt Group, which are all Erosional Channel springs).

Figure 4–30: Petermorra Springs complex, showing cattle grazing and pugging damage around a flowing spring (top) and extinct Travertine Mound in the west of the spring complex (bottom)

4.4.3.4 Twelve

Twelve Springs is a single group complex that contains 72 spring vents, and was formerly part of the Mt Hopeless complex. The springs are located on a low diffuse discharge scald (Gotch 2013) to the edge of Twelfth Station Creek in the upper catchment of Yerila Creek. The springs are at the edge of the basin adjacent to the Flinders Ranges.

The springs here are periodically grazed, but, at the time of the survey, were in excellent condition. Access is difficult and springs may be vulnerable to periodic flooding.

The springs here are low and mainly vegetated with *C. laevigatus* (Figure 4–31). Like Petermorra, this spring group has low diversity of macroinvertebrates, and wolf spiders are the only significant species found here to date. Floristically, this group is diverse, with populations of the endemic *E. carsonii* and the rare *U. fenshamii*, *F. sieberiana* and *Glossostigma* sp.

As with all of the springs in this study, Twelve Springs is in Pirlatapa country. The stories that remain for these sites are looked after by the Adnyamathanha people (Hercus and Sutton 1985).

These springs have been ecologically surveyed three times before this investigation. The first was McLaren et al. (1985). Gotch surveyed these springs for their spider fauna in 2004, and, in 2005, BHP Billiton (WMC) undertook a detailed study of the springs as part of their third expansion pre-feasibility study (D. Niejalke, BHP Billiton (WMC), pers. comm., 2005).

The springs in this complex are nearly all Sand Mounds.

Figure 4–31: Twelve Springs (top), and a close-up of a vent (bottom)

4.4.3.5 Mulligan

Mulligan Group consists of three spring clusters on the western edge of Lake Callabonna. Mulligan South includes a cluster of distinct mounds and a scattering of isolated mud mounds. Most of the flows are small and many lack free water. Mulligan Mid includes some large flows that flood out onto the lake bed, and a sparse scattering of smaller silt and mud mounds spread over a large area. Some mounds are large, and one has an old ruin on top. Mulligan North is a cluster of silty mounds on a rise on the western edge of Lake Callabonna. Most mounds in the complex are formed by fine silty sediments, but remnant travertine is found in some areas. The mud mounds (Figure 4–32) at Mulligan are some of the best examples of true Mud Springs in South Australia. The complex was surveyed extensively in September 2015 by the Department of Environment, Water and Natural Resources (DEWNR), and a total of 73 spring vents have been mapped.

Wilsonia backhousei (narrow-leaf wilsonia), a creeping mat-forming succulent, is common on a cluster of mounds in the Mulligan South Group. The first records of this species (collected by DEWNR at Mulligan and Lake Callabonna complex in 2015) are the only known records for the Lake Eyre Basin, and the only records from the arid zone of South Australia. This species typically occurs in saline areas near the coast of southern Australia. *W. backhousei* is a threatened species in NSW (OEH 2011), but is not currently listed in South Australia. No other GAB spring–endemic, disjunct or relictual plant species have been recorded at Mulligan to date.

The salinity at all springs in the complex is higher than most other complexes in South Australia, and this is likely to influence the biological composition. There was little or no grazing impact by domestic stock during a survey in 2015, possibly due to the high salinity. The vegetation cover is very dense on the larger spring flows. Stands of *Typha* sp. (bulrush) dominate the vent of the good flows, and *Juncus kraussii* (rush), *Samolus repens* (brookweed), *Bolboschoenus caldwellii* (clubrush) and *P. monspeliensis* are common on the spring outflow.

No evidence of rare or endemic spring invertebrates have been recorded from the Mulligan complex; however, sediment and invertebrate samples collected by DEWNR in September 2015 are yet to be inspected in the laboratory.

Historical surveys of Mulligan springs have been limited, and the first comprehensive biological survey and spring vent mapping was completed in September 2015. Historical surveys only sampled a small proportion of the springs present. A general biological and cultural survey of springs by Social and Ecological only sampled one spring in the Mulligan Group (McLaren et al. 1985).

Figure 4–32: Large Mud Spring at Mulligan South

4.4.3.6 Lake Callabonna

The Lake Callabonna spring complex forms a long (approximately 30 km), undulating peninsula and intermittent islands running up the middle of Lake Callabonna in the Lake Callabonna Fossil Reserve, and includes the Mulligan spring groups to the west (described above). It is likely that spring activity has formed the peninsula and islands through the ancient accumulation of fine silty sediments, forming spring mounds and associated aeolian deposits. The spring types vary from distinct mounds to erosional gullies with no mound. Mounds in the complex are composed of fine silty sediments, sand and travertine. Most are vegetated, but unvegetated mud mounds are also present. Lake Callabonna spring complex includes some springs that have very large flows with wetland complexes covering an area of up to 3 hectares. The salinity at the springs in the complex is similar to the Mulligan springs, and higher than most other complexes in South Australia. There have been little or no grazing impacts by domestic stock due to the remote location and high salinity.

Historical surveys of the Lake Callabonna complex are limited to brief visits by Glover, Ponder and Ziedler in the 1970s and 1980s to sample fish and aquatic invertebrates. The first general biological and cultural survey of the springs was undertaken by Social and Ecological in 1984 (McLaren et al. 1985). Thirteen of the larger flows in the complex were visited by helicopter by Social and Ecological (Figure 4–33, top).

The complex is divided in four semicontiguous groups. Callabonna South consists of extensive areas of diffuse leakage, with many small and indistinct springs. Nine springs were surveyed by DEWNR in September 2015, but many springs (possibly more than 100) remain unsurveyed. Callabonna Mid was surveyed extensively in 2015, with 50 springs mapped to date. Limited survey has been undertaken at Callabonna North-East and Far North, with just one spring mapped. Inspection of satellite images suggests that many vents in these groups remain unsurveyed.

W. backhousei occurs on springs in the Lake Callabonna complex, including the Mulligan Group, with extensive colonies in the Callabonna South Group. This plant has never been recorded on mound springs before, and is listed as a vulnerable species in NSW (OEH 2011). Stands of *T. domingensis*) dominate the vent of the larger flows, with *J. kraussii*, *S. repens*, *B. caldwellii, Myoporum* sp. and *P. monspeliensis* common on the spring outflow. Many of the dominant vegetation species on these springs hay-off in winter (Figure 4–33, bottom). No other GAB spring–endemic, disjunct or relictual plant species have been recorded at Lake Callabonna to date.

Hydrobiid snails recorded by Ponder during the 1980s are the only significant invertebrate species record from the Lake Callabonna complex; however, sediment and invertebrate samples collected by DEWNR in September 2015 have not been inspected in the laboratory, and many springs remain unsurveyed.

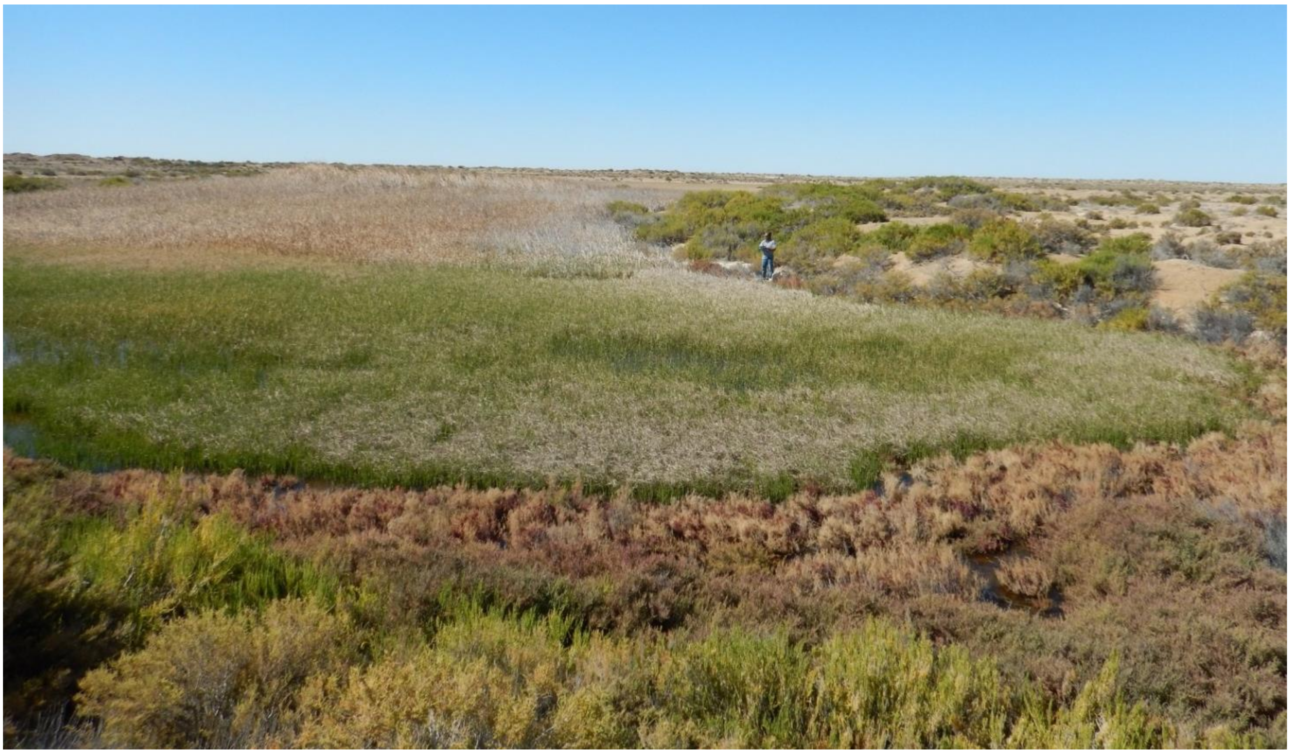


Figure 4–33: Large flow in the Lake Callabonna complex surveyed by Social and Ecological in 1984 (top), and a large flow at Callabonna Mid showing spring regrowth following vegetation hay-off in winter (bottom)

5 Discussion

5.1 Coorikiana Sandstone (?) aquifer

An analysis of historical logging data for a number of bore holes located in the investigation area indicate that there are two artesian aquifers within the Great Artesian Basin (GAB) that require consideration. The deepest is the Cadna-owie Formation/Algebuckina Sandstone aquifer, otherwise known as the J-K aquifer. The other is a shallower, thin (1–37 m) sand unit that may be interpreted as the Coorikiana Sandstone. Although the Coorikiana Sandstone has been recognised in parts of the basin to the north of the investigation area, a review of historical logs has found sandstone and other sandy sediments at a similar depth throughout the investigation area, as far south as drill hole 693800014 (BBDH0501). In the cases of wells 683800006 (Lake Crossing No. 4) and 673900011 (Warraninna Tank Bore), bore logs strongly indicate that well completion was undertaken in this shallower sand unit (Figure 2-7; Table 5-1).

The interpretation of Coorikiana Sandstone for this shallow sandstone unit found in wells 683800006 (Lake Crossing No. 4) and 683900003 (Montecollina Bore) was made by Sheard and Cockshell (1992).

Figure 5–1, Figure 5-2 and Figure 5-3 present cross-sections of the investigation area that highlight a stratigraphic interpretation based on the classification of this shallow sandstone aquifer as the Coorikiana Sandstone. Interpretation of the Coorikiana Sandstone is also based on the thicknesses encountered, which are typically less than 25 m, with the exception of thicknesses of 34 m at bore 683800234 (SNDH0501) and 37 m at bore 673900034 (New Toonketchen Bore) (Figure 2-7, Figure 5–1 and Table 5-1). Reported yields from this unit vary from 0.36 L/s to 10 L/sec. Table 5-1 summarises mapped occurrence and reported yields identified in historical logs during this investigation.

Groundwater from Lake Crossing No. 4 is notably different to other wells completed within the GAB. Furthermore, although Montecollina Bore is ostensibly completed within the J-K aquifer, monitoring and bore repair records indicate that, not only was significant groundwater encountered within this shallow sandstone unit, but it is highly likely that the aquifer currently leaks groundwater into this well. This is evidenced by its history of corrosion, maintenance issues and current state, as well as complementary historical salinity records and water chemistry. A summary of construction and maintenance records for Montecollina Bore are provided in Appendix G.

5.2 Hydrochemistry of springs and relationship to groundwater types

As discussed in Section 4.2.1.6 , although the majority of spring water samples using historical and current hydrochemistry results can be compared favourably to the J-K aquifer, results from a number of spring waters are more similar to other groundwater types, suggesting that these springs are supplied by groundwater from aquifers other than the J-K aquifer (Figure 4-3). In particular, hydrochemistry data from groundwater samples collected from the Lake Blanche (approximately 4 km from the margin of the Cooper Basin) and the Lake Callabonna spring complexes suggest that shallow aquifers such as the Coorikiana Sandstone and the Cenozoic are supplying spring water at these locations under the current hydrogeological conditions (Figure 2-1 and Figure 2-3).

In contrast, hydrochemistry data from groundwater samples collected from the Reedy Springs complex (ORE012 and ORE019), approximately 13 km from the margin of the Cooper Basin, suggest the primary source of water is from the J-K aquifer. As discussed in Section 4, the differences in hydrochemistry between groundwater from the J-K and Patchawarra Formation aquifers is small compared with groundwater from other aquifers. Additionally, the structural model interpreted for the Reedy Springs complex is one related to a large regional fault structure, which is mapped to extend towards the southern margin of the Cooper Basin, thus providing a potential means of connectivity to the Cooper Basin. Therefore, the risk to spring water supply to Reedy Springs is considered slightly higher than that of Lake Blanche and other spring complexes, although the distance of 13 km might mitigate potential impacts.

Table 5-1: Wells and drill holes with logs with Coorikiana Sandstone interpreted within the investigation area

Unit number	Name	Depth to (m)	Thickness (m)	Reported groundwater/yield
663800022	Mt Distance 5	32.31	16.46	
663800082	MPRM033	8	12	
663800083	MPRM034	6	12	
663900010	Toopawarinna Bore	374.9	7.1	Water cut noted on log (fresh water)
663900011	Nick-O-Time Bore	144.17	3.35	Subartesian (SWL 21 mbgs)
663900018	Tarkaninna 2 ("Bull Ant")	175	1	
664000023	BHPB-C1	346	2	
673800032	MPE1	17.7	3.02	
673800189	BHPB-C4	158	8	
673900002	Toonketchen Bore	287.12	5.49	0.36 L/s at time of drilling
673900006	Meteor Bore	40.84	15.85	Water cut logged
673900011	Warraninna Tank Bore	414	3	1.0–7.0 L/s
673900016	BHPB-C2	369	6	
673900017	BHPB-C3	304	6	
683800003	Dean's Lookout Bore	40.8	7.35	14,000 gpd (0.74 L/s) flow salty water at time of drilling
683800004	Petermorra Bore	169.16	21.04	Water cut (?) noted on log
683800006	Lake Crossing No.4 Bore	411.78	13.11	6.8–10 L/s
683800007	Yerila Bore	302.67	17.07	Water cut logged
683800054		56	5	2.0 L/s (pump)
683800060	CBH2	307	9	
683800099	588-7	44.2	10.86	
683800201	Yerila-1	401	28	
683800234	SNDH0501	292	34	
683900003	Montecollina Bore	507.5	24.4	Flow up to 30,000 gpd (1.6 L/sec) at time of drilling. Salinity 9,354 mg/L
683900004	Weena 1	606.6	9.1	
693800001	Yandama Bore	252.37	7.32	
693800014	BBDH0501	201	16	
693900005	Gurra 1	577.6	7.6	
693900025	LB001	408	4	
673900034	New Toonketchen Bore	260	37	
694000110	Noarlunga-1	860.5	16.5	

gpd = gallons per day; mbgs = metres below ground surface

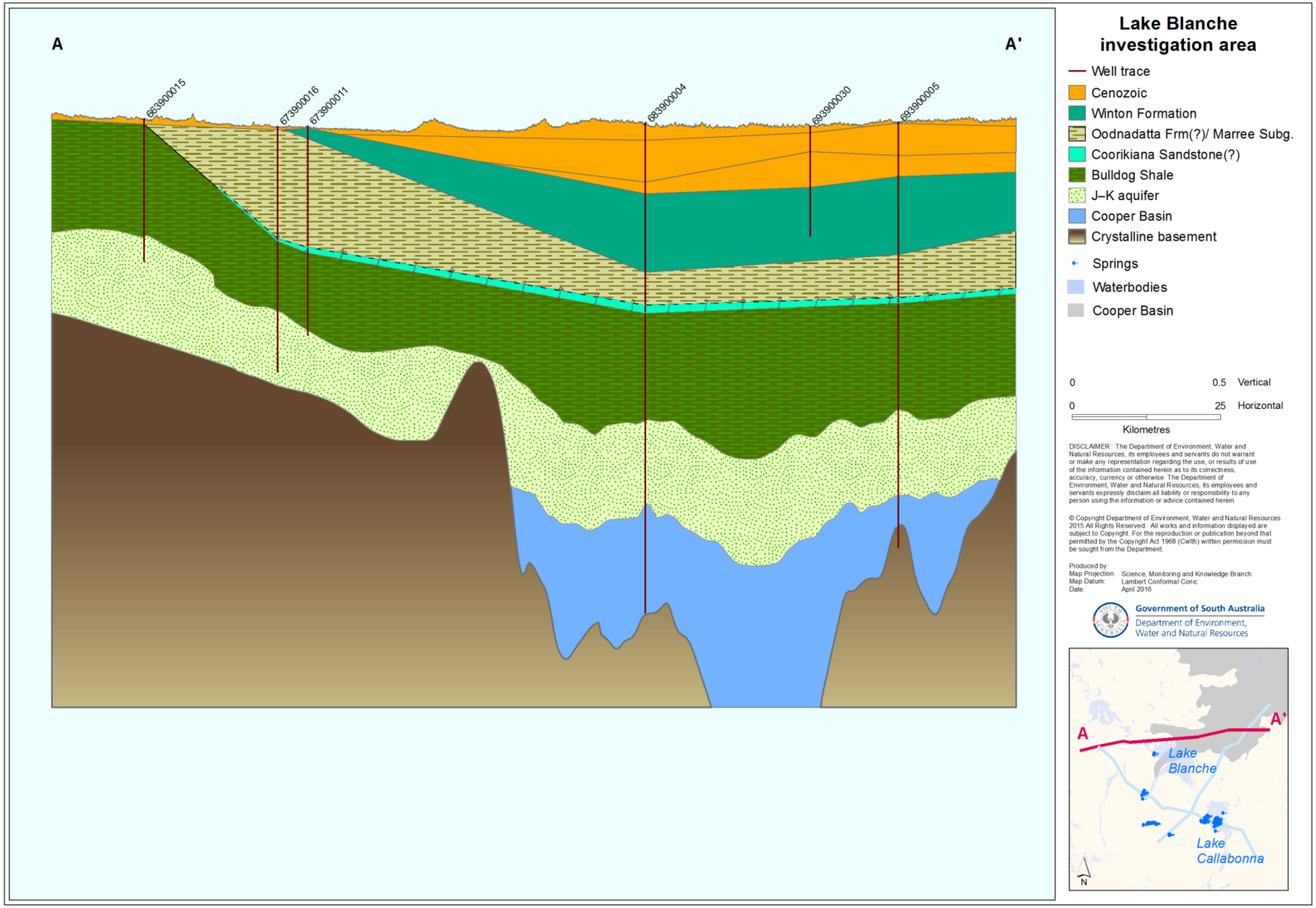


Figure 5–1: Cross-section A–A′ through investigation area, highlighting the interpretation of Coorikiana Sandstone

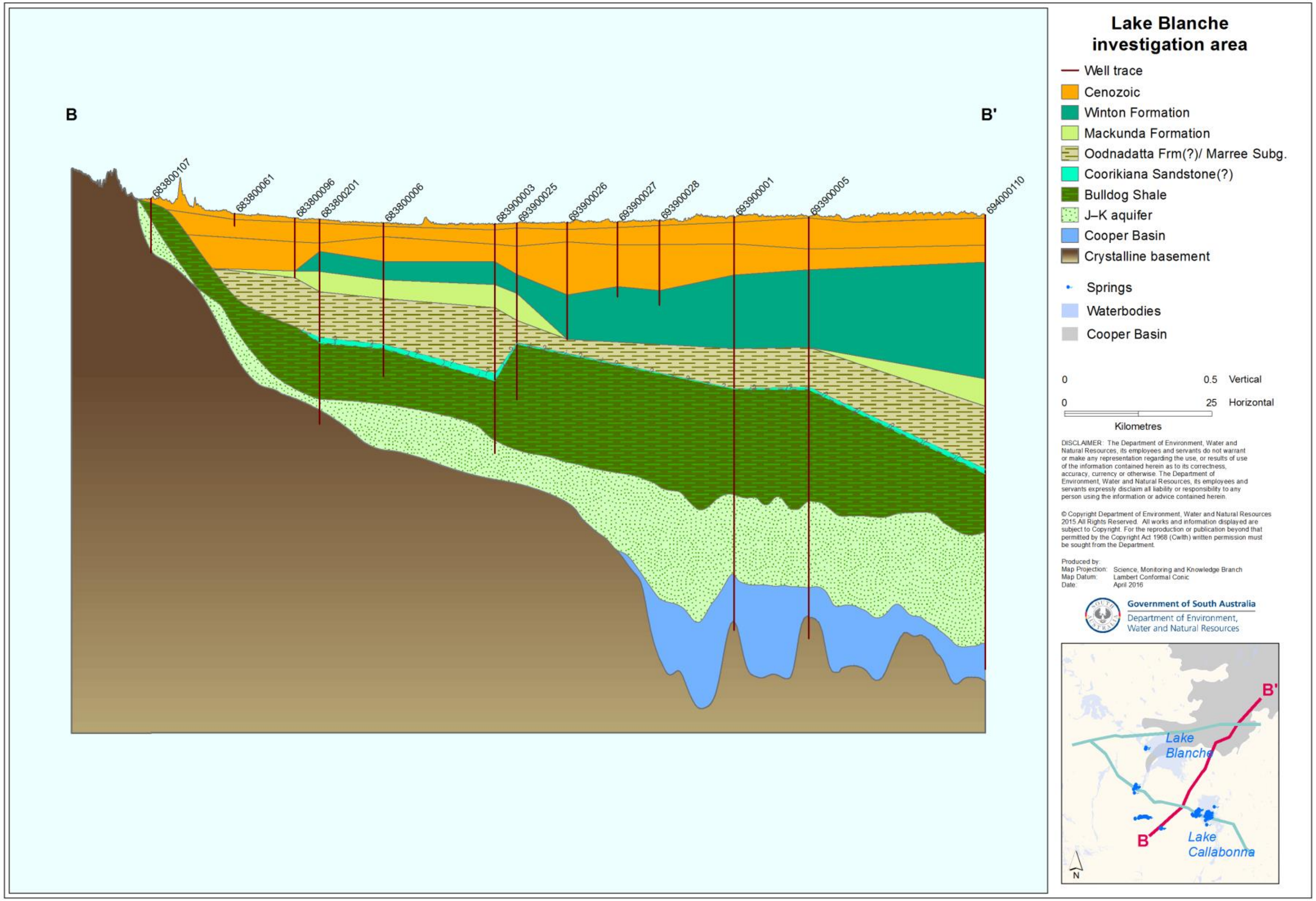


Figure 5–2: Cross-section B–B′ through investigation area, highlighting the interpretation of Coorikiana Sandstone

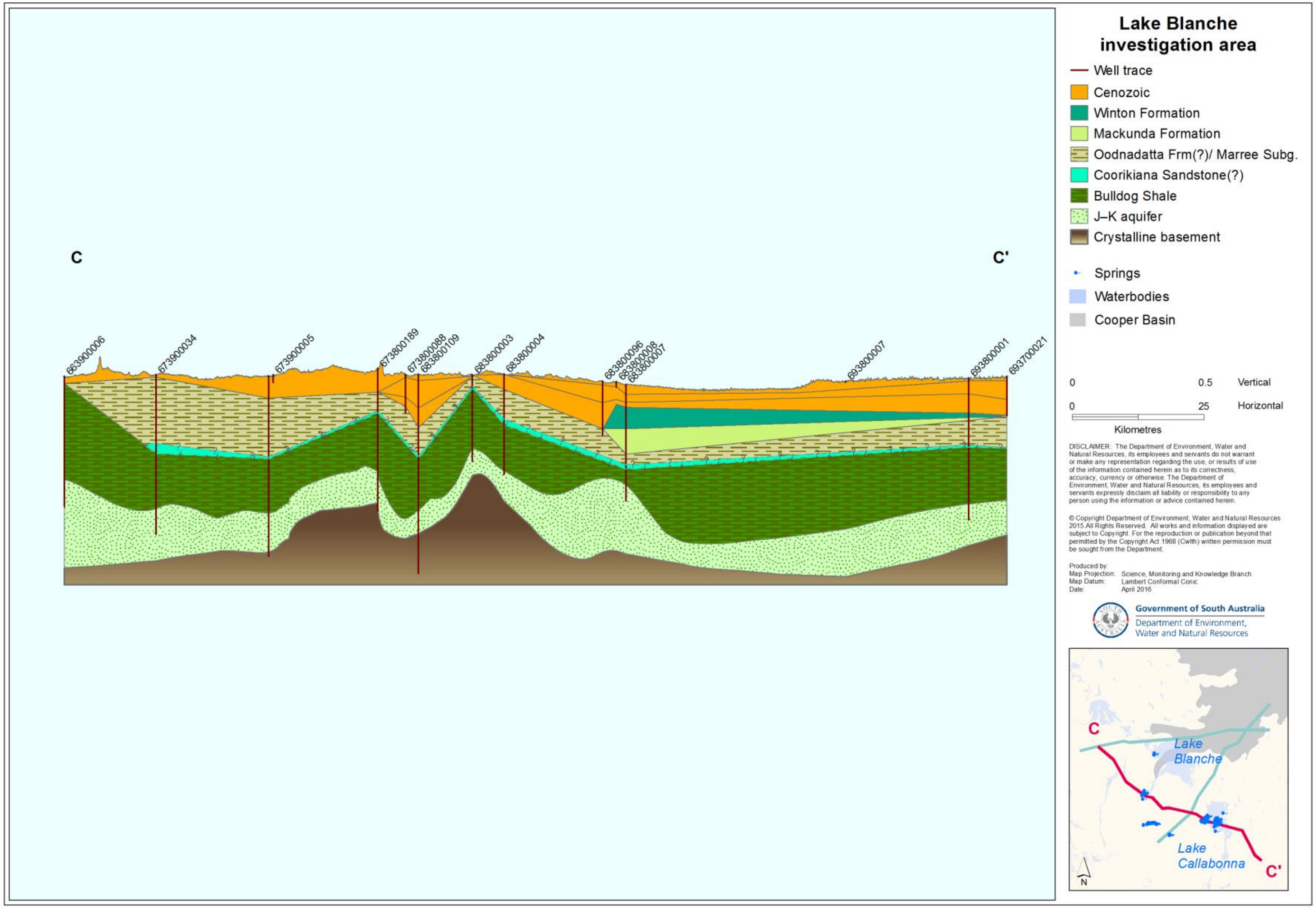


Figure 5–3: Cross-section C–C′ through investigation area, highlighting the interpretation of Coorikiana Sandstone

In both the cases of the Lake Blanche and Reedy Springs complexes, it is not known how coal seam gas (CSG) development may change the hydrogeological conditions in the larger groundwater environment, and whether this may alter the current hydrogeological conditions as observed. Examining such scenarios will require further study.

Springs that have the most similar hydrochemical profile to groundwater from the Cooper Basin are highly likely to be supplied by the J-K aquifer, given the large distances between these spring complexes and the Cooper Basin. These include Twelve Springs and Petermorra Springs, which are both located approximately 40 km south of the southern margin of the Cooper Basin. Consequently, they are considered unlikely to be affected by CSG-related developments within the Cooper Basin.

5.3 Data gaps associated with risks and hydrogeological conditions

5.3.1 Refining knowledge about the structural connectivity between springs and deep aquifers

Crossey et al. (2013) identified mantle-derived gases using $^{3}He/^{4}He$ ratios within spring waters collected from Twelve Springs and Reedy Springs. This is indicative of a structural connection between the springs and the mantle via a deep-seated fault structure in the investigation area; however, it does not necessarily indicate that groundwater from deeper sources is feeding springs. This is pertinent if potential groundwater-affecting developments change current-day conditions such as confining pressure, fracture porosity or permeability, which may be currently preventing deep groundwater migration. Although this is a possibility, there is currently no data available to indicate whether such deep-seated connecting structures exist beneath the Lake Blanche spring complex, which is the closest to the Cooper Basin and Weena Trough.

Fracking has been practised during normal conventional hydrocarbon extraction since the late 1960s (Carnell 1991; Freaner 1998). In particular, the Moomba, Toolachi and Daralinge gas fields and reservoirs provide good examples where gas found in tight formations has been successfully developed using fracking (Freaner 1998). Given this established history, it is not anticipated that the potential for induced seismicity will change markedly as a consequence of fracking with the advent of CSG extraction from the Cooper Basin compared with predominantly conventional extraction seen today.

6 Overview

6.1 Determination of hydrogeology-based risks to springs

As previously discussed in Keppel et al. (2015c), risks to spring wetland environments from developments affecting groundwater in the area 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
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. Green and Berens (2013) demonstrated that groundwater pressure head could not be used to predict the flow at a given spring. For instance, a large pressure head may be reportable near a particular spring complex; however, conduit formation that relies 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 speculated that geological controls on spring flow may also entail variations in regolith development, given recent work by OGIA (2015) stressing the importance of regolith processes in the formation and maintenance of springs.

6.2 Summaries for springs

The following tables and figures summarise the structure, hydrogeological and hydrochemical characteristics of a number of spring groups within the Lake Blanche region. Table 6-1 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 1	Basin margin, fault structure
Structure	Model 2	Basin margin, sediment thinning and outcropping aquifer unit
Structure	Model 3	Basin margin, sediment thinning and structure combination
Hydrochemistry	Group 1	Crystalline basement (fractured rock) aquifer
Hydrochemistry	Group 2	Patchawarra Formation aquifer
Hydrochemistry	Group 3	J-K aquifer
Hydrochemistry	Group 4	Shallow Great Artesian Basin aquifer (Coorikiana Sandstone)
Hydrochemistry	Group 5	Cenozoic aquifer

Group name	Spring complex	No. of springs	Structural model	Hydrochemical characterisation	Geology/Surficial materials	Est. SWL (mbgs) & flow (L/s)	Notes
Petermorra, Public House, Chimney and Catt Springs (OPC, OPH)	Petermorra	199	Primary: model 2 Secondary: model 3	Group 1 & 3	Fresh to highly weathered Rolling Downs Group and Proterozoic crystalline basement outcrop. Spring deposits, Quaternary, colluvial and alluvial sediments. Erosional and depositional environment.	-12 to 4, no flow estimated	Petermorra, Public House, Chimney and Catt Springs form a long chain of springs near the northern margin of the Flinders Ranges. Proterozoic crystalline basement, J-K aquifer, Rolling Downs Group and Quaternary colluvial and alluvial rocks and sediments all occur in the area. The thickness of the confining layer varies greatly from 0 m to 170 m.

The springs' position close to outcropping crystalline basement suggests that a thin or absent confining layer is the primary cause of spring formation at this location. However, the depth of confining layer sedimentary rock deepens to the north at a steep repose, and therefore fracturing associated with localised faulting, as evidenced in outcrop exposures of Rolling Downs Group rocks, may also be important to spring development.

Groundwater is currently thought to be primarily sourced from the J-K aquifer based on groundwater flow and hydrochemistry, with the crystalline basement fractured rock aquifer also contributing at some locations, most notably Petermorra Mound Spring.

Spring ecology

Spring types present here include Abutment, Erosional Channels and Travertine Mounds (Gotch et al. 2016). They have low macroinvertebrate diversity but high abundance and diversity of significant flora (1 endemic, 1 rare, 1 relict). The springs are in moderate to good condition due to lower grazing pressure. They are subject to occasional flooding.

Culturally, these springs are sensitive to the Pirlatapa and Adnyamathanha peoples.

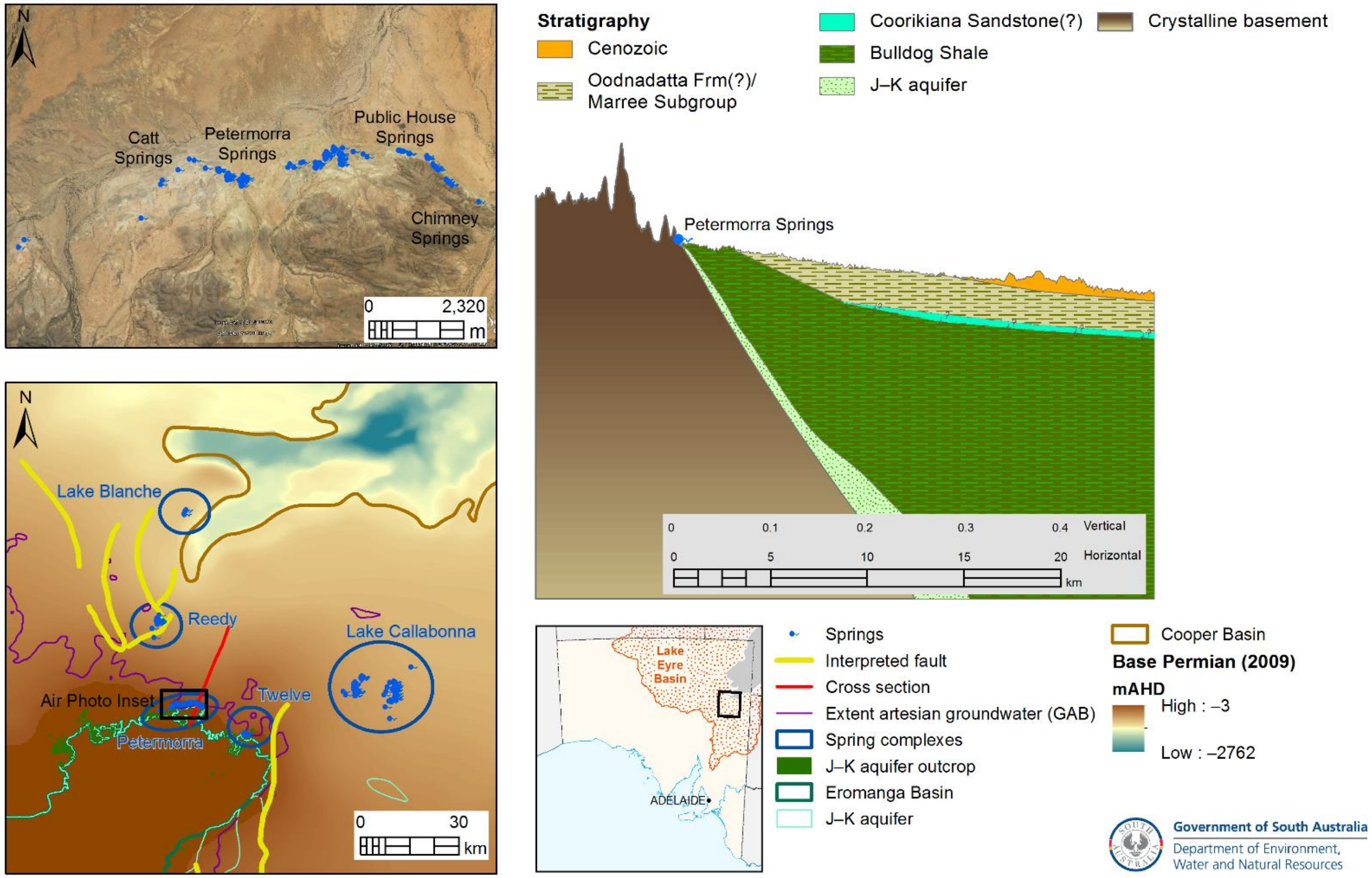
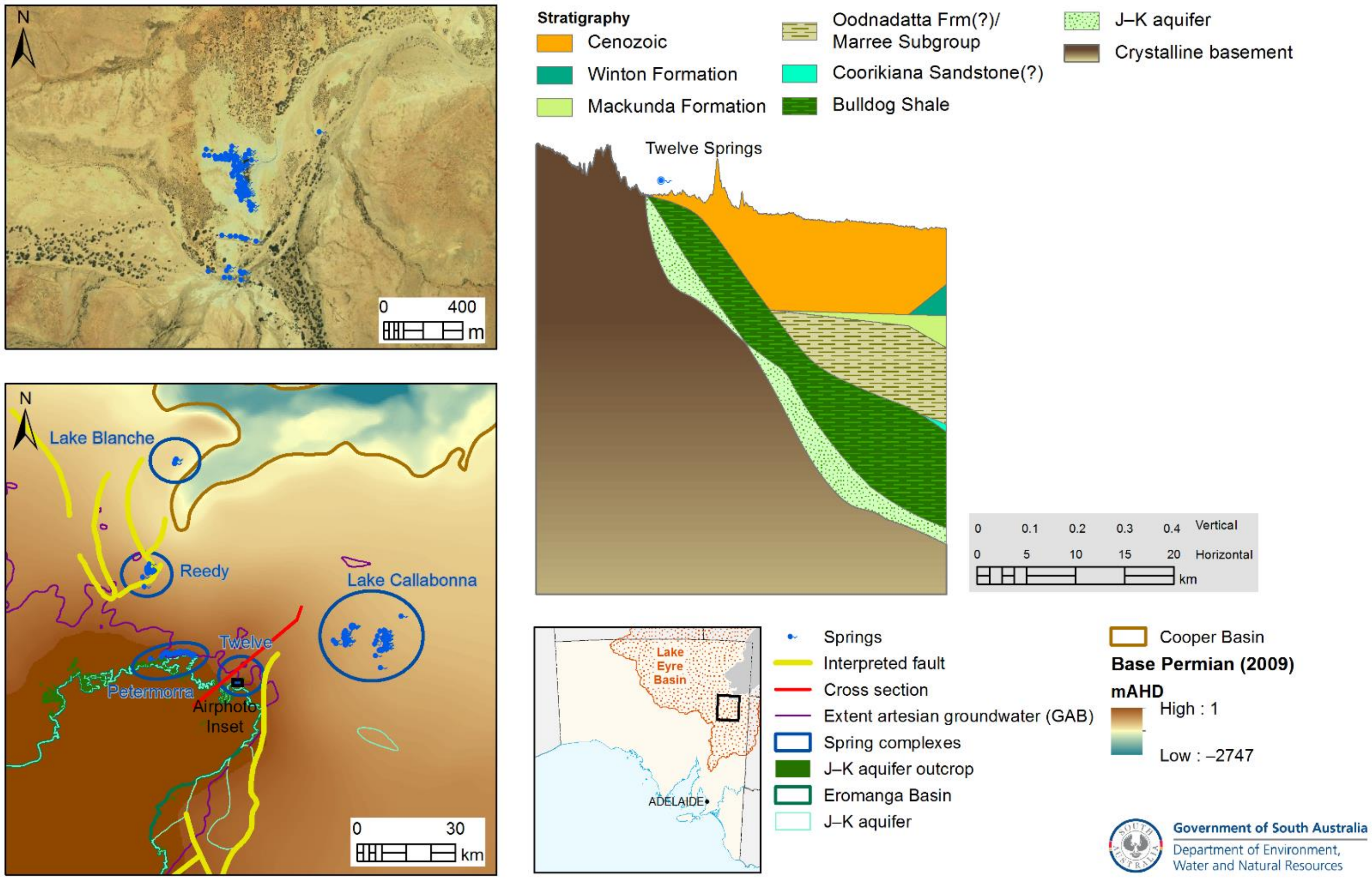


Figure 6–1: Petermorra Springs Group summary

Group name	Spring complex	No. of springs	Structural model	Hydrochemical characterisation	Geology/Surficial materials	Est. SWL (mbgs) & flow (L/s)	Notes
Twelve Springs (OTS)	Twelve	72	Primary: model 2	Group 3	Quaternary alluvial and colluvial sediments. Moderately to highly weathered Rolling Downs Group rocks. Fresh to moderately weathered crystalline basement rocks. Depositional to erosional environment.	–10, no flow estimated	Twelve Springs is near the northern margin of the Flinders Ranges. Proterozoic crystalline basement rocks, J-K aquifer rocks, Rolling Downs Group rocks and Quaternary colluvial and alluvial sediments all occur in the area. The thickness of the confining layer is generally thin (0–5 m). The springs' position close to outcropping crystalline basement suggests that a thin or absent confining layer is the primary cause of spring formation at this location. Groundwater is thought to be primarily sourced from the J-K aquifer, on the basis of groundwater flow and hydrochemistry.



Spring ecology

Spring types present here are Sand Mounds (Gotch et al. 2016). They have low macroinvertebrate diversity but high abundance and diversity of significant flora (1 endemic, 1 rare, 1 relict, 1 uncommon). The springs are in good condition due to lower grazing pressure. They are subject to occasional flooding.

Culturally, these springs are sensitive to the Pirlatapa and Adnyamathanha peoples.

Figure 6–2: Twelve Springs Group summary

Group name	Spring complex	No. of springs	Structural model	Hydrochemical characterisation	Geology/Surficial materials	Est. SWL (mbgs) & flow (L/s)	Notes
Reedy Springs, Rocky Springs, St Mary Pool (ORE)	Reedy	384	Primary: model 1c	Groups 3 & 5	Moderately to highly weathered Rolling Downs Group outcrop. Spring deposits, Quaternary, colluvial, alluvial and lacustrine sediments. Erosional and depositional environment.	–8 to –24, no flow estimated	Rocky and Reedy Springs form a chain of springs approximately 30 km north of the North Flinders Ranges and the crystalline basement outcrop therein. Rolling Downs Group rocks, and Cenozoic and Quaternary colluvial and alluvial sediments all occur in the area. The depth to the J-K aquifer is approximately 270 mbgs, and the depth to the interpreted Coorikiana Sandstone (?) aquifer is approximately 150 mbgs. The springs are some distance from the margins of either the Great Artesian Basin or the Cooper Basin. They are in an area of considerable confining layer thickness, but close to an interpreted fault that has displaced Mesozoic sedimentary rocks. Along with evidence from electrical geophysical surveys, this indicates that the primary cause of spring formation at this location is faulting. Regional groundwater flow and hydrochemistry suggest the J-K aquifer is the primary source of groundwater, although one historical hydrochemistry result from spring vent ORE275 suggests that the Cenozoic aquifers may also be a source. **Spring ecology** Springs present here are mostly Sand Mounds (Gotch et al. 2016) or Erosional Channel springs. They have low endemic diversity and low abundances of significant flora (2 relict plants). The springs are in poor condition due to heavy grazing by cattle.

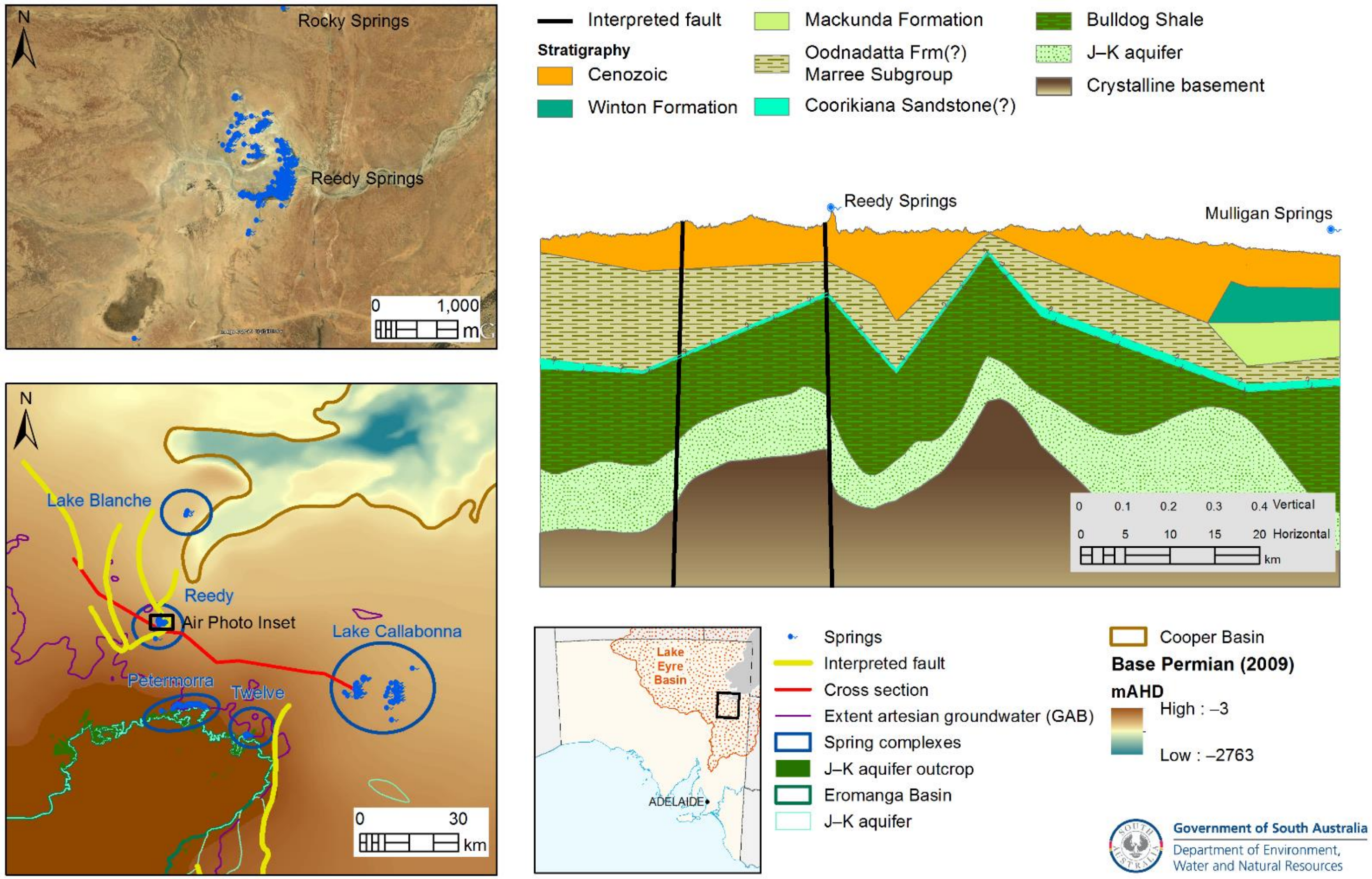


Figure 6–3: Reedy Springs Group summary

Group name	Spring complex	No. of springs	Structural model	Hydrochemical characterisation	Geology/Surficial materials	Est. SWL (mbgs) & flow (L/s)	Notes
Sunday Springs (OSU). Lake Blanche Spring (QLB)	Lake Blanche	10	Primary: model 1c	Groups 4 & 5	Spring deposits, Quaternary lacustrine, alluvial and aeolian sediments. Depositional environment.	–60 to –65, no flow estimated	Sunday Springs and Lake Blanche Springs form a chain of springs approximately 60 km north of the North Flinders Ranges and the crystalline basement outcrop therein. Quaternary lacustrine, alluvial and aeolian sediments all occur in the area. The depth to the J-K aquifer is approximately 785 mbgs, and the depth to the interpreted Coorikiana Sandstone (?) aquifer is approximately 365 mbgs. The springs are near the southern margin of the Cooper Basin, in an area of considerable confining layer thickness, but close to an interpreted fault that has displaced Mesozoic sedimentary rocks. This indicates that the primary cause of spring formation at this location is faulting. Electrical geophysical surveys indicate that a dominantly north-north-east-trending regional fault and 'flower structure' or fault duplex (Aldam and Kuang 1988) may be present. Regional groundwater flow and hydrochemistry suggest a source from the Coorikiana Sandstone (?) aquifer, although Cenozoic aquifer groundwater may also be possible. Although a regional-scale fault is indicated at this location, and therefore a potential for connectivity between the springs and deeper aquifers, the lack of hydrochemical evidence suggests that depth-related confining pressure is significantly limiting the formation of porosity and permeability at depth. **Spring ecology** Spring types represented in this complex are predominantly Flat Depressions or Salt Lake (non–Brine Density) Springs (Gotch et al. 2016). They have low biological diversity (1 uncommon plant) and are heavily impacted by invasive species (*Polypogon monspeliensis*). Their cultural significance is not known.

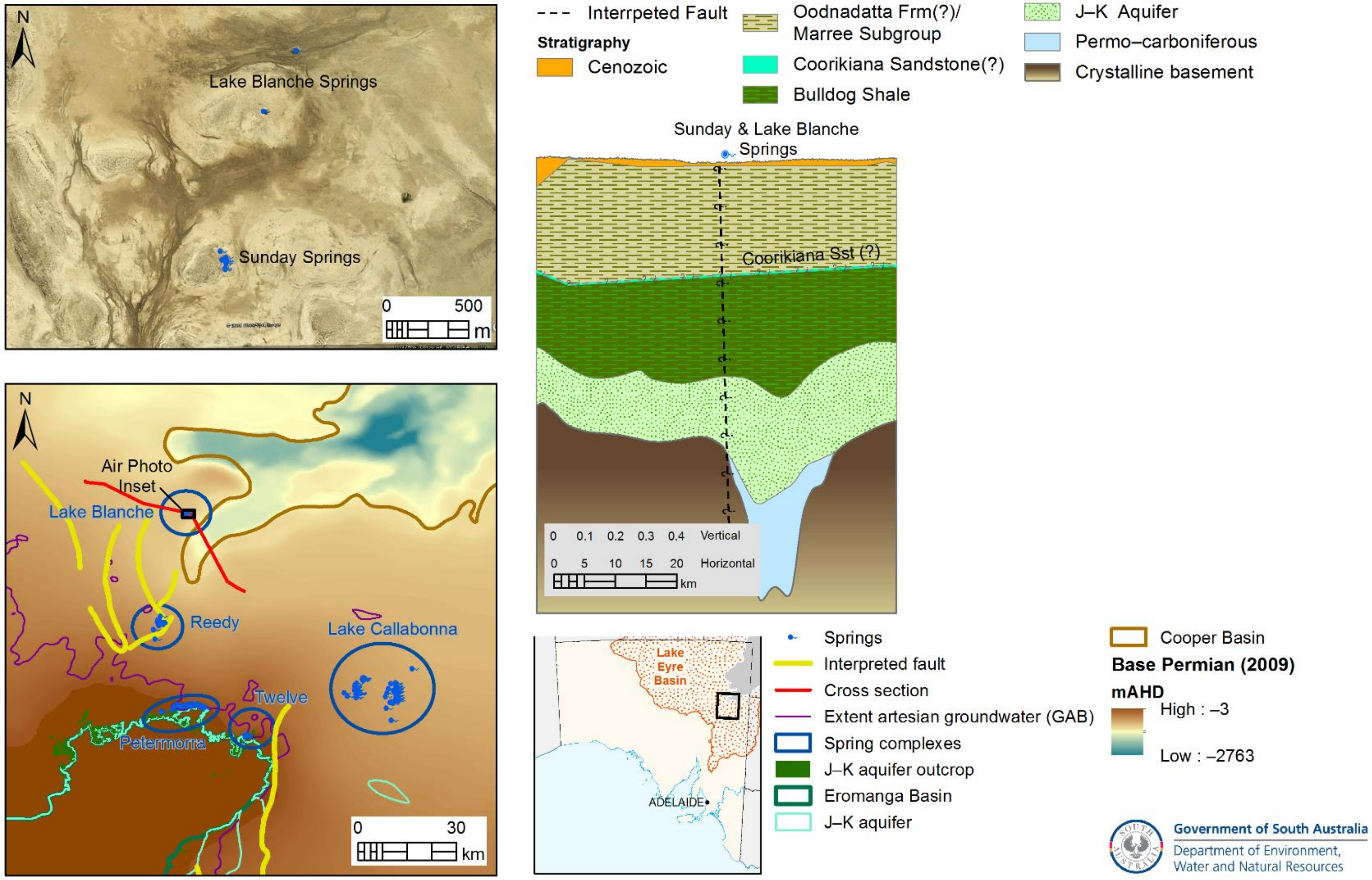
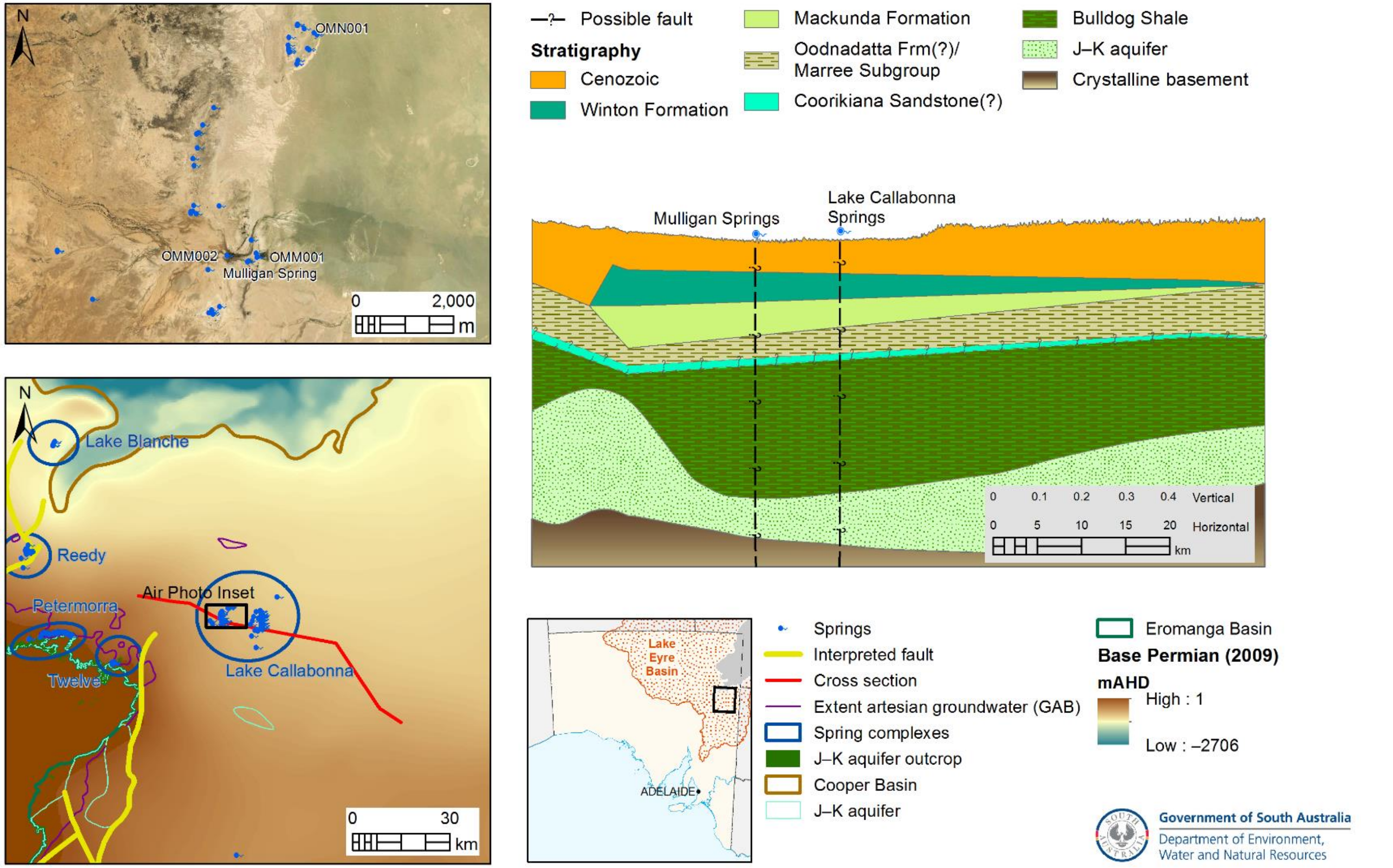


Figure 6–4: Lake Blanche Springs Group summary

Group name	Spring complex	No. of springs	Structural model	Hydrochemical characterisation	Geology/Surficial materials	Est. SWL (mbgs) & flow (L/s)	Notes
Mulligan Springs (OMM) (subgroup of Callabonna)	Lake Callabonna	47	Primary: model 1c	Groups 3, 4 and 5? (mix)	Spring deposits, Quaternary alluvial, lacustrine and playa beach sediments. Moderately to highly weathered Cenozoic outcrop. Depositional environment.	–70, no flow estimated	Mulligan Springs form a chain of springs approximately 30 km north-east of the North Flinders Ranges and the crystalline basement outcrop therein. Quaternary alluvial, lacustrine and playa beach sediments all occur in the area. Outcropping Cenozoic rocks (Namba and Eyre formations) also occur approximately 3 km to the west. The depth to the J-K aquifer is approximately 695 mbgs, and the depth to the interpreted Coorikiana Sandstone (?) aquifer is approximately 275 mbgs.



The springs are some distance from the margins of either the Great Artesian Basin or the Cooper Basin, and in an area of considerable confining layer thickness. This suggests that the primary cause of spring formation at this location is faulting. However, there is currently little evidence for faulting, although this may be due to a lack of appropriate data.

Regional groundwater flow and hydrochemistry suggest a source from the Cenozoic, the Coorikiana Sandstone (?) and possibly the J-K aquifer. Major ion hydrochemistry suggests that a mix of these groundwaters may be supplying springs. Faulting is tentatively interpreted to account for groundwater migration from depth.

Spring ecology

Springs in this complex are mainly Sand Mounds, Erosional Channels, Mud Mounds and Flat Depression types.

These springs were a major campsite for the Pirlatapa people.

Figure 6–5: Mulligan Springs Group summary

Group name	Spring complex	No. of springs	Structural model	Hydrochemical characterisation	Geology/Surficial materials	Est. SWL (mbgs) & flow (L/s)	Notes
Lake Callabonna Springs (OZN, OZM, OZS)	Lake Callabonna	57	Primary: model 1	Groups 3, 4 and 5? (mix)	Spring deposits, Quaternary lacustrine sediments. Depositional environment.	–36 to –73, no flow estimated	Lake Callabonna Springs form a long chain of springs approximately 40 km north-east of the North Flinders Ranges and the crystalline basement outcrop therein. Quaternary lacustrine sediments dominate surficial materials. The depth to the J-K aquifer is approximately 570 mbgs, and the depth to the interpreted Coorikiana Sandstone (?) aquifer is approximately 255 mbgs. The springs are some distance from the margins of either the Great Artesian Basin or the Cooper Basin, and in an area of considerable confining layer thickness. This suggests that the primary cause of spring formation at this location is faulting. However, there is currently little evidence for faulting, although this may be due to a lack of appropriate data. Regional groundwater flow and hydrochemistry suggest a source from the Cenozoic, the Coorikiana Sandstone (?) and possibly the J-K aquifer. Major ion hydrochemistry suggests that a mix of these groundwaters may be supplying springs. Faulting is tentatively interpreted to account for groundwater migration from depth. **Spring ecology** Springs in this complex are mainly Sand Mounds, Travertine Mounds, Mud Mounds and Flat Depression types. Their cultural significance is not known.

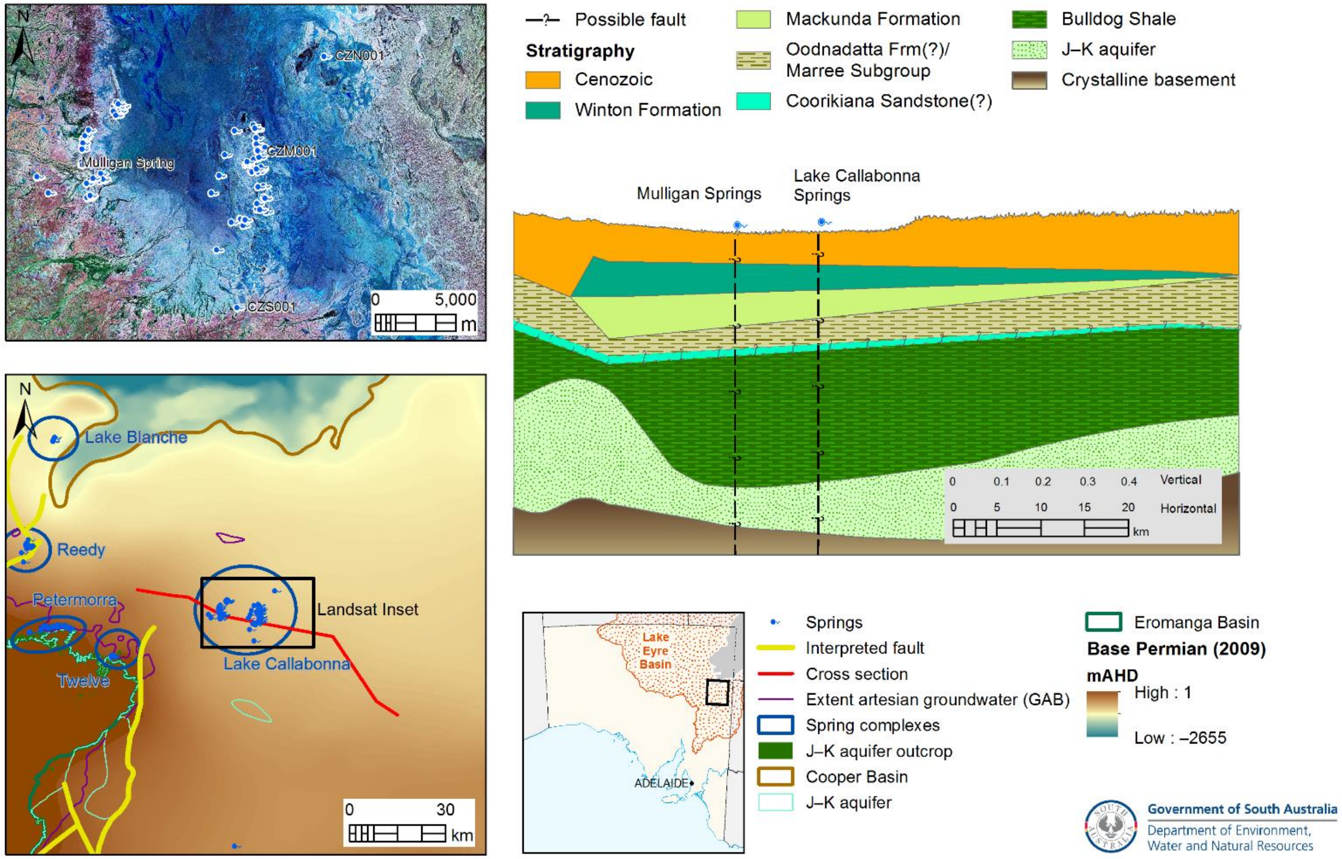


Figure 6–6: Lake Callabonna Springs Group summary

7 Conclusions and recommendations

The specific objectives of this study were to provide an initial description of the geological structural setting and primary controls on spring formation using previously published basin architecture interpretations, an interpretation of near-surface conditions using acquired geophysical data, and a description of the primary groundwater source based on hydrochemistry data. These descriptions 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 were developed, describing the regional architecture primarily responsible for spring formation within the investigation area. The models are:

- 1c – Mid-basin, Structure (fault zone)
- 2 – Basin margin, sediment thinning
- 3 – Basin margin, structure/sediment thinning combination.

Springs that are classified as having any variation within primary structural models of 1c and 3 are at higher risk of impacts associated with potential coal seam gas (CSG) or coalmining activities within the Cooper Basin than springs classified as model 2. This is related to the potential for groundwater connectivity between aquifers within the Great Artesian Basin (GAB) and those of the underlying Cooper Basin, afforded by regional deformation structures, such as fracture and fault zones. In contrast, springs classified using conceptual model 2 may have at least shallow, localised structures, but the distance between these spring environments at the margin of the GAB and the Cooper Basin, as well as the lack of evidence for deeper structures linking such spring environments with the Cooper Basin, diminishes the risk of development impacting deep aquifers within the Cooper Basin and adversely affecting these springs.

7.2 Hydrochemistry

Hydrochemistry-based methods proved useful to distinguish groundwater from different aquifers within the investigation area, and also to determine the source of groundwater to the spring groups. Five hydrochemical classifications for groundwater were developed that are related to the aquifer from which groundwater is sourced:

- 1 – crystalline basement (fractured rock) aquifer
- 2 – Patchawarra Formation aquifer
- 3 – J-K aquifer
- 4 – Shallow GAB aquifer (Coorikiana Sandstone)
- 5 – Cenozoic aquifer.

With respect to spring water supply, Table 7–1 summarises the most likely source of groundwater for each spring complex within the investigation area.

Table 7–1: Summary of possible sources of spring water based on hydrochemistry

Spring complex	Possible supplying aquifer	Distance from margin of Cooper Basin (km)
Lake Blanche	Coorikiana Sandstone/Cenozoic	4
Reedy	J-K aquifer and Cenozoic	13
Petermorra	J-K aquifer and crystalline basement	37
Twelve	J-K aquifer	48
Lake Callabonna (Mulligan Group)	Cenozoic, Coorikiana Sandstone and J-K aquifer (?) (mix)	55
Lake Callabonna (Callabonna Group)	Cenozoic, Coorikiana Sandstone and J-K aquifer (?) (mix)	62

It is significant that no spring system could be definitively linked to the Patchawarra Formation aquifers using hydrochemistry, although the hydrochemical differences between the J-K aquifer and the Patchawarra Formation aquifer are small. Youngs (1971), and Altmann and Gordon (2004) noted that groundwater from these two aquifers can intermix if confining layers between the two aquifers have been removed via erosion before the deposition of GAB sedimentary sequences. Future analysis of groundwater may include statistical methods such as principal component analysis or hierarchical cluster analysis to determine if there is a need to consider mixing or multiple source conceptual models for groundwater. With respect to the source of spring water, the distances between most spring complexes and the southern margin of the Cooper Basin could mitigate impacts to these spring systems associated with CSG resource development.

The spring complex closest to the Cooper Basin (Lake Blanche) is most likely to be supplied with spring water from shallow aquifer systems, with the Coorikiana Sandstone and Cenozoic aquifers interpreted as the primary potential sources under current hydrogeological conditions. In contrast, the Reedy Springs complex, 13 km south of the southern margin of the Cooper Basin, potentially has a slightly higher risk profile given the relatively short distance to the margin of the Cooper Basin, the source of groundwater identified as predominantly from the J-K aquifer, and a structural model related to a large regional fault structure that is mapped to extend towards the southern margin of the Cooper Basin. However, the distance of 13 km between this spring complex and the southern margin of the Cooper Basin could mitigate impacts of groundwater-affecting activity associated with CSG developments in the Weena Trough.

However, as mentioned in Section 5, it is currently unknown how CSG development may change the hydrogeological conditions in the larger groundwater environment of the Lake Blanche and Reedy Springs complexes, and whether this may alter the current hydrogeological conditions as observed. Examining such scenarios will require further study, and such modelling could be considered for CSG proponents to include in any future environmental impact statements.

Although groundwater hydrochemistry can be successfully used to discriminate groundwater of different hydrostratigraphic origin, some data (especially from springs located in the Mulligan/Lake Callabonna Spring complex) suggest that a mix of groundwater from a number of different aquifers may be possible. To determine the likelihood of such a scenario, hydrochemical modelling is recommended as a first step. In this case, a mixing model between groundwater from different aquifers is recommended to determine the likely contribution to springs of groundwater from each aquifer.

7.3 Geophysical results

Geophysical data collected at two of the spring groups (Lake Blanche–Sunday Springs Group and Reedy Springs Group) suggest that faulting and possibly fold-related deformation play an important role at both sites. These results relate to investigations at depths of 150–1,000 m.

Near-surface surveys indicate different conditions at the two sites:

- Reedy Springs Group – The surveys indicate that the large, slightly elevated mound in the centre of the group (containing several hundred possibly ephemeral vents) acts as a large, single vent, with electromagnetic (EM) surveys measuring water of apparently consistent salinity across the mound, and self-potential (SP) surveys suggesting that there is upward flow underneath the whole area, rather than in isolated spots underneath individual vents on the surface.

- Lake Blanche Springs Group – In contrast to Reedy Springs Group, SP data at QLB001 suggest that water is flowing vertically upwards in a very narrow zone, perhaps only 10–30 m wide. Other EM evidence indicates that this zone is part of, or adjacent to, a common fault structure striking north-north-east that the QLB001 and QLB002 vents both lie on. This suggests that, although faults play a role in providing connectivity from deeper aquifers to the spring groups (either as conduits themselves, or as a barrier in channeling flow), conduit permeability must be created or increased, and maintained, through additional processes.

7.4 Coorikiana Sandstone interpretation

A major finding of this study was the potential importance of groundwater from a shallow sandstone aquifer found within the confining layer sequences to the supply of groundwater to the Lake Blanche and Lake Callabonna spring complexes. This sandstone aquifer has been interpreted in the report as the Coorikiana Sandstone, based on depths, general lithological descriptions and occurrences. It is recognised, however, that the adoption of such a stratigraphic interpretation for this sandstone would necessitate other changes to stratigraphic nomenclature within the wider region, given the Coorikiana Sandstone is generally interpreted to be a marker bed between the Oodnadatta Formation above and the Bulldog Shale below. Consequently, it is recommended that further work is done to verify this interpretation, if possible; this could include palynological work on archived core samples (if such core samples can be found), as well as a review and potential reinterpretation of seismic data for the region.

The status of the Coorikiana Sandstone (?) aquifer as a groundwater resource may require review with respect to the water allocation plan for the South Australian Arid Lands Natural Resources Management (SAAL NRM) area. There may also be implications with regards to the source of groundwater to springs currently listed as Threatened Ecological Communities under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act).

7.5 Future work recommendations

Future work that could be conducted to extend the findings or to begin filling data gaps identified by this work includes the following:

- Undertake a review of seismic data and stratigraphic interpretation in the Lake Blanche region. This is required for two reasons. Firstly, given the potential importance of the Coorikiana Sandstone as an aquifer in the region, knowing the extent and magnitude of this unit is important to define this resource. Secondly, because the Coorikiana Sandstone is a marker unit between the Oodnadatta Formation above and the Bulldog Shale below, properly identifying this unit may have wider ramifications for the stratigraphic interpretation of the Mesozoic in this region.
- Compare SP, TEM and audio-magnetotellurics (AMT) data and interpretation with regional seismic data and interpretation. This would help establish the scaling and technical limitations of each technique with respect to identifying fault and other deformation structures related to spring conduit formation. Of particular concern are the depth limitations of each technique.
- Commence a study to determine the timing and nature of faulting in the region with respect to spring conduit formation and understanding impacts to regional hydrogeology.

- Undertake both hydrochemical and hydrogeological modelling to test the interpretations regarding the sources of springwater to the various spring complexes covered in this investigation. This may help to determine the likelihood of, and quantify, the interpretations made using hydrochemistry in this report.
- Perform noble gas sampling within the Lake Blanche and Lake Callabonna spring systems. Such sampling, including $^{3}He/^{4}He$, ^{81}Kr and gaseous radiocarbon, will help determine if there is connectivity between these spring systems and the mantle. Identification of mantle gases in springwater may not be definitive evidence that groundwater from deeper sources is feeding springs. However, it may indicate that a structure connecting the springs with deeper sources potentially exists, and therefore it is current-day conditions such as confining pressure, lack of fracture porosity or permeability that may be preventing deep groundwater migration, rather than the lack of a conduit. This is important to understand given the potential for CSG extraction activities to change the hydrogeological conditions, especially by lowering groundwater pressures in the affected aquifers.
- Develop an overall geological and hydrochemical characterisation for the wider GAB and Lake Eyre Basin regions in South Australia. This report and Keppel et al. (2015c) have developed structural and hydrochemical characterisation studies for the Lake Blanche, Neales River Catchment and Lake Cadibarrawirracanna regions. Future studies could focus more on determining linkages between the geology, related structure, and hydrochemistry and spring morphology types. Although some linkages are clearly apparent, such as the relationship between faulting and spring development near fault-related escarpments, other more subtle linkages may also be evident after further scrutiny.
- Complete a thorough review, processing and interpretation of soil and plant samples that have been collected as part of ecological survey work during this and previous field campaigns. Given the remote and underexplored nature of a number of these spring complexes within the investigation area, such work is considered important to fully understand these environments and appreciate the magnitude of the conservation task.
- Review the legislative and legal protections of springs within the region, if it is confirmed that the springs are not solely reliant on J-K aquifer groundwater. It is known that the EPBC Act only covers springs supplied by GAB (J-K aquifer) groundwater. Other springs may be covered by the SAAL NRM water allocation plan. A review of the various legislations protecting springs is recommended to ensure that non–GAB supplied springs are protected. Additionally, other legislative requirements coving groundwater-affecting developments, such as requirements regarding the completion and decommissioning of wells and drill holes, may also require review.

Appendix A Groundwater sampling sites

Unit no.	Spring ID	Name	Depth to water (m)[a]	Current depth (m)	Aquifer	Easting[b]	Northing[b]	Sampling date
673800024		Happy Thoughts	8.51	9.15	Cenozoic	350815.4	6729360	10/10/2015
673800189		BHPB C4	–21.36	497	J-K	347735	6729162	9/06/2015
673900006		Meteor Bore	–25.89	286	J-K	348521.05	6740716.96	8/06/2015
673900016		BHPB C2	–80.03	782	J-K	326500	6774605	10/06/2015
673900034		New Toonketchen	–43.81	603	J-K	318761.7	6758378.55	10/06/2015
683800003		Dean's Lookout	–23.87	326	J-K	362176.04	6719806.03	10/06/2015
683800006		Lake Crossing No.4	–26.64	519	Kmc	391596	67313-30	7/06/2015
683800013		New Lignum Bore	0.3	49.6	Cenozoic	378370.04	6710207.05	25/08/2015
683800029		Woolatchi	–38.42	577	J-K	390575	6694912	26/08/2015
683800037?		Mt Fitton OS Bore	4.32	37	N	360456	6683426	26/08/2015
683800046		Bellinger Bore	–17.34	142	J-K	372603.03	6700208.96	25/08/2015
683800048		Mosquito Well 2	14.55	57.65	Cenozoic	394888	6704714	27/08/2015
683800705	OTS032	Twelve Spr. OTS032	–	–		371027.55	6697942.48	25/08/2015
683900003		Montecollina	–14.4	777	J-K/Kmc	401801.5	6747229	7/06/2015
		Klebb-1	–	2193	Pgp	400482.5	6789592.7	5/06/2015
693900015		Bob's Bore	4	80	Cenozoic	412022.5	6771578	5/06/2015
		LeChiffre-1	–	2085	Pgp	407762.32	6785962.88	6/06/2015
703900005		Fortville 3	–7.65	968	J-K	490259.1	6778174	6/06/2015
683800810	OMM001	Mulligan Mid Spr. 1	–	–		401146	6710898	27/08/2015
683800016	OMM002	Mulligan Mid Spr. 2	–	–		400513	6710935	27/08/2015
683800833	OMN001	Mulligan North Spr.	–	–		409825	6715013	27/08/2015
693800072	ZCA001	L. Callabonna S. Spr.	–	–		409522	6702873	28/08/2015
693800117	ZCM036	L. Callabonna M. Spr.	–	–		410813	6712673	28/08/2015
693800081	ZCE001	L. Callabonna E. Spr.	–	–		414959	6718555	28/08/2015
683900049	QLB001	Lake Blanche Spring 1	–	–		354537	6765784	8/06/2015
673801051	ORE012	Reedy Spring 12	–	–		347488	6731431	7/06/2015

Unit no.	Spring ID	Name	Depth to water (m)[a]	Current depth (m)	Aquifer	Easting[b]	Northing[b]	Sampling date
673800758	ORE019	Reedy Spring 19	–	–		347562	6732348	7/06/2015
673900031	QSU004	Sunday Springs 4	–	–		354081	6764589	8/06/2015
683800435	OPC000B	Public House Springs OPC000B	–	–		359024	6706342	11/06/2015
683800001	OPC104	Public House Springs OPC104	–	–		357854	6707152	11/06/2015

– = not measurable; Kmc = Coorikiana Sandstone; N = Neoproterozoic; Pgp = Patchawarra Formation

a Negative values indicate artesian conditions

b Coordinates use the datum GDA94 Zone 54

Appendix B Major ions, trace elements and water quality

Sample name	Unit no.	Field alk	pH	Field EC	Temp	F^-	Cl^-	Br^-	NO_3^-	SO_4^{2-}	Ca	K	Mg	Na	Si	Sr
		mg/L		μS/cm	°C	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Happy Thoughts	673800024	530	7.19	10086	21.5	0.7	2426	3.2	0.7	1941.1	399.0	3.0	201.0	1820	32.8	9.4
BHPB C4	673800189	726	7.12	2393	42.5	2.1	109	0.2	0.2	0.4	11.5	14.1	1.1	386	13.1	0.5
Meteor Bore	673900006	808	7.56	2745	40.5	1.6	183	0.3	0.2	3.2	11.8	5.0	1.8	470	17.8	0.3
BHPB C2	673900016	711	7.04	2188	40.8	2.4	99	0.2	0.1	0.1	10.5	15.6	1.2	358	16.2	0.4
New Toonketchen	673900034	616	7.47	2588	54	2.0	112	0.2	0.1	0.2	10.4	11.9	0.8	353	12.5	0.3
Dean's Lookout	683800003	436	7.54	4666	46.1	1.0	741	0.6	0.1	0.2	22.1	8.6	3.3	621	11.2	0.8
Lake Crossing No.4	683800006	88	7.3	23300	44.1	0.2	5432	3.7	2.4	1253.8	304.0	17.1	36.1	3380	10.8	8.5
New Lignum Bore	683800013	184	6.74	7381	25.1	0.5	2049	1.4	0.2	864.3	198.0	7.0	133.0	1260	7.8	4.0
Woolatchi	683800029	538	7.47	4721	61.6	9.0	460	0.6	<0.05	0.7	8.4	8.5	0.8	562	16.1	0.5
Mt Fitton OS Bore	683800037?	419	6.91	4548	25.5	0.6	891	2.3	0.1	719.0	100.0	7.6	133.0	666	13.4	1.8
Bellinger Bore	683800046	628	7.5	2437	35	10.3	280	0.4	<0.05	<0.05	11.4	5.1	1.6	448	10.0	0.5
Mosquito Well 2	683800048	206	7.03	5753	24.5	0.5	1452	0.9	40.1	405.2	202.0	6.0	44.7	911	39.1	2.6
Twelve Spr. OTS032	683800705	618	7.53	1872	21.5	8.8	249	0.4	0.1	<0.05	11.7	5.9	2.0	473	9.2	0.4
Montecollina	683900003	157	7.48	17145	46.6	0.2	3616	4.7	0.3	89.8	125.0	14.1	20.2	2230	13.2	3.6
Klebb-1		1137	6.23	5257	32.3	0.3	764	2.0	0.7	10.1	40.5	71.8	6.6	1070	53.4	0.2
Bob's Bore	693900015	97	6.47	16065	24.6	0.3	4323	6.0	0.8	1886.4	259.0	20.1	118.0	3100	7.5	4.4
LeChiffre-1		920	6.34	6002	22.4	0.3	1475	4.7	0.5	6.4	71.4	71.6	7.7	1390	37.8	1.9
Fortville 3	703900005	851	7.02	6093	72.5	1.4	300	1.0	1.2	0.3	11.4	22.0	2.0	620	21.3	0.3

Sample name	Unit no.	Field alk	pH	Field EC	Temp	F^-	Cl^-	Br^-	NO_3^-	SO_4^{2-}	Ca	K	Mg	Na	Si	Sr
		mg/L		µS/cm	°C	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
Mulligan Mid Spr. 1	683800810	312	7.07	3773	19.8	1.4	1089	0.7	0.1	225.0	60.5	13.7	29.5	783	9.7	1.2
Mulligan Mid Spr. 2	683800016	291	7	4223	21.1	1.5	1288	0.9	0.2	242.1	67.0	14.4	33.3	865	7.6	1.3
Mulligan North Spr.	683800833	–	7.12	6148	20.7	2.1	2234	1.5	0.5	465.9	116.0	37.8	55.6	1460	6.2	2.3
L. Callabonna S. Spr.	693800072	392	7.49	6258	16.3	0.6	2206	2.0	0.2	329.3	48.1	17.8	26.2	1590	6.5	1.1
L. Callabonna M. Spr.	693800117	430	7.29	5692	15.6	0.9	1924	1.4	0.2	357.2	74.4	23.6	46.1	1380	6.3	1.7
L. Callabonna E. Spr.	693800081	118	7.18	15553	19.3	0.6	6584	6.1	0.4	1967.5	231.0	23.7	130.0	4170	6.6	4.2
QLB001	683900049	207	6.88	12949	19.3	0.4	4264	7.0	0.3	1176.2	165.0	20.0	88.8	2890	5.8	3.1
ORE012	673801051	1120	7.49	2093	19.7	3.6	251	0.4	0.3	201.3	11.9	8.0	6.6	781	11.7	0.7
ORE019	673800758	714	7.3	1929	36.1	1.6	145	0.2	0.5	3.2	16.6	14.5	4.3	402	41.1	0.5
QSU004	673900031	256	6.77	9322	21.4	0.3	4535	7.5	0.5	1218.6	179.0	26.6	95.5	3030	7.0	3.3
OPC000B	683800435	699	7.81	2089	23.1	15.2	245	0.3	0.1	65.7	11.9	6.6	2.4	497	12.0	0.4
OPC104	683800001	730	7.6	1909	22.2	6.7	199	0.3	0.2	5.5	15.1	7.5	2.7	442	11.6	0.4

– = no measurement possible

Appendix C Stable isotope and $^{87}Sr/^{86}Sr$ results

Unit no.	Spring ID	Name	Aquifer	$\delta^{18}O$ ‰	$\delta^{2}H$‰	$^{87}Sr:^{86}Sr$	2se
673800024		Happy Thoughts	Cenozoic	–5.34	–37.1	0.71197954	0.000003
673800189		BHPB C4	J-K	–7.33	–47.5	0.71444982	0.000004
673900006		Meteor Bore	J-K	–7.22	–47.2	0.70643565	0.000003
673900016		BHPB C2	J-K	–7.39	–48.1	0.71939384	0.000004
673900034		New Toonketchen	J-K	–7.31	–47.6	0.71126888	0.000003
683800003		Dean's Lookout	J-K	–7.17	–46.2	0.70909665	0.000003
683800006		Lake Crossing No.4	Kmc	–6.27	–42.08	0.70574066	0.000003
683800013		New Lignum Bore	Cenozoic	–5.55	–40.4	0.71202804	0.000003
683800029		Woolatchi	J-K	–7.41	–47.2	0.71219994	0.000003
683800037?		Mt Fitton OS Bore	N	–7.24	–46.5	0.71942160	0.000003
683800046		Bellinger Bore	J-K	–5.56	–38.4	0.70991779	0.000003
683800048		Mosquito Well 2	Cenozoic	–7.26	–46.8	0.71370602	0.000003
683800705	OTS032	Twelve Spr. OTS032		–6.66	–43.1	0.71001391	0.000003
683900003		Montecollina	J-K/Kmc	–8.03	–48.8	0.70588773	0.000003
		Klebb-1	Pgp	–4.24	–34.4	0.71673837	0.000006
693900015		Bob's Bore	Cenozoic	–8.48	–52.3	0.70790656	0.000003
		LeChiffre-1	Pgp	–7.58	–48.4	0.71806382	0.000003
703900005		Fortville 3	J-K	–7.06	–47.0	0.71201216	0.000003
683800810	OMM001	Mulligan Mid Spr. 1		–6.81	–45.9	0.71910540	0.000003
683800016	OMM002	Mulligan Mid Spr. 2		–6.96	–45.6	0.71975430	0.000003
683800833	OMN001	Mulligan North Spr.		–6.47	–43.2	0.72195187	0.000003
693800072	ZCA001	L. Callabonna S. Spr.		–6.81	–44.0	0.71174507	0.000003
693800117	ZCM036	L. Callabonna M. Spr.		–6.86	–44.1	0.71291711	0.000003
693800081	ZCE001	L. Callabonna E. Spr.		–3.29	–32.1	0.70864585	0.000003
683900049	QLB001	Lake Blanche Spring 1		–3.96	–32.7	0.70694515	0.000003
673801051	ORE012	Reedy Spring 12		–6.71	–44.7	0.70755946	0.000003
673800758	ORE019	Reedy Spring 19		–7.16	–47.3	0.71182757	0.000003
673900031	QSU004	Sunday Springs 4		–3.81	–32.8	0.70703463	0.000003

Unit no.	Spring ID	Name	Aquifer	$\delta^{18}O$ ‰	$\delta^{2}H$‰	$^{87}Sr:^{86}Sr$	2se
683800435	OPC000B	Public House Springs OPC000B		–7.26	–47.8	0.73612925	0.000003
683800001	OPC104	Public House Springs OPC104		–6.86	–45.7	0.72031497	0.000003

Kmc = Coorikiana Sandstone; N = Neoproterozoic; Pgp = Patchawarra Formation

Appendix D Radiocarbon results

Unit no.	Spring ID	Name	Aquifer	pMC (%)	pMC (%) error	δ^{13}C	δ^{13}C error	δ^{14}C	δ^{14}C error
673800024		Happy Thoughts	Cenozoic	10409	0.34	–12.6	0.2	53.7	3.4
673800189		BHP C4	J-K	2.02	0.12	–3.9	0.2	–979.6	1.2
673900006		Meteor Bore	J-K	0.42	0.12	–5.7	0.2	–995.8	1.2
673900016		BHP C2	J-K	0.55	0.12	–3.4	0.2	–994.4	1.2
673900034		New Toonketchen	J-K	0.68	0.12	–3.7	0.2	–993.1	1.2
683800003		Dean's Lookout	J-K	0.59	0.15	–6.4	0.2	–994.0	1.5
683800006		Lake Crossing No. 4	Kmc	17.15	0.13	–9.8	0.2	–826.4	1.4
683800013		New Lignum Bore	Cenozoic	14.5	0.21	–10.7	0.2	–853.2	2.1
683800029		Woolatchi	J-K	0.34	0.22	–5.2	0.2	–996.6	2.3
683800037?		Mt Fitton OS Bore	N	29.94	0.21	–8.2	0.2	–696.9	2.1
683800046		Bellinger Bore	J-K	0.27	0.22	–5.8	0.2	–997.3	2.3
683800048		Mosquito Well 2	Cenozoic	81.69	0.29	–8.6	0.2	–173.1	2.9
683800705	OTS032	Twelve Spring 32		0.89	0.22	–6.5	0.2	–991	2.3
683900003		Montecollina	J-K/Kmc	1.63	0.12	–9.2	0.2	–983.5	1.2
		Klebb-1	Pgp	0.77	0.12	–5.3	0.2	–992.2	1.2
693900015		Bob's Bore	Cenozoic	4.59	0.12	–8.4	0.2	–953.5	1.2
		LeChiffre-1	Pgp	2.65	0.12	–10.2	0.2	–973.2	1.2
703900005		Fortville3	J-K	0.65	0.12	–1.3	0.2	–993.5	1.2
683800810	OMM001	Mulligan Mid Spr. 1		6.49	0.22	–	–	–934.3	2.2
683800016	OMM002	Mulligan Mid Spr. 2		1.52	0.22	–9.8	0.2	–984.6	2.3
683800833	OMN001	Mulligan North Spr.		30.92	0.21	–13	0.2	–687	2.1
693800081	ZCE001	L. Callabonna E. Spr.		22.93	0.18	–12.3	0.2	–767.9	1.8
693800117	ZCM036	L. Callabonna M. Spr.		25.97	0.18	–12.9	0.2	–737.1	1.8
693800072	ZCA001	L. Callabonna S. Spr.		16.48	0.18	–11	0.2	–833.1	1.8
683900049	QLB001	Lake Blanche Spring 1		3.47	0.12	–10.8	0.2	–964.9	1.2
673801051	ORE012	Reedy Spring 12		38.88	0.17	–7.3	0.2	–606.4	1.8
673800758	ORE019	Reedy Spring 19		2.15	0.12	–5.1	0.2	–978.3	1.2
673900031	QSU004	Sunday Spring 4		30.01	0.16	–12.1	0.2	–696.2	1.6

Unit no.	Spring ID	Name	Aquifer	pMC (%)	pMC (%) error	δ^{13}C	δ^{13}C error	δ^{14}C	δ^{14}C error
683800435	OPC000B	Public House Spring OPC000B		3.11	0.15	–7.4	0.2	–968.5	1.5
683800001	OPC104	Public House Spring OPC104		6.12	0.15	–6.6	0.2	–938.0	1.5

– = no measurement possible; Kmc = Coorikiana Sandstone; N = Neoproterozoic; Pgp = Patchawarra Formation

Appendix E Chlorine-36 results

Unit no.	Spring ID	Name	Aquifer	$^{36}Cl/Cl$ ($\times 10^{-15}$)	Error	^{36}Cl atoms/L $\times 10^{-7}$
673800024		Happy Thoughts	Cenozoic	91.1	3.9	374.78
673800189		BHP C4	J-K	11.9	1.2	2.20
673900006		Meteor Bore	J-K	16.9	1.3	5.25
673900016		BHP C2	J-K	13.2	1.6	2.22
673900034		New Toonketchen	J-K	7.6	0.9	1.44
683800003		Dean's Lookout	J-K	6.0	0.8	7.54
683800006		Lake Crossing No. 4	Kmc	19.5	1.5	179.63
683800013		New Lignum Bore	Cenozoic	55.5	2.9	192.82
683800029		Woolatchi	J-K	14.5	1.1	11.32
683800037?		Mt Fitton OS Bore	N	86.6	4.0	130.77
683800046		Bellinger Bore	J-K	19.7	1.2	9.33
683800048		Mosquito Well 2	Cenozoic	79.8	3.8	196.47
683800705	OTS032	Twelve Spring 32		16.6	0.9	7.01
683900003		Montecollina	J-K/Kmc	5.9	0.7	36.18
		Klebb-1	Pgp	12.6	1.1	16.33
693900015		Bob's Bore	Cenozoic	64.4	2.9	472.12
		LeChiffre-1	Pgp	10.5	1.0	26.27
703900005		Fortville3	J-K	8.4	0.9	4.28
683800810	OMM001	Mulligan Mid Spr. 1		62.5	3.2	115.35
683800016	OMM002	Mulligan Mid Spr. 2		51.7	2.7	112.95
683800833	OMN001	Mulligan North Spr.		30.3	2.4	114.73
693800081	ZCE001	L. Callabonna E. Spr.		51.2	2.9	571.38
693800117	ZCM036	L. Callabonna M. Spr.		47.8	2.9	156.08
693800072	ZCA001	L. Callabonna S. Spr.		32.1	1.7	119.90
683900049	QLB001	Lake Blanche Spring 1		38.5	2.2	278.40
673801051	ORE012	Reedy Spring 12		15.4	1.2	6.57
673800758	ORE019	Reedy Spring 19		10.3	0.9	2.54
673900031	QSU004	Sunday Spring 4		40.4	2.1	310.67

Unit no.	Spring ID	Name	Aquifer	$^{36}Cl/Cl$ ($\times10^{-15}$)	Error	^{36}Cl atoms/L $\times10^{-7}$
683800435	OPC000B	OPC000B		45.0	2.3	18.72
683800001	OPC104	OPC104		49.5	2.5	16.67

Kmc = Coorikiana Sandstone; N = Neoproterozoic; Pgp = Patchawarra Formation

Appendix F Evidence base table for springs (abridged)

These tables represent an expansion to the evidence base tables presented in Gotch et al. (2016), based on new data and observations undertaken as part of the Lake Blanche expansion of the original Lake Eyre Basin Springs Assessment study area. A numbered reference list is presented after the tables.

Generalised GAB spring model evidence base table: hydrology

Values	Ecosystem response to impacts				
	Reduced flow	**Reduced wetland area**	**Reduced wetland connectivity**	**Reduced groundwater temperature**	**Contamination of groundwater**
Spring types					
Erosional Channel Springs	• Wetland area reduced proportionally to flow reduction (3, 26) • Loss of open water habitat and vent pools (1) • Less resilience to disturbance (1)	• Loss of habitat (1, 4) • Loss of habitat resilience to extreme climatic events (1)	• Reduced habitat function (1, 4) • Restriction in intraspring colonisation and dispersal (6, 8, 13, 18) • Potential for species loss (1, 6, 8)	• Not applicable	• Unknown impact/knowledge gap (1)
Salt Lake Brine Springs	• Flow not related to pressure • Not likely to be impacted	• Not applicable	• Not applicable	• Not applicable	• Potential for groundwater contamination due to shallow water depths and proximity to developments
Vegetation communities					
Utricularia fenshamii	• Loss of habitat with wetland drying out (3)	• Loss of habitat (1, 20) • Loss of resilience (1) • Decrease in habitat complexity (1) • Local extinctions (1, 20) • Reduction in propagule source (1) • Increased competition for space with *Phragmites* spp. (20)	• Reduced habitat function (1) • Restriction to intraspring colonisation and dispersal (1)	• Unknown impact/knowledge gap (1)	• Unknown impact/knowledge gap (1)
Wilsonia backhousei	• Loss of condition (1, 20) • Loss of habitat area (3, 20, 26)	• Loss of habitat (1, 20) • Loss of resilience (1) • Decrease in habitat complexity (1) • Local extinctions (1, 20) • Reduction in propagule source (1)	• Reduced habitat function (1) • Restriction to intraspring colonisation and dispersal (1)	• Unknown impact/knowledge gap (1)	• Unknown impact/knowledge gap (1)

Values	Ecosystem response to impacts				
	Reduced flow	**Reduced wetland area**	**Reduced wetland connectivity**	**Reduced groundwater temperature**	**Contamination of groundwater**
Relict sedges (*Juncus* spp., *Fimbristylis* spp.)	• Loss of condition (1, 20) • Loss of habitat area (3, 20, 26)	• Loss of habitat (1, 20) • Loss of resilience (1) • Decrease in habitat complexity (1) • Local extinctions (1, 20) • Reduction in propagule source (1) • Species richness correlates with number of vents rather than total wetland area. As wetland area declines, so will the number of vents, resulting in species loss (20)	• Reduced habitat function (1) • Restriction to intraspring colonisation and dispersal (1)	• Unknown impact/knowledge gap (1)	• Unknown impact/knowledge gap (1)

Generalised GAB spring model evidence base table: water chemistry and quality

Values	Ecosystem response to impacts				
	Decreasing pH	**Changing conductivity**	**Change in dissolved oxygen**	**Increased nutrients**	**Increased turbidity**
Spring types					
Erosional Channel Springs	• Acidification of springs (2, 16) • Loss of biodiversity values (2, 16) • Extinction of short-range endemics (1) • Impact on floristic diversity (1)	• Loss of biodiversity values (1)	• Spring source water very low in dissolved oxygen DO then rapidly approaches saturation due to surface area and depth (1)	• Increased growth of wetland veg, particularly *Phragmites* spp. resulting in increased transpiration and reduced wetland area and free water habitat (1)	• Not likely to be a major issue due to water depth (1)
Salt Lake Brine Springs	• Unknown impact/knowledge gap (1)	• Flora or fauna likely to be very dependent on consistent salinity range in the spring (1)	• Spring source water very low in DO then rapidly approaches saturation due to surface area and depth (1)	• Unknown impact / knowledge gap (1)	• Unknown impact / knowledge gap (1)
Vegetation communities					
Eriocaulon carsonii	• Intolerant of low pH, resulting in species loss (1, 33)	• Unknown/knowledge gap (1)	• Not applicable	• *Eriocaulon* spp. benefits from elevated nutrients (33). However, it competes poorly against aggressive species such as *Phragmites*, so will be reduced in area and/or pushed to spring margins when occurring with these species (20)	• Not applicable
Utricularia fenshamii	• Found mainly in fen substrates (alkaline) so likely to be negatively affected by reducing pH (1)	• Unknown; however, distributions of this species correlate with low-conductivity springs, so increase in conductivity likely to negatively impact on springs (1)	• Not applicable	• Adapted to low-nutrient environments, unlikely to be able to compete with nutrient-limited plants such as *Phragmites australis*	• Not applicable
Relict sedges (*Juncus* spp., *Fimbristylis* spp.)	• Intolerant of very low pH, resulting in species loss (1)	• Unknown/knowledge gap (1)	• Not applicable	• Response to elevated nutrients unknown/knowledge gap (1) • Will be negatively impacted by increased *Phragmites* density (1)	• Not applicable
Wilsonia backhousei	• Unknown impact/knowledge gap (1)	• Tolerant of fluctuating conductivity but will be negatively impacted by long-term changes to conductivity (41)	• Not applicable	• Unknown/knowledge gap (1)	• Not applicable

Generalised GAB spring model evidence base table: impacts

	Ecosystem response to impacts				
Spring types	**Grazing and pugging**	**Invasive species**	**Physical disturbance (excavation, exploration impacts, etc.)**	**Fencing**	**Tourism**
Erosional Channel Springs	• Loss of vegetation biomass and diversity (36, 37) • Erosion and breaking down of mound (1) • Increased nutrient loading into springs from faecal matter (1) • Change in habitat (36) • Loss of habitat quality (1, 36) • Change in vegetation community structure (36) • Dispersal of weeds (1)	• Grazing pressure from introduced herbivores (1) • Predation by feral predators (1) • Reduction in resilience (1) • Reduced flows from transpiration by weeds (39) • Introduction of nutrients to the system (1) • Dispersal of weeds (1)	• Erosion and breaking down of travertine (1) • Damage to spring habitats (1, 36) • Changes to flow regime (1) • Loss of endemic species (1) • Loss/creation of vent pools (1) • Dispersal of weeds (1) • Loss of mounds from periodic flooding (1)	Small-scale fencing: • Increased *Phragmites* growth (1) • Loss of habitat complexity (1) • Change in habitat structure (1) • Loss of species (1) • Protection of mounds (1) Larger scale fencing or fences with implemented management plans: • Initial increased *Phragmites* growth (1) • Protection of grazing-sensitive plants (1) • Improved habitat complexity and health (1) • Protection of mounds (1)	• Erosion of soft mounds (1) • Compaction of spring vegetation (1) • Dispersal of weeds (1)
Salt Lake Brine Springs	• Limited grazing pressure due to unfavourable habitat (1) • Erosion around springs (1) • Increased nutrient loading into springs from faecal matter (1) • Change in habitat (36) • Loss of habitat quality (1, 36) • Change in vegetation community structure (36) • Dispersal of weeds (1)	• Grazing pressure from introduced herbivores (1) • Predation by feral predators (1) • Reduction in resilience (1) • Reduced flows from transpiration by weeds (39) • Introduction of nutrients to the system (1) • Dispersal of weeds (1)	• Damage to spring habitats (1, 36) • Changes to flow regime (1) • Dispersal of weeds (1)	Small-scale fencing: • Increased *Phragmites* growth (1) • Loss of habitat complexity (1) • Change in habitat structure (1) • Loss of species (1) • Protection of mounds (1) Larger scale fencing or fences with implemented management plans: • Initial increased *Phragmites* growth (1) • Protection of grazing-sensitive plants (1) • Improved habitat complexity and health (1) • Protection of mounds (1)	• No public access
Vegetation communities					

	Ecosystem response to impacts				
Eriocaulon carsonii	• Very sensitive to grazing and pugging (20)	• Grazing impacts from feral herbivores (1) • Can be excluded by introduced plants such as *Polypogon* (1)	• Loss of habitat area (1) • Changes to flow paths can result in loss of wetland habitat (1)	• Overgrowth of *Phragmites* in response to fencing pushes *Eriocaulon* to the margins, resulting in more exposure to grazing (20)	• Not applicable
Utricularia fenshamii	• Likely to be sensitive to grazing and pugging (1)	• Grazing impacts from feral herbivores (1) • Can be excluded by introduced plants such as *Polypogon* (1)	• Loss of habitat area (1) • Changes to flow paths can result in loss of wetland habitat (1)	• Overgrowth of *Phragmites* in response to fencing pushes *Utricularia* to the margins, resulting in more exposure to grazing (20)	• Not applicable
Relict sedges (*Juncus* spp., *Fimbristylis* spp.)	• Targeted species for grazers (1) • Loss of cover from overgrazing and pugging (1)	• Grazing impacts from feral herbivores (1) • Can be excluded by introduced plants such as *Polypogon* (1)	• Loss of habitat area (1) • Changes to flow paths can result in loss of wetland habitat (1)	• Moderately positive effect from exclusion of grazers; this can be neutralised by aggressive growth of *Phragmites* or weeds (1)	• Not applicable
Wilsonia backhousei	• Very sensitive to trampling and pugging (41)	• Can be excluded by introduced plants such as *Polypogon* (1)	• Loss of habitat area (1) • Changes to flow paths can result in loss of wetland habitat (1)	• Positive effect from exclusion of grazers (41)	• No public access

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Appendix G Construction and maintenance record of Montecollina Bore

G.1 Construction summary

Montecollina is open hole from 772.67 mbgs to 777.24 mbgs. The original casing construction consisted of surficial casing of 203 mm from 0 to 172.5 m, intermediate casing of 165 mm from 0 to 569.06 m and production casing of 127 mm from 0 to 772.67 m recorded. In all cases, casing was constructed from steel. Construction notes also state that the top 39.62 m of the bore was relined with intermediate casing of 152 mm in 1991 during rehabilitation works.

G.2 Coorikiana Sandstone occurrence

A 'sand unit' (Coorikiana Sandstone) was logged to occur between 507.5 mbgs and 531.9 mbgs at the time of drilling. In the original log, the following note concerning groundwater from this unit was made: 'Flow of 11,700 gallons per day (gpd) struck at 1665 feet, increased to 30,000 gpd at 1680 feet. Solids 1.5 ozs to gallon. Temperature 110 deg.'

G.3 Maintenance history

At the same time that new intermediate casing was fitted in 1991, new head works were also fitted. A note in the rehabilitation report states: 'The old casing strings in this well caused problems because as each plug was spotted, the water would bypass the plug up the outside of the old casing. Three attempts were made before flow killed.'

An inability to shut the bore in during monitoring rounds was noted in 1986 and 1996. The last recorded time that a shut-in pressure measurement was possible was in 1996. A 2004 monitoring report on file states that head works were already badly corroded.

G.4 Salinity records

Salinity records for Montecollina Bore document a notable increase in salinity between 1924 and 1940 to a range in keeping with groundwater from the upper sand unit (Coorikiana Sandstone) (Table F–1). A small decrease in salinity was reported after rehabilitation works in 1991; however, measurements since 2013 indicate salinity has risen to post-1940 levels again.

Table F–1: Salinity records from monitoring of Montecollina Bore

Date	EC (mS/cm)	TDS
11/09/1920	7105	4004
12/11/1922	6055	3398
01/12/1924	5966	3346
06/06/1940	10123	5768
12/06/1975	11648	6687
02/04/1978	11669	7159
11/07/1980	12022	7056
18/12/1986	12400	7010
07/11/1990	12376	7119
17/09/2004	9570	5446
17/09/2004	9730	5540
24/08/2013	11010	6309
07/06/2015	17145	7885

Units

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

Abbreviations and acronyms

CSG	coal seam gas
DEWNR	Department of Environment, Water and Natural Resources
GAB	Great Artesian Basin
LEB	Lake Eyre Basin
LEBSA	Lake Eyre Basin Springs Assessment
pMC	percent modern carbon
SP	self-potential

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