Review of groundwater discharge processes at Dalhousie Springs

DEWNR Technical note 2015/02

Government of South Australia
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1 Introduction

1.1 Background

In 2012, the Australian Government established an Independent Expert Scientific Committee (IESC) on Coal Seam Gas (CSG) and Large Coal Mining (LCM) developments to provide independent, expert scientific advice on the future impact these activities may have on water resources. The IESC is a statutory body under the *Environment Protection and Biodiversity Conservation Act 1999* (EPBC Act) which provides scientific advice to Australian governments on the water-related impacts of CSG and LCM development proposals. Under the EPBC Act, the IESC has several legislative functions, *viz.* to:

- provide scientific advice to the Commonwealth Environment Minister and relevant state ministers on the water-related impacts of proposed CSG or LCM 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 LCM activities on water resources.

The Bioregional Assessment Programme is a transparent and accessible programme of baseline assessments that increase the available science for decision making associated with potential water-related impacts of CSG and LCM 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 LCM development on water resources. This Programme draws on the best-available scientific information and knowledge from many sources, including government, industry and regional communities, to produce bioregional assessments that are independent, scientifically robust, and relevant and meaningful at the regional scale. For more information on bioregional assessments, visit <http://www.bioregionalassessments.gov.au>.

The Australian Government through the Department of the Environment provided funding to the South Australian Department of Environment, Water and Natural Resources (DEWNR) to collate and ground-truth baseline groundwater, surface water and ecology information to inform the Bioregional Assessment Programme in the Lake Eyre Basin (LEB). The LEB bioregion has been identified as one of six priority areas for bioregional assessments across Australia. This report is part of a series of studies forming part of the *Arckaringa Basin and Pedirka Basin Groundwater Assessment* project. The *Arckaringa Basin and Pedirka Basin Groundwater Assessment* project is one of three water-knowledge projects undertaken by DEWNR in the western LEB bioregion, including the:

- *LEB Rivers Monitoring* project
- *Arckaringa Basin and Pedirka Basin Groundwater Assessment* project
- *LEB Springs* project.

This report documents the scope of work required to reduce uncertainties in identifying the groundwater source supporting Dalhousie Springs and forms a key component of the *Arckaringa Basin and Pedirka Basin Groundwater Assessment*.

1.2 Pedirka Basin Groundwater Assessment

In 2013, DEWNR undertook a desktop assessment aimed at benchmarking the level of hydrogeological knowledge in the Arckaringa and Pedirka Basins (Figure 1.1) (Wohling *et al.*, 2013b). The review identified fundamental data gaps in the characterisation of the Pedirka Basin groundwater system. These include:

- limited information on the hydrogeology and hydraulic behaviour of the two Permian units (Crown Point formation and Purni formation); in particular, there is insufficient information to determine whether the Permian Aquifers are hydraulically separate from the overlying Great Artesian Basin (GAB) Aquifer
- an absence of dedicated investigation wells completed in the Crown Point formation and Purni formation; consequently, there is no information on vertical hydraulic gradients between the Permian formations and the GAB sequence, and no assessment of inter-aquifer and inter-basin hydraulic connectivity
- uncertainty surrounding recharge mechanisms, recharge rates and spatial extent of recharge zones providing inflow to the Pedirka Basin
- very limited information on the permeability of Permian Formations and no published aquifer parameters (transmissivity, storage coefficients) for either the Purni or Crown Point Formations
- uncertainty surrounding the potential connection between Permian Formations and Dalhousie Springs, including the nature and magnitude of any discharge mechanism from the Pedirka Basin.

As part of the *Pedirka Basin Groundwater Assessment*, DEWNR has developed an investigation program to address these knowledge gaps. The program aims to deliver several targeted studies that will feed into a broader assessment of the Pedirka Basin hydrogeology and inform the *LEB Bioregional Assessment*. There are three key themes for targeted investigation: aquifer connectivity, focussed ephemeral river recharge and Dalhousie Springs discharge. This report details the findings from the desktop review of Dalhousie Springs discharge.

1.3 The Great Artesian Basin and Dalhousie Springs

The GAB is among the world's largest groundwater basins (Figure 1.1), spanning around 1.7 million km^2, which represents greater than 20% of Australia's continental landmass (Habermehl, 1980). With the exception of the far eastern and far northern extents of the basin, the GAB occurs beneath mainly semi-arid and arid regions of the continent and is often the only reliable source of fresh water. Consequently, this vast resource supports many cultural, agricultural and civil communities, and sustains a range of environmental assets, whilst also underpinning the viability of industries such as tourism and mining.

Underlying the GAB, the Pedirka Basin is located in remote northern South Australia and southern Northern Territory (Figure 1.2). This area is commonly referred to as the 'western margin of the GAB' (or 'western GAB'), which is the focus for the recent *Allocating Water and Maintaining Springs in the Great Artesian Basin* project (Keppel *et al.*, 2013b). The western GAB has been identified as comprising important recharge zones but, importantly, this is also an area of groundwater convergence and natural discharge that supports many of the ecologically-significant GAB springs. Dalhousie Springs, which is located on the south-western margin of the GAB (Figure 1.2), is the largest of all GAB spring complexes in this part of South Australia.

The areal extent of Dalhousie Springs is greater than 200 km^2 and comprises over 114 spring vents (Lewis *et al.*, 2013). The springs are an important water source for the Lower Southern Arunda people and consequently, the area has extensive archaeological deposits (Ah Chee, 2002) and many sites of high cultural significance. In addition to the extremely high geological and cultural conservation importance associated with Dalhousie Springs (Harris, 1981; Zeidler & Ponder, 1989; Morton *et al.*, 1995), it is also the most biologically significant spring group in South Australia (McLaren *et al.*, 1986).

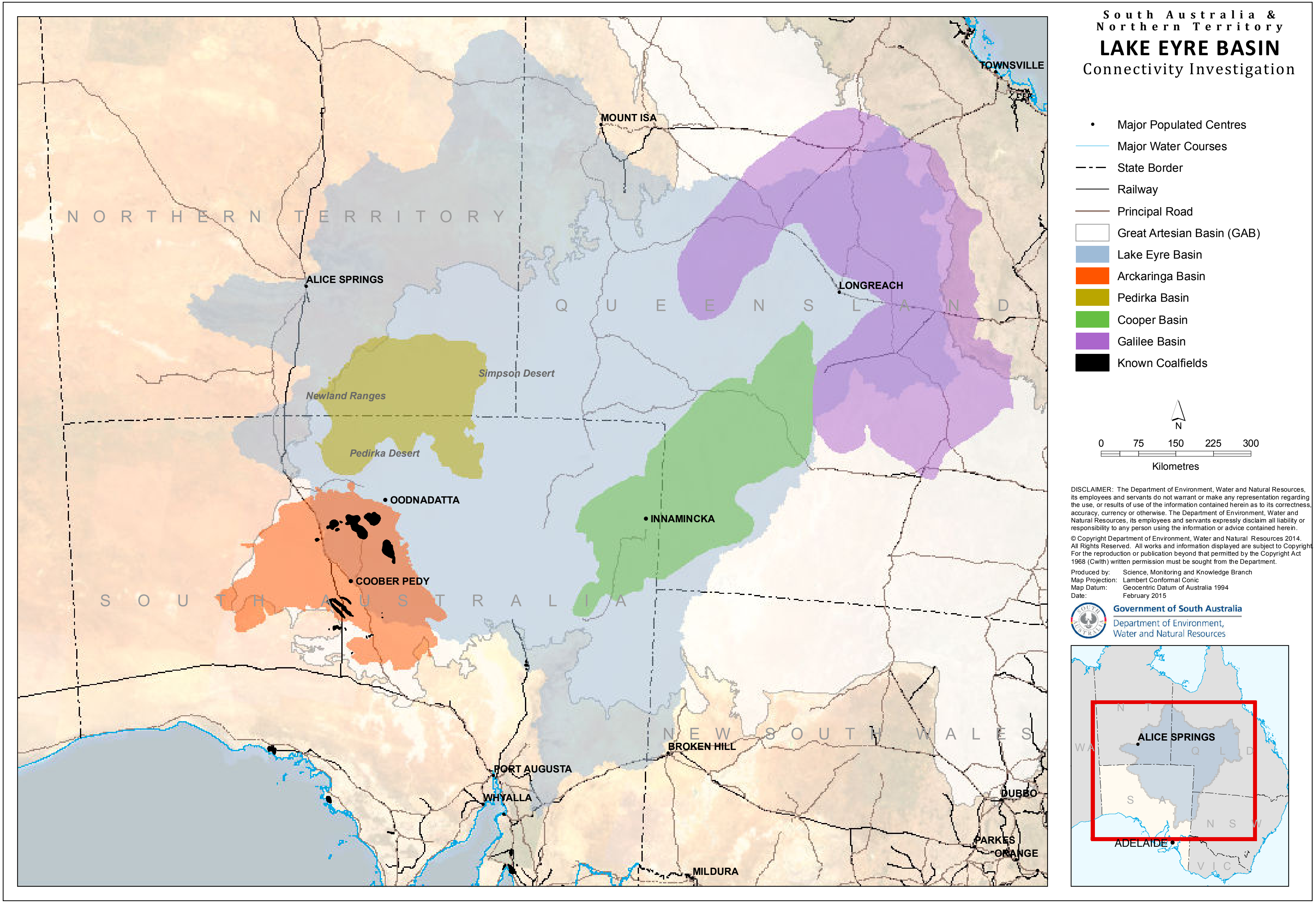

Figure 1.1. Location map

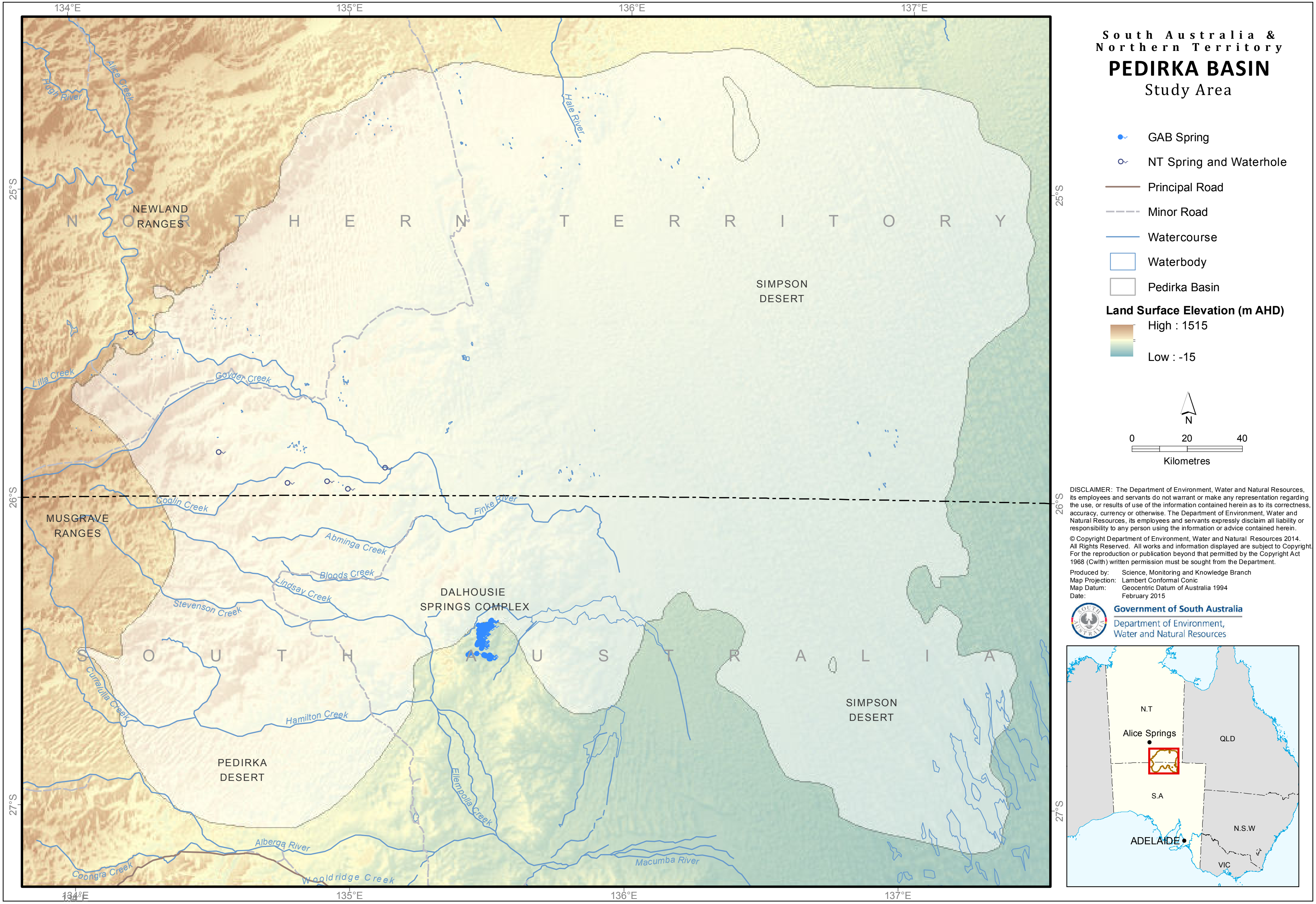

Figure 1.2. Study area

The groundwater-dependent wetlands around Dalhousie Springs cover around 1000 ha (White *et al.*, 2013) which include an extremely complex composition and distribution of plant species. Further, Gotch (2005) reported 32 relict, rare or endemic faunal species within the Dalhousie Springs complex, including endemic invertebrate species of molluscs and crustaceans and several species of endemic fish. Around 155 native bird species have been identified (Gotch & Noack, 2013), whilst other vertebrate species include frogs, reptiles and several mammal species. This diversity of flora and fauna, in concert with high Aboriginal and European heritage conservation value, has resulted in federal protection of Dalhousie Springs under the auspices of the EPBC Act. In order to evaluate the potential impacts on groundwater-dependent ecosystems (GDEs) (i.e. GAB springs) from competing land uses, a robust understanding of the underlying hydrogeology at the local and regional scale is required.

1.4 Aims and objectives

The aim of the current study is to evaluate the conceptualisation of groundwater flow around the Dalhousie Springs area and identify the main sources of uncertainty in the model. The current study will also identify what further work is required to refine the model so that it can be an effective tool to aid in the effective management of water resources that support the Dalhousie Spring GDEs.

These aims will be achieved through completing the following four objectives:

1. summarise the current understanding of the hydrogeology of Dalhousie Springs and surrounding area
2. review the veracity of evidence used to develop the current hydrogeological conceptual model of Dalhousie Springs
3. identify any knowledge gaps that limit this understanding, particularly in the context of identifying the source water for the spring complex at Dalhousie Springs
4. provide recommendations for future investigations aimed at resolving these knowledge gaps with a view to the long-term health of the ecosystems that are dependent on groundwater discharge in the greater Dalhousie Springs area.

2 Physiography and hydrogeology of the western Great Artesian Basin

2.1 Overview of the climate and hydrogeology of the western GAB

The climate and hydrogeology of the western GAB has been described in detail by Keppel *et al.* (2013a) and Keppel *et al.* (2013c). These authors defined the extent of the western GAB for their study as that part of the GAB which falls within the borders of South Australia and the Northern Territory. Traditionally, the western boundary of the western GAB has been delineated by the mapped western extent of the Eromanga Basin.

2.1.1 Climate

The western GAB is typically described as an arid environment; Tetzlaff and Bye (1978) estimate the evaporation rate to be around 3 m/y. Rainfall in arid areas of central Australia becomes increasingly episodic and unpredictable with decreasing latitude (Alcoe *et al.*, 2012). Climate data for Marla (located around 200 km southwest of Dalhousie Springs) are shown in a box plot of monthly rainfall, where the solid green line shows the average monthly potential evapotranspiration (PET) (Figure 2.1). The entire period of available SILO rainfall records (1891–2011, inclusive) are shown (Jeffrey *et al.*, 2001). The average monthly PET greatly exceeds the median monthly rainfall for all months and there are only a small number of extreme monthly rainfall totals that have exceeded the average monthly PET over the 121 years of climate data. Importantly, rain in arid areas may not fall for several years but conversely, intense rainfall can deliver the total annual rainfall in a single event. Consequently, conventional rainfall statistics (e.g. mean annual rainfall) are often misleading in these extreme climatic environments.

2.1.2 Hydrogeology

The two main composite groups of aquifers within the GAB, as proposed by Habermehl (1980) and Seidel (1980), are the Jurassic Algebuckina Sandstone Aquifer (commonly termed the J Aquifer) and the Cretaceous confined to semi-confined Cadna-owie formation Aquifer (K Aquifer) (Table 3.1). Within the study region, the Algebuckina Sandstone and the Cadna-owie formation are often continuous and are herein referred to as the J–K Aquifer.

2.2 Pedirka Basin

The Pedirka Basin is located around 860 km north of Adelaide and approximately 160 km south of Alice Springs (Figure 1.1). The basin is centred on the South Australia–Northern Territory border and spans an area of around 60 000 km^2 (Wohling *et al.*, 2013b). A major north-west structural feature named the McDills–Dalhousie Ridge dissects the basin into the Madigan and Poolowanna Troughs to the east and the Eringa Trough to the west, which are connected by a thin sedimentary horizon. The Eringa Trough reaches a maximum total thickness of around 1500 m (Karlstrom *et al.*, 2013) and comprises aquifers of Permian (P), Jurassic (J) and Cretaceous (K) age.

Within the Pedirka Basin subregion, the J Aquifer and K Aquifer display both confined and unconfined conditions. The Cretaceous Bulldog Shale and Oodnadatta formation (and lateral equivalents) comprise the main confining beds, whilst the J–K Aquifer is the only regionally-extensive hydrostratigraphic unit suitable for economic development (e.g. for stock and domestic purposes). The water quality in the J–K Aquifer ranges between fresh (generally found in wells closest to the Finke River) to brackish. In contrast, the Cretaceous Winton and Mackunda formations are discontinuous with highly variable water quality, ranging from fresh to hypersaline.

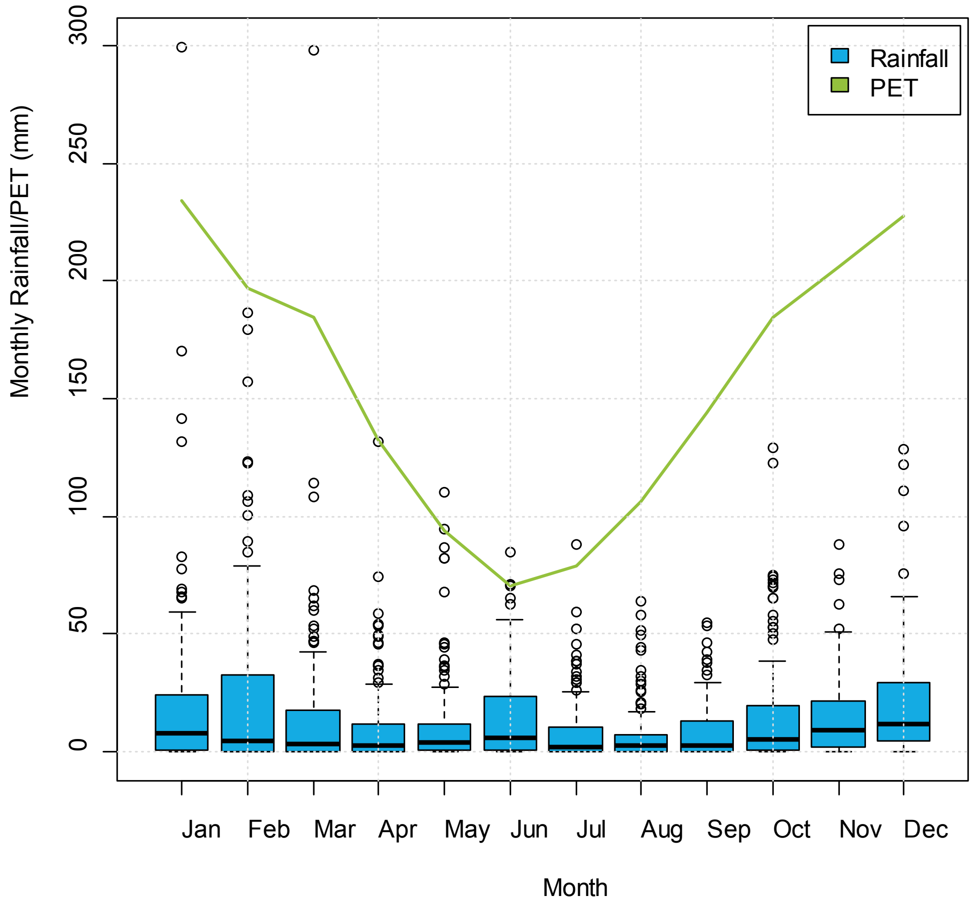

Figure 2.1. Monthly rainfall and potential evapotranspiration (PET) at the BoM rainfall station Marla (016085) (Jeffrey 2001). The whiskers extending beyond each box represent 1.5 times the range of rainfall within the box and circles represent monthly rainfall totals that fall outside this range, which can be considered extreme events (Alcoe *et al.*, 2012).

3 Hydrogeology of the Dalhousie Springs area

Wohling *et al.* (2013b) and Wolaver *et al.* (2013) have respectively reported on the hydrogeology of the Pedirka Basin and Dalhousie Springs. Both of these reports included extensive reviews of previously published scientific literature, whilst Wolaver *et al.* (2013) presented new data analyses that aimed to refine the hydrogeological conceptual model of Dalhousie Springs. This section summarises the existing published literature and provides an assessment of Wolaver *et al.* (2013) findings that have been drawn from their analysis of groundwater and spring-vent data.

3.1 Hydrostratigraphy of the Dalhousie Springs area

The hydrostratigraphy of the Dalhousie Springs area has been summarised by Wolaver *et al.* (2013) (Table 3.1). They reported that earlier researchers agreed that the J–K sediments of the Eromanga Basin discharge to western-GAB springs, including the Dalhousie Spring complex. The Cretaceous Bulldog Shale is recognised as the primary confining bed of the western GAB but has been erosionally stripped from the McDills–Dalhousie Ridge. The Permian Purni formation may have lower permeability units that confine the underlying Permian Crown Point formation of the Pedirka Basin.

Table 3.1. Generalised hydrostratigraphy of the Dalhousie Springs area

Basin	Period/Era (abbreviation)	Formation	Aquifer or aquitard
Lake Eyre	Paleogene (T)	undifferentiated	Unlikely hydrogeological linkage to Dalhousie Springs
Eromanga	Cretaceous (K)	Winton; Mackunda; Oodnadatta	Unlikely hydrogeological linkage to Dalhousie Springs
		Bulldog Shale	Aquitard
		Cadna-owie	Aquifer
	Jurassic (J)	Algebuckina Sandstone	Aquifer
Pedirka	Permian (P)	Purni	Aquifer
		Crown Point	Aquifer
South-east Amadeus	Paleoproterozoic (L)	undifferentiated	
Western Warburton	Cambrian	undifferentiated	
Adelaide Geosyncline	Neoproterozoic (N)	undifferentiated	

Simplified stratigraphic cross-sections of the Pedirka Basin have been constructed from drillhole data and seismic data collected by Wohling *et al.* (2013b) (Figures 3.1 and 3.2).

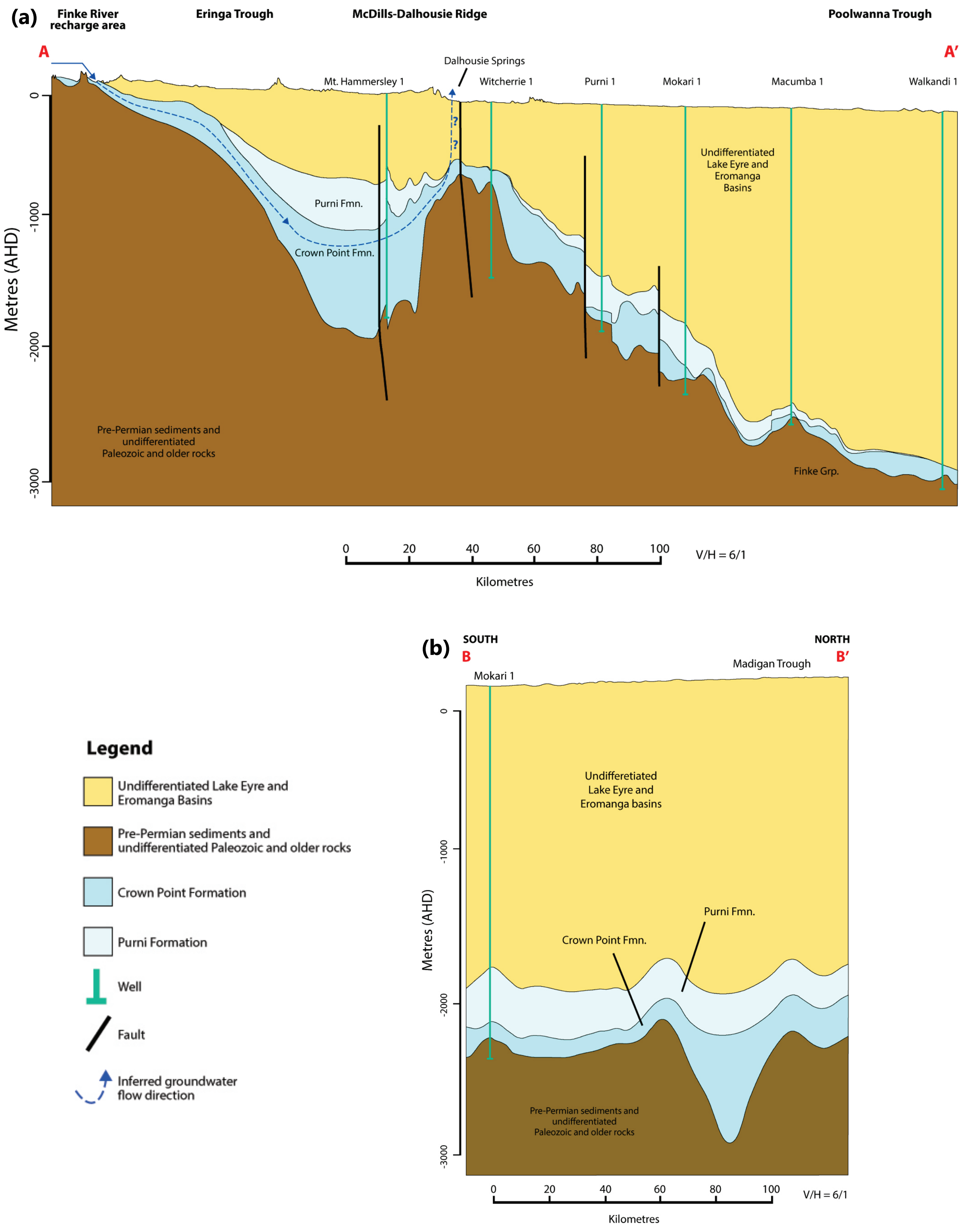

Figure 3.1. Simplified stratigraphic cross-section of the Pedirka Basin, from (a) east to west and (b) south to north. Note that the AA′ trace lies 5–20 km to the north of Dalhousie Springs (Figure 3.2). At Dalhousie Springs, the Crown Point formation is erosionally stripped from the crest of the McDills–Dalhousie Ridge (which is a feature not apparent in the cross-section AA′).

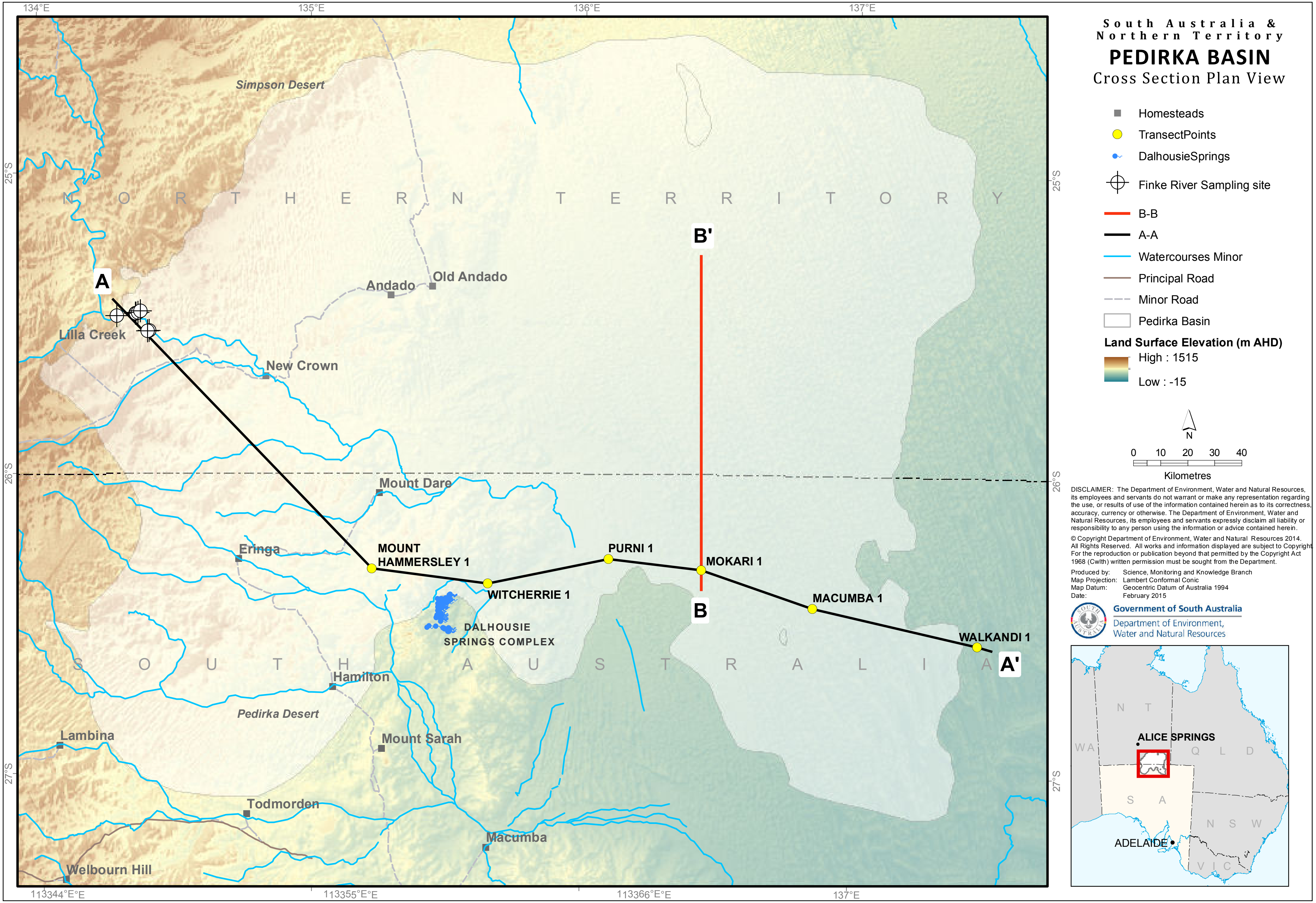

Figure 3.2. Plan view of cross-section traces AA′ and BB′ (see cross-sections in Figure 3.1)

3.2 Spring formation

Spring complexes of the GAB are observed to occur along faults. Karlstrom *et al.* (2013) reported that springs located in central South Australia and northern South Australia (i.e. the Dalhousie Springs complex) closely align with the Torrens Hinge Zone and Tasman Line (Shaw, 1996), suggesting that their formation resulted from deep Neoproterozoic-era normal faults (Preiss, 1987) that act as conduits for modern discharge. More specifically, the location of the Dalhousie Springs complex is coincident with the McDills–Dalhousie Ridge.

Krieg (1989) observed that the Dalhousie Springs complex was structurally controlled, and interpretation of seismic imagery of the area by Aldam and Kuang (1989) identified a number of faults that are postulated to be likely spring conduits. This faulting and fracturing that underpin flows to the Dalhousie Springs complex is likely to be explained by the McDills–Dalhousie Ridge (Krieg *et al.*, 1985; Krieg, 1989). Karlstrom *et al.* (2013) suggest that anticlinal structures may be "… oppositely facing monoclines above a horst structure that resulted from inversion of a Proterozoic graben". This interpretation implies a lithospheric-scale system, where upward leakage of CO_2 and Helium-3 from mantle depths are likely to influence hydrochemical signatures (Crossey *et al.*, 2006; Crossey *et al.*, 2009).

3.3 Spring discharge

Spring complexes located in the western GAB are important areas of groundwater discharge. The Dalhousie Springs complex and Lake Eyre Supergroup are estimated to account for discharge of around 58 ML/d and 9–17 ML/d, respectively (Habermehl, 1980), whilst more recent estimates of the basin-wide water balance suggest that all GAB springs account for discharge of around 140 ML/day (SAAL NRM Board, 2009). Crossey *et al.* (2013) estimated the Dalhousie Springs complex and Lake Eyre Supergroup discharge to be less than 10% of contemporary GAB discharge, with the balance attributed to groundwater extraction and diffuse vertical leakage.

3.4 Identifying source water for the Dalhousie Springs complex

Wolaver *et al.* (2013) and Wohling *et al.* (2013b) suggested that in addition to the widely-accepted hydrogeological conceptual models that identify the J–K Aquifer as the main source, Permian formations of the Pedirka Basin are also likely to have hydrogeological linkages with the Dalhousie Springs complex. This latter conclusion drawn by Wolaver *et al.* (2013) and Wohling *et al.* (2013b) was based on a number of lines of evidence.

3.4.1 Direction of groundwater flow

Rousseau-Gueutin *et al.* (2013) mapped potentiometric surfaces for the J–K Aquifer across the extent of the GAB. These are the first published potentiometric surfaces of the GAB that accounted for variations in the density of groundwater due to the influence of salinity, temperature and pressure. Based on these corrected data, the authors concluded that gravity is the main driving force of groundwater flow at the regional scale. However variations in density due to temperature gradients were found to have a marked impact on groundwater flow at the local scale.

Wolaver *et al.* (2013) used the J–K Aquifer potentiometric surface created by Rousseau-Gueutin *et al.* (2013) to generate a potentiometric surface map for the greater Dalhousie Springs region (Figure 3.3). Based on these data, groundwater was inferred to flow from the western margin of the GAB, between the Alberga and Finke Rivers, in an approximately south-easterly direction towards Dalhousie Springs.

Wohling *et al.* (2013b) constructed a time-composite regional potentiometric surface for the Permian aquifers of the Pedirka Basin (Figure 3.4). The surface was constructed from only 26 data points (freshwater-equivalent heads) that were clustered around the north-west extent of the basin and consequently, the confidence in the interpolated surface is greatest in this region. The authors concluded that the direction of groundwater flow in the P Aquifers of the Pedirka Basin is generally from north-west to south-east, which is consistent with the flow direction in the J–K Aquifer reported by Rousseau-Gueutin *et al.* (2013). Moreover, toward the north-western extent of the western GAB, the surface outcrops of the Crown Point formation suggest this may be an area of active or historical recharge, especially where the Finke River may provide ephemeral river recharge to this aquifer. Targeted investigations on focussed ephemeral river recharge in the Finke River region are currently underway as part of the *Pedirka Basin Groundwater Assessment* (Sect. 1.2).

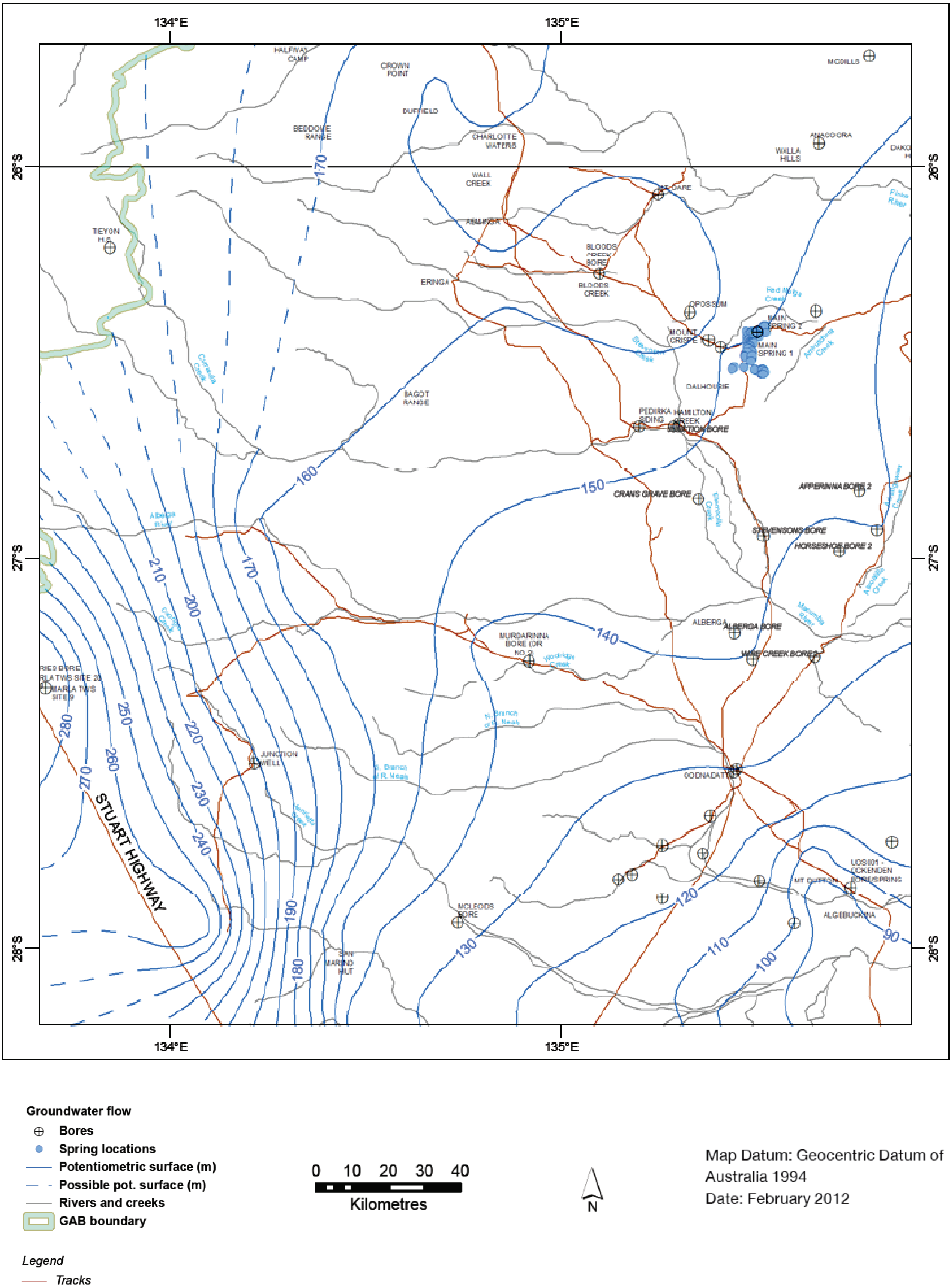

Figure 3.3. J–K Aquifer potentiometric surface of the greater Dalhousie Springs area

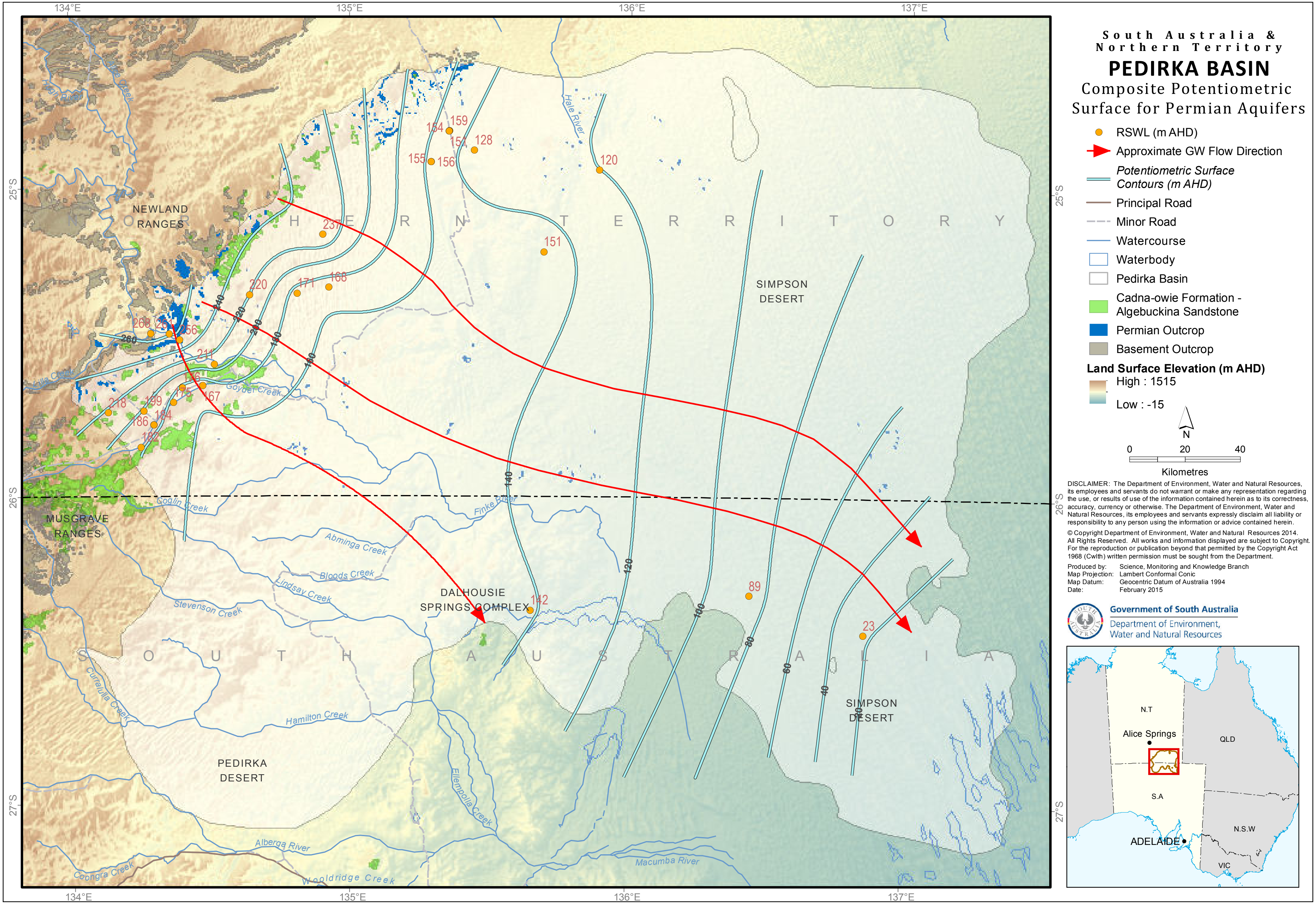

Figure 3.4. Time composite potentiometric surface of Permian aquifers of the Pedirka Basin (Wohling et al., 2013b)

3.4.2 Hydrochemical analyses

A number of previous studies have focussed on the hydrogeochemistry of the western GAB (e.g. Torgersen & Clarke, 1985; Collerson *et al.*, 1988; Love *et al.*, 2000; Radke *et al.*, 2000; Zhang *et al.*, 2007; Mahara *et al.*, 2009; Priestley *et al.*, 2013). Hydrochemical data used by most of these studies were sampled from J–K Aquifer (Figure 3.5) however, very few studies have sampled the P Aquifers (Figure 3.6). A comprehensive suite of hydrochemical data have also been sampled from the Dalhousie Springs complex (Figure 3.7).

3.4.2.1 Groundwater and spring water

Wolaver *et al.* (2013) reported results of selected water samples from the greater Dalhousie Springs area. Data were sourced from historical records of groundwater wells and petroleum exploration drillholes. Dalhousie Spring complex samples were generally indicative of spring water discharge of a Na-Cl and Na-Cl-SO_4 type (Figure 3.8). These hydrochemical facies are similar to the water samples from:

1. artesian flow from the McDills No. 1 well (Na-Mg-Cl-SO_4 signature) (Amerada Petroleum Company of Australia Limited, 1965), which was originally screened over the Jurassic Algebuckina Sandstone, however some groundwater contribution may also come from the Permian Purni and Crown Point Formations due to failed casing
2. Charlotte Waters and Andado Station wells, which are screened within Jurassic/Cretaceous age sediments (Radke *et al.*, 2000)
3. Witcherrie petroleum exploration drillhole, which is completed within Jurassic-age sediments (Magnier, 1964).

These results indicate that the hydrochemical signature of Dalhousie Springs spring water is consistent with (1) (the widely accepted) groundwater sources of Jurassic-Cretaceous age; and (2) sources of Permian age (i.e. Crown Point formation and/or Purni formation) as suggested more recently by Wolaver *et al.* (2013).

Although water samples from a drill stem test at Mount Crispe No. 1 Well (which is completed in Cambrian–Ordovician formations) belong to the Na-Cl-SO_4 type (Jacque, 1966), salinities of around 10 000 mg/L here suggest that formations of Cambrian–Ordovician age are unlikely sources of spring-vent discharge at Dalhousie Springs (Wolaver *et al.*, 2013).

Wohling *et al.* (2013b) reported on the interpretation of hydrochemistry data for the Permian Crown Point formation, based on data presented in published literature (Matthews, 1997; Radke *et al.*, 2000; Priestley *et al.*, 2013). These authors found that there are major ion chemistry and physical parameter data available for the Permian Crown Point formation, which has been collected almost exclusively from the north-west margin of the Pedirka Basin. However, there was an absence of hydrochemistry data for the Permian Purni formation.

Wohling *et al.* (2013b) reported that Piper plots of Permian Crown Point formation hydrochemistry data (Figure 3.9) show that these data cluster into two distinct groups:

- Group 1 with a HCO_3-Ca dominant water type, which suggests groundwater from recent recharge
- Group 2 with a Cl-Na dominant water type, which suggests groundwater with a long residence time and evolution during transport along groundwater flow paths.

All of the Group 1 wells are located contiguous with the Finke River and the Goyder Creek suggesting that ephemeral river recharge to the Permian Crown Point formation is occurring in these areas.

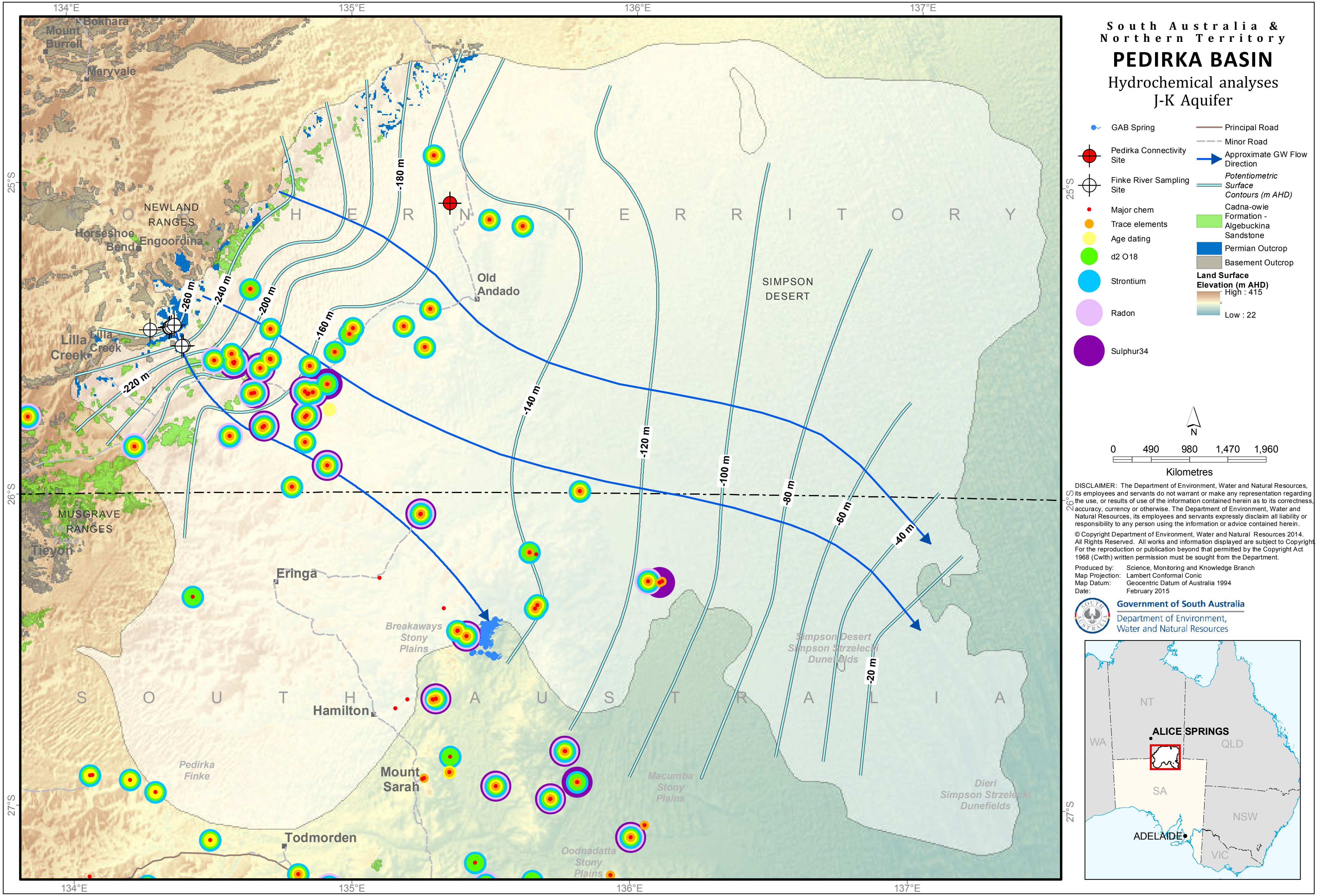

Figure 3.5. Hydrochemical analyses from previous studies sampled from the J–K Aquifer and location of current investigation sites

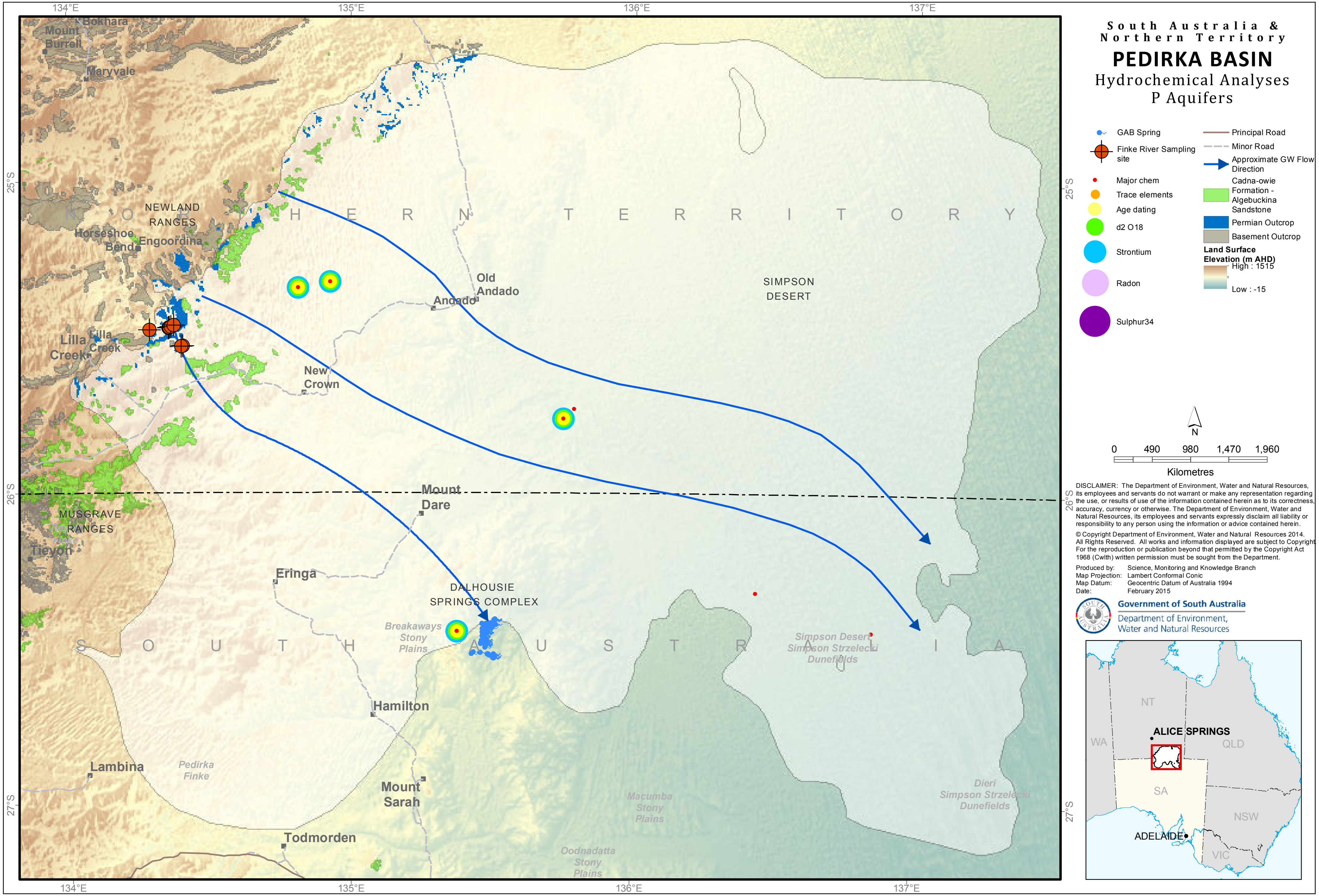

Figure 3.6. Hydrochemical analyses from previous studies sampled from the P Aquifer (or from multiple aquifers that include the P Aquifer)

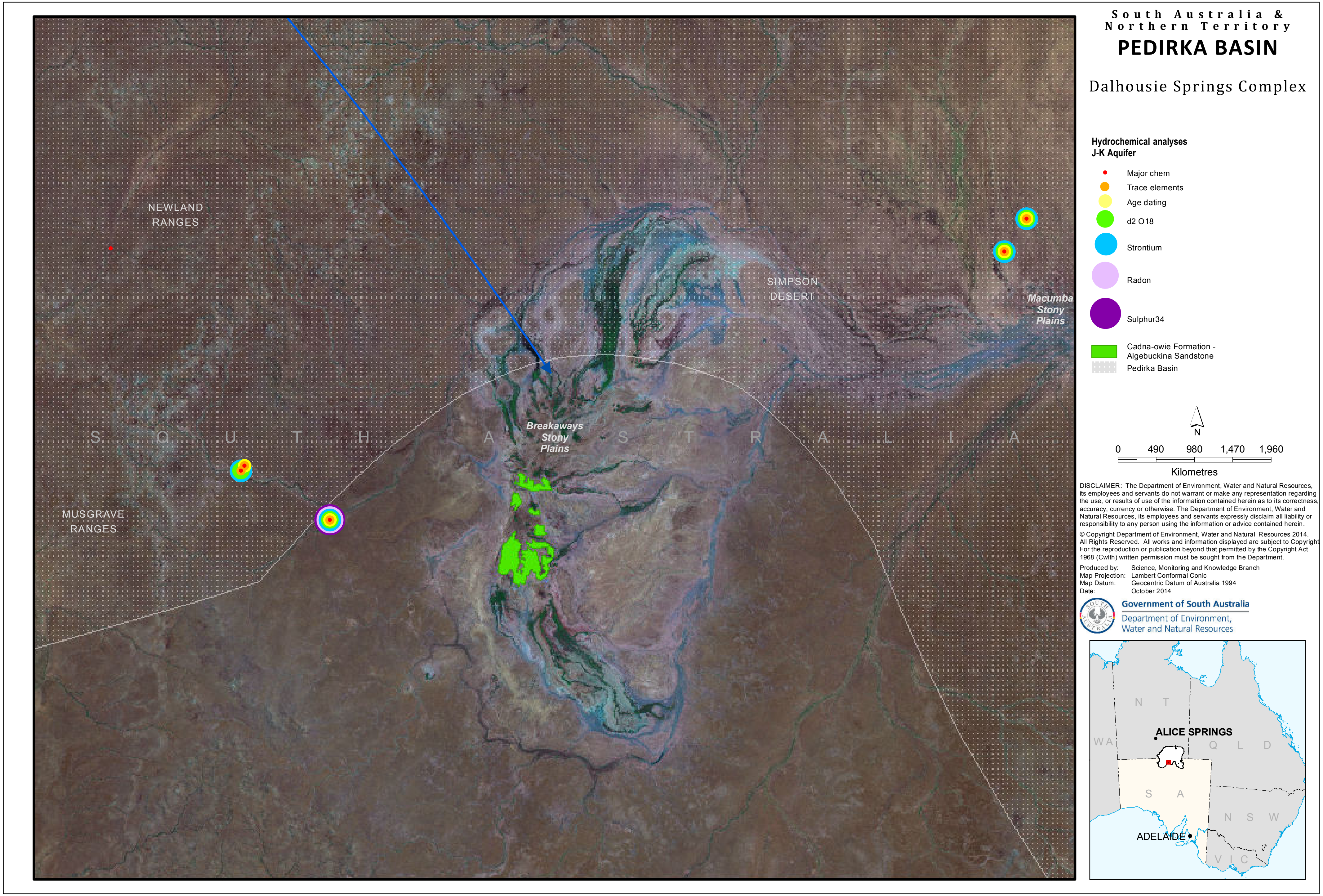

Figure 3.7. Hydrochemical analyses from previous studies sampled from the Dalhousie Springs complex

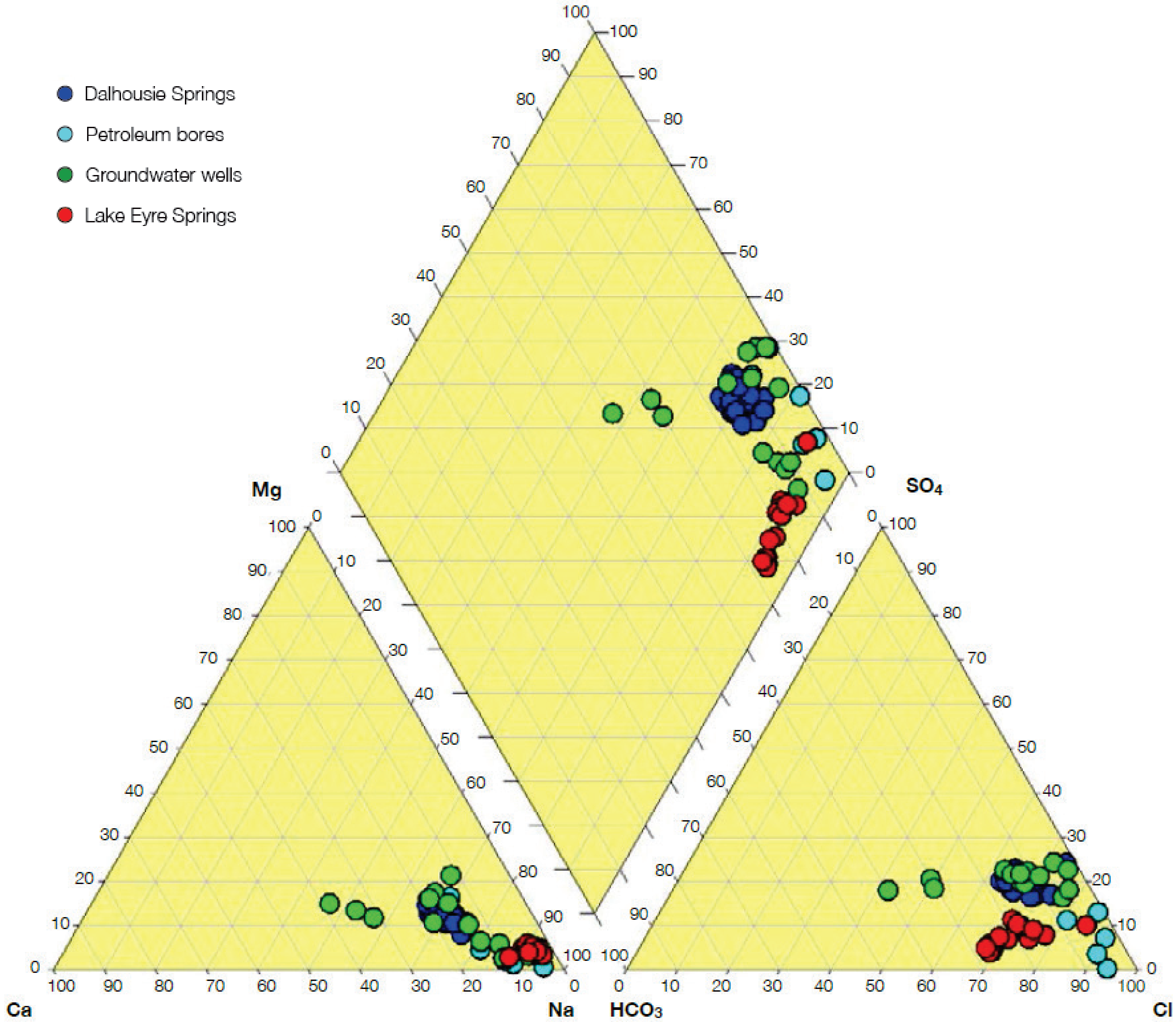

Figure 3.8. Hydrochemical signatures of Dalhousie Springs complex discharge, groundwater and Lake Eyre Springs (Wolaver *et al.*, 2013)

3.4.2.2 Well-spring couplets

Crossey *et al.* (2013) analysed groupings of springs and wells that were separated by less than 30 km. The wells selected for this analysis were all completed within Jurassic-age aquifers. Results showed that in general, all well-spring couplets had similar hydrochemical signatures, suggesting that most GAB spring discharge comprises groundwater predominantly from the J–K Aquifer. However the authors reported that the Dalhousie Springs complex shows relatively high radiogenic strontium ratios, suggesting that a component of the vent discharge at Dalhousie Springs is explained by a source with elevated radiogenic strontium.

Furthermore, well-spring couplets located around the Dalhousie Springs showed stable sodium and chloride ratios, but changing sodium and chloride concentrations. Crossey *et al.* (2013) concluded that these results may indicate (1) groundwater mixing; (2) different source aquifers or depths; or (3) the effects of evapotranspiration of spring water. Also, ion concentration plots for all western-GAB well-spring couplets, including Dalhousie Springs, indicated that groundwater and springs are sourced from similar waters. However, because only J–K Aquifer groundwater was analysed, it was not possible to compare results with groundwater sourced from aquifers above or below the J–

K Aquifer and consequently, the authors reported that it is impossible to estimate mixing proportions of J Aquifer water with that from other aquifers.

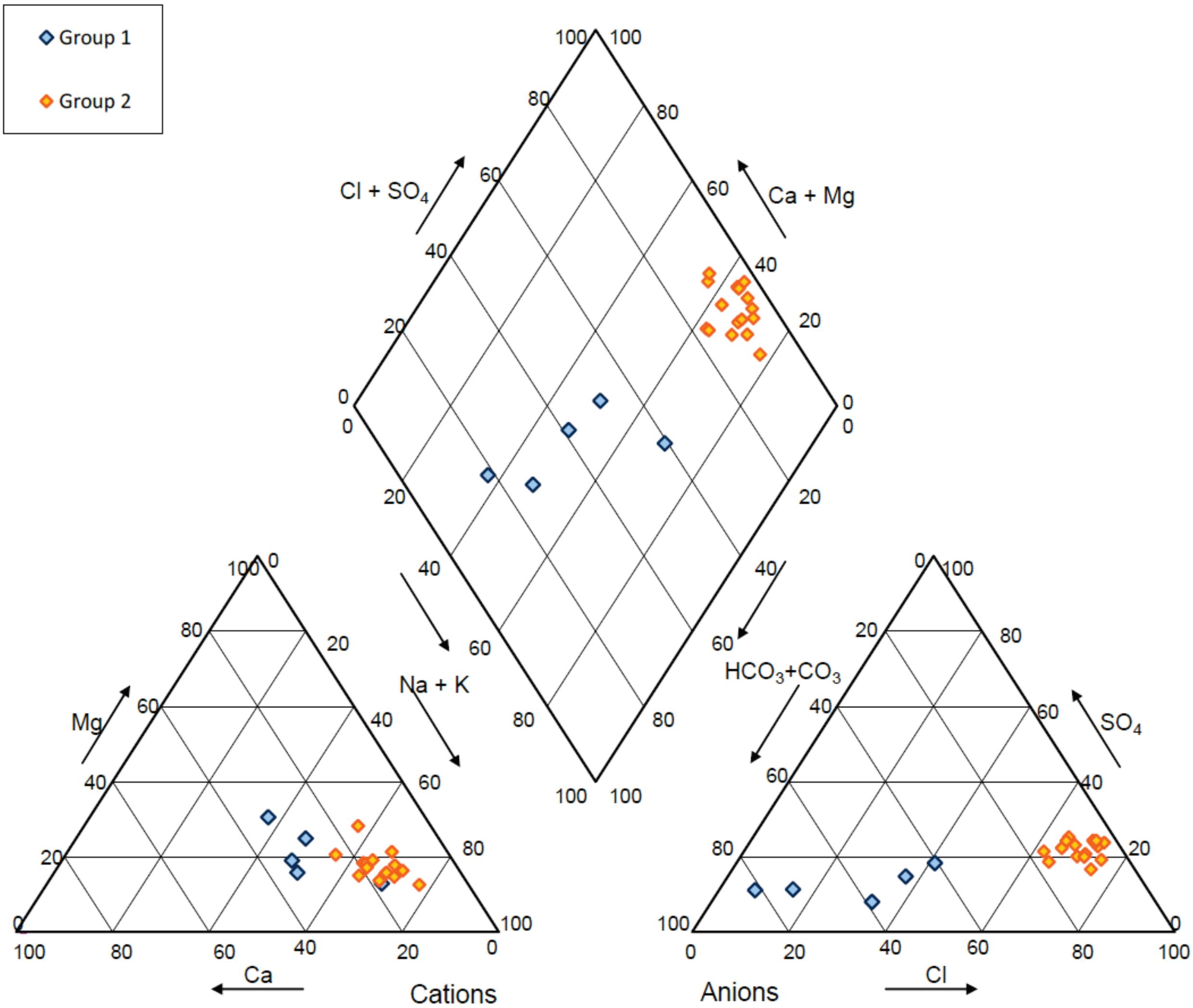

Figure 3.9. Piper plot of Permian Crown Point formation groundwater samples showing two distinct groupings (Wohling *et al.*, 2013b)

3.4.2.3 Geochemical evolution along groundwater flow paths

Love *et al.* (2000) investigated processes that influence Cl and ^{36}Cl distribution in the western GAB with the aim of refining estimates of groundwater age, flow direction and recharge rates. Priestley *et al.* (2013) used two transects first delineated by Love *et al.* (2000) in an analysis of geochemical evolution of western GAB J–K Aquifer groundwater and investigations into determining potential end member sources. One of these transects followed a potential groundwater flow path between Finke River and Dalhousie Springs, in a flow direction from north-west to south-east.

The results of Priestley *et al.* (2013) analysis (Figure 3.10) showed low concentrations of chloride, sodium and sulfate at Finke River (a likely recharge zone for this flow path) which increased sharply at around 40 km distance – the location at which the J–K Aquifer transitions from unconfined to confined conditions. Carbon-14 concentrations in groundwater (Figure 3.11) were reportedly greatest at Finke River (indicating young groundwater of less than 60-years residence time) and steadily decreased along the transect until around 60 km distance, at which point very low carbon-14 concentrations were observed and these data indicated groundwater residence times in the order of thousands of years. There was no apparent trend identified in alkalinity with distance along the transect, in contrast to the aforementioned analytes.

The interpretation of these data by Fulton *et al.* (2013) suggests that the Finke River is an active source of J–K Aquifer recharge estimated to be in the range 380–850 mm/y. Priestley *et al.* (2013) concluded from their analysis of all transects, that groundwater chemistry showed variability of up to four orders of magnitude across the western margin of the GAB, with salinities ranging from fresh to hypersaline. However, the direction of proposed groundwater flow pathways were supported by observations of increasing concentrations of most major solutes analysed along these pathways.

3.4.2.4 Modelling spring water source depth using an adiabatic approach

The depth of the source aquifer from which spring discharge originates can be estimated using the temperature of spring-vent discharge, an understanding of the geothermal gradient and a mathematical model that is underpinned by a number of assumptions. Due to the simplifications and assumptions required in its application, Wolaver *et al.* (2013) concede that this adiabatic-modelling approach can provide only crude estimates of spring source depth; however, the authors note that in the absence of more comprehensive data, this approach may provide a useful first-order estimate.

The adiabatic-lapse approach was first proposed by McCallie (1913) and a full account of the theory and application of the method is outlined by Wolaver *et al.* (2013). In summary, the method uses a simple mathematical model that considers spring discharge temperature, mean annual air temperature and an assumed geothermal gradient (Figure 3.12). Other assumptions include: (1) nil spring conduit heat loss; and (2) that the ground temperature can be estimated via extrapolation of a borehole temperature log.

Results of the analysis presented by Wolaver *et al.* (2013) indicate that thermal spring aquifer source depths are in the range 270–800 m below ground level, or around -130 to -700 m AHD. New hydrogeological maps of the western GAB indicate that the top of the Cretaceous Cadna-owie formation ranges from around 50 to -90 m AHD (Sampson *et al.*, 2013), leading Wolaver *et al.* (2013) to surmise that the source of groundwater for the Dalhousie Springs complex may originate in the deeper aquifers toward the bottom of the GAB (i.e. the bottom of the Permian Crown Point formation).

3.4.3 Conceptual groundwater model of the greater Dalhousie Springs area

Wohling *et al.* (2013b) developed a new conceptual groundwater model for the Pedirka Basin, based on (1) newly-defined basin architecture (from seismic and logging data); (2) groundwater level and chemistry data; and (3) previously published literature; this model is reproduced in full (see Appendix). The conceptual model incorporates a summary of both current information and knowledge gaps for the components of recharge, aquifer parameters, hydrodynamics and discharge.

An abridged version of Wohling *et al.* (2013b) conceptual groundwater model, based on current information and its relevance to the hydrogeology of the Dalhousie Springs complex, follows.

3.4.3.1 Recharge

- Wells *et al.* (1970) suggested that diffuse recharge probably occurs where the Permian Crown Point formation outcrops, toward the north-western margin of the Pedirka Basin.
- Evidence from hydraulic heads, groundwater chloride concentrations and the distribution of hydrochemical facies suggests active recharge is occurring from losing reaches of the Finke River (Fulton *et al.*, 2013; Wohling *et al.*, 2013a)

3.4.3.2 *Aquifer parameters*

- Few data are available that reasonably describe aquifer parameters (Appendix)

3.4.3.3 *Hydrodynamics*

- Regional groundwater flow is from northwest to southeast; the direction of flow appears to be consistent across the J–K Aquifer and the P Aquifers
- Uncertainty dominates most aspects of the hydrodynamics of the Pedirka Basin

3.4.3.4 *Discharge*

- Groundwater from the Permian Crown Point formation is likely to contribute towards discharge at Dalhousie Springs (Wolaver *et al.*, 2013)
- Regional discharge at Dalhousie Springs is likely to be structurally controlled by faulting and fracturing associated with the McDills–Dalhousie Ridge

3.5 Pedirka Basin aquifer connectivity investigation

Existing information on the hydrogeology of the Pedirka Basin and its potential connection with the GAB Aquifer is extremely limited. The absence of wells in the Purni formation and the limited number of wells in the Crown Point formation restrict the application of a number of methods described by Commonwealth of Australia (2014). The *Pedirka Basin Groundwater Assessment* addressed these fundamental data gaps by establishing a dedicated aquifer connectivity study site on Andado Station in the Northern Territory. A nested piezometer site was completed with observation wells constructed in the Cadna-Owie formation (110 m), Algebuckina Sandstone (199 m), Purni formation (242) and the Crown Point formation (531 m). A multi-well 48-hour aquifer test was undertaken pumping the Purni formation well allowed aquifer parameters to be derived for each aquifer (Fulton *et al.*, 2014). All nested wells were sampled for groundwater chemistry and environmental tracers with the results supporting connectivity between the aquifers. In particular, the similarity in apparent groundwater age across the three aquifers suggests a degree of vertical connection between them and may indicate that palaeo-recharge to the Pedirka Basin and GAB Basin was contemporaneous in this area.

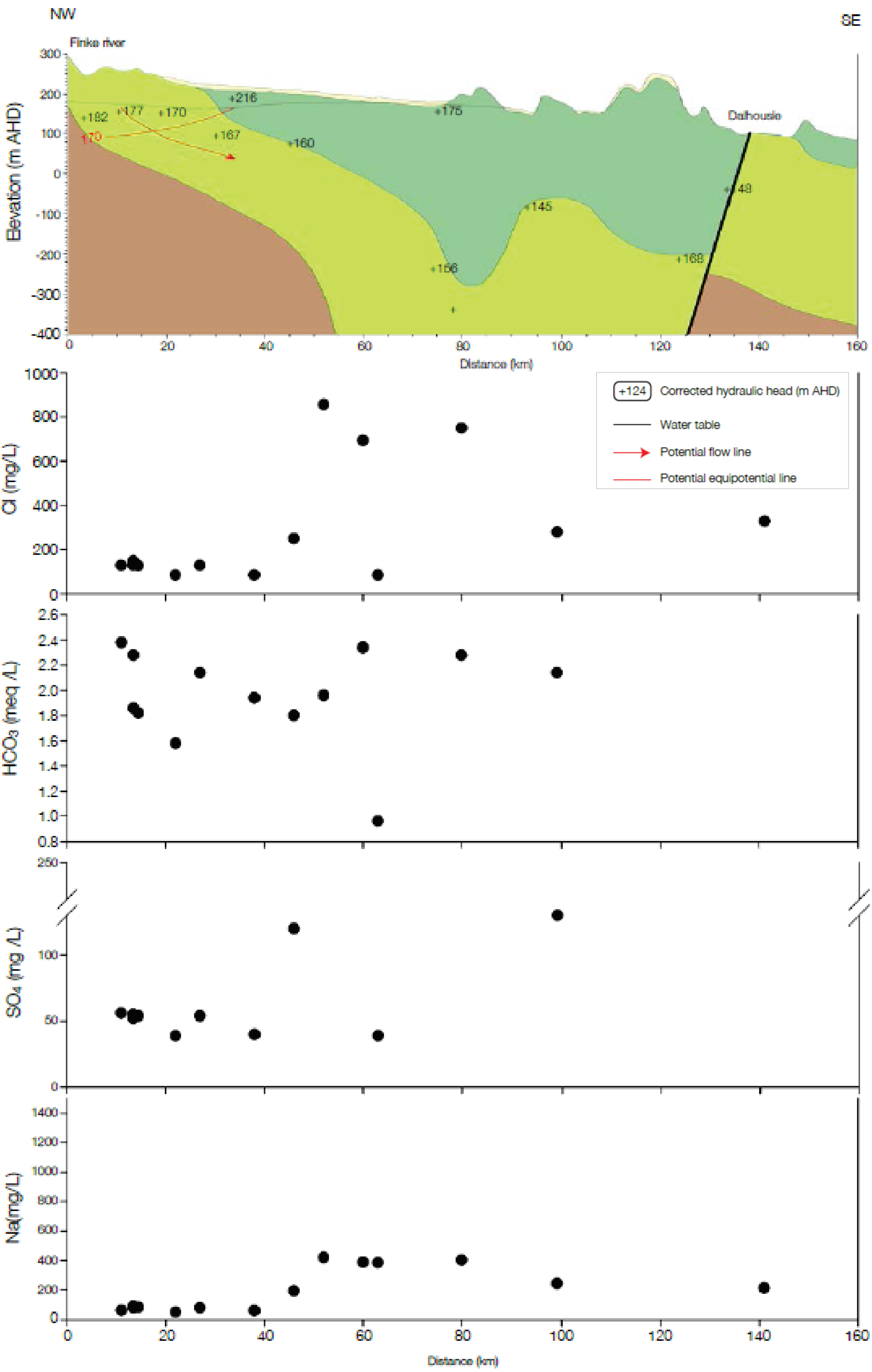

Figure 3.10. Schematic geological cross-section from Finke River to Dalhousie Springs and groundwater concentrations of chloride, alkalinity, sulfate and sodium (Priestley *et al.*, 2013)

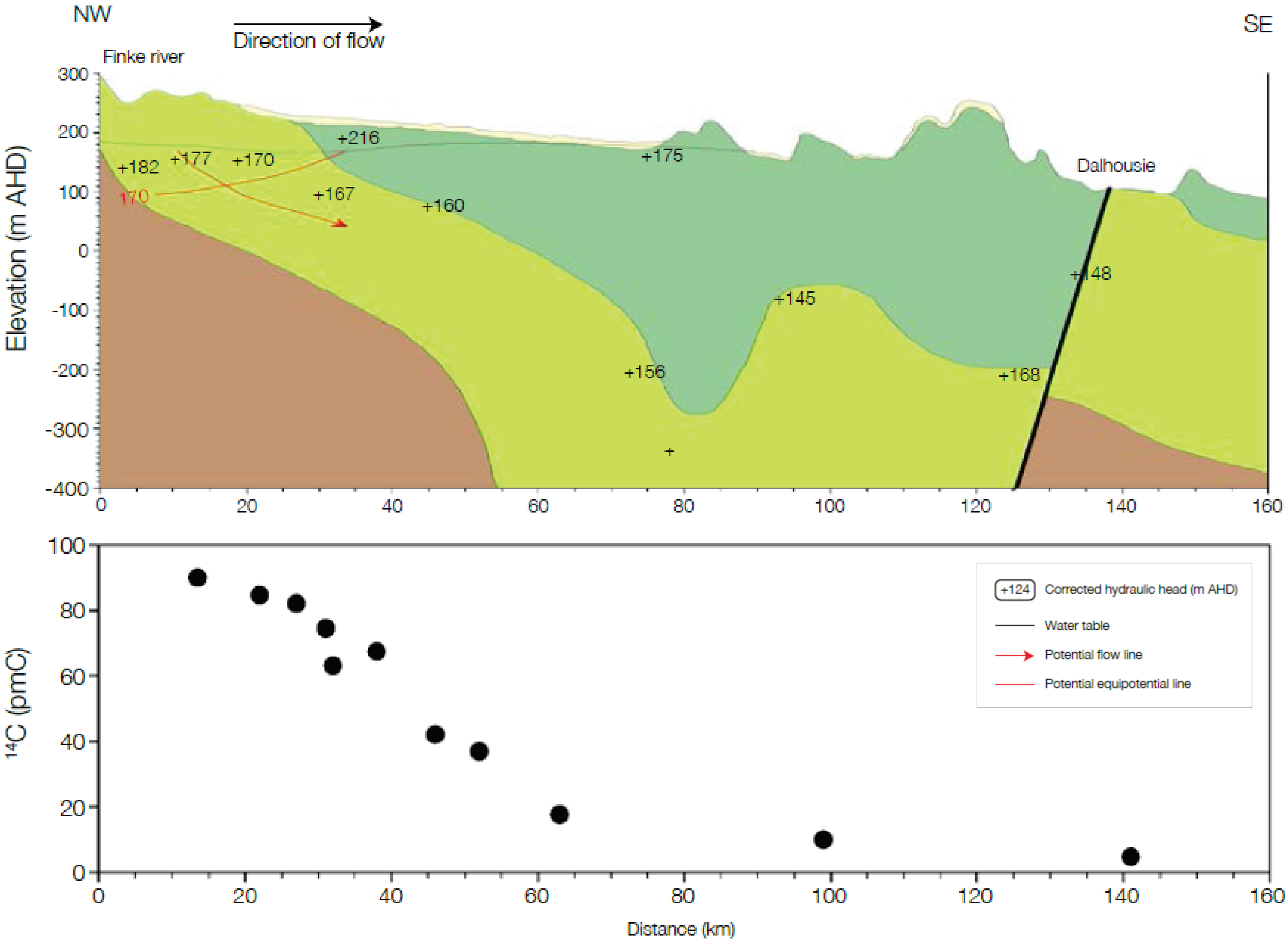

Figure 3.11. Schematic geological cross-section from Finke River to Dalhousie Springs and groundwater concentrations of ^{14}C (percent modern carbon) (Priestley *et al.*, 2013)

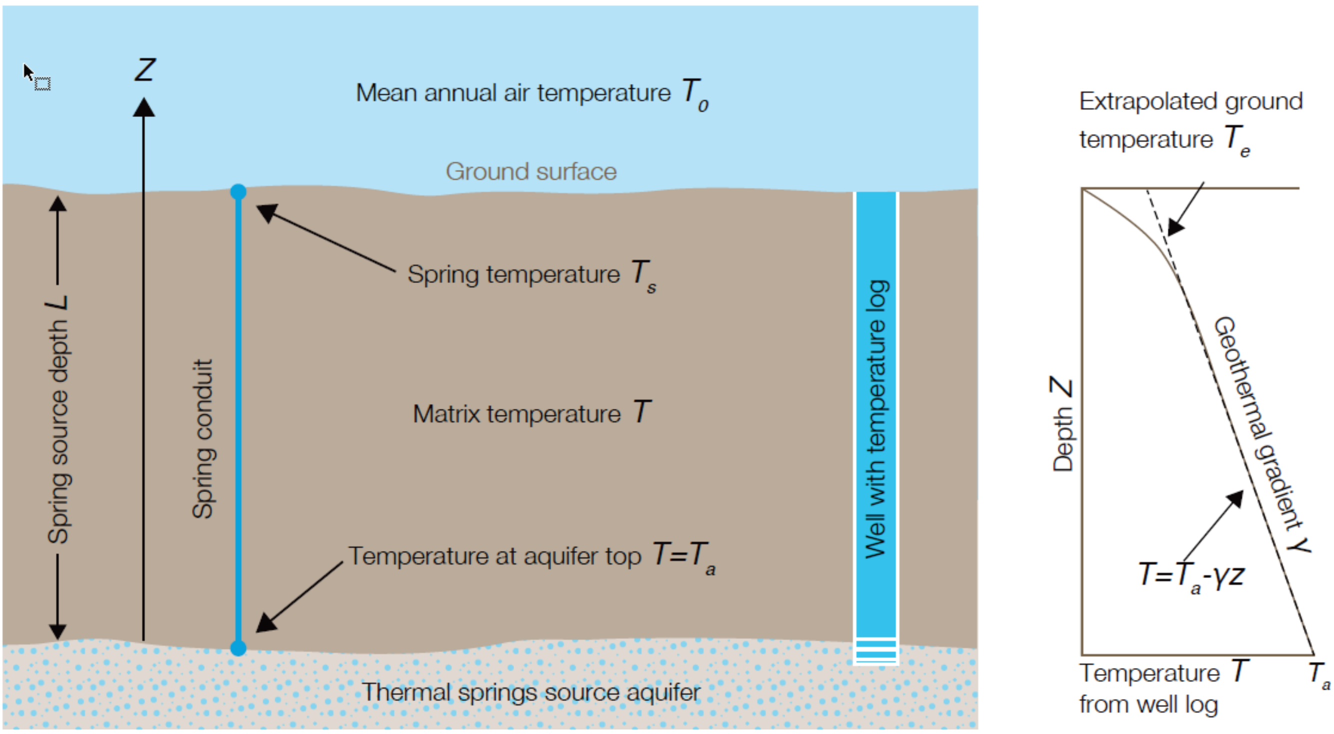

Figure 3.12. Schematic showing modelled thermal spring source depth (Wolaver *et al.*, 2013)

4 Conclusions and recommendations

This review of the hydrogeology of the greater Dalhousie Springs area has summarised the current hydrogeological knowledge of the groundwater systems of the area, as encapsulated in the current hydrogeological conceptual model for Dalhousie Springs described by Wolaver *et al.* (2013).

4.1 Knowledge gaps

Perhaps the greatest knowledge gap pertaining to the greater Dalhousie Springs area is the nature of inter-aquifer connectivity and the degree of mixing between the Permian sequences and the overlying J–K Aquifer. Little is known about the vertical hydraulic gradients between these aquifers. These potential connections might have implications for the effective management of water resources and for the assessment of potential impacts on GDEs from the future development of groundwater resources in the region.

The occurrence of good quality water in the shallow J–K Aquifer has resulted in very little deep drilling and a lack of information for the deeper P Aquifers. Outside the north-west margin of the Pedirka Basin, groundwater information is extremely limited as only a single well (McDills No. 1, a failed petroleum investigation well) is recorded as intersecting the P Aquifers. Consequently, the areas of uncertainly include:

- flow directions and potentiometric surfaces of the Permian Crown Point formation and Permian Purni formation
- whether the two P Aquifers are interconnected or operate as separate aquifers
- inter-aquifer connectivity, particularly between the Permian formations and the overlying GAB Aquifer in the vicinity of Dalhousie Springs.

There are few hydrochemical data beyond the western margin of the Pedirka Basin with which to reliably estimate recharge rates or aquifer residence times. The analyses by Wolaver *et al.* (2013) indicate that the hydrochemical signature of Dalhousie Springs water was consistent with both GAB or Permian Aquifer sources. However, these findings are qualitative in nature and Wohling *et al.* (2013b) note that:

> *This study did not review the over-arching architecture of the Permian and basement formations in the Dalhousie region, and did not consider groundwater chemistry samples from the Crown Point aquifer on the edge of the basin. The findings from this study regarding the source aquifer for Dalhousie Springs are equivocal.*

Seismic imagery suggest that most springs within the Dalhousie Springs complex are likely to be controlled by fracturing and faulting (Aldam & Kuang, 1989). Furthermore, Krieg *et al.* (1985) and (Krieg, 1989) suggest that the McDills–Dalhousie Ridge is responsible for the faulting and fracturing that has led to spring conduit formation. However Wolaver *et al.* (2013) conclude that this is "… the most plausible …" discharge mechanism for the P Aquifer and K Aquifer discharge. Targeted geophysical investigations could help resolve these uncertainties.

4.2 Conceptual model of groundwater flow at Dalhousie Springs

The refinement of Wolaver *et al.* (2013) conceptual hydrogeological model of the greater Dalhousie Springs area is constrained by insufficient data and knowledge of the fundamental hydrogeological parameters of recharge mechanisms, discharge mechanisms, hydrogeochemistry and hydrodynamics and uncertainties around the nature of subsurface structures and how these may govern or influence spring discharge. Most of the knowledge gaps, and the greatest uncertainties, pertain to the Permian Crown Point formation and Permian Purni formation. To address these knowledge gaps, a program of future works and investigations are recommended, including water-well drilling, hydrochemical sampling, geophysical investigations and hydraulic testing.

4.3 Recommendations for future work

A first-order hydrogeological investigation at a single site is the minimum scope of works required to begin addressing knowledge gaps around the fundamental hydrogeological parameters outlined above. To gain a full and robust understanding of the hydrodynamics of the Dalhousie Springs complex, hydrogeological investigations using multi-completion wells at multiple sites are required.

4.3.1 First-order hydrogeological investigation

4.3.1.1 Water well drilling, aquifer testing and hydrogeochemical sampling

The minimum scope for field investigations that are required to address knowledge gaps around the aforementioned fundamental hydrogeological parameters include the drilling of a new multi-completion site, at or near Dalhousie Springs, with nested observation wells across J–K Aquifer, P Aquifer and the Finke Group. Long-term aquifer tests carried out at the proposed multi-completion site will produce estimates of aquifer parameters for the three aquifers and give an indication of the degree of inter-aquifer connectivity at that particular site. Drilling depths of up to around 2000 m are likely to be required, dependent on the location chosen for the nested well site (Table 4.1).

A hydrochemical sampling program is essential to refining the conceptual model of groundwater flow at Dalhousie Springs. The work of Priestley *et al.* (2013) provides a hydrochemical baseline and lays the foundations for an assessment of the origin of spring waters across the western GAB. Sampling of the proposed observation wells should establish the chemical facies for the various aquifers and their end members which will allow the development of a mixing model to quantify the spring-discharge contributions from the different source aquifers.

Table 4.1. Depths to bottom of formations showing indicative depths (metres below ground level (m bgl)) for drilling programs, based on aquifer depths recorded at various Pedirka Basin water wells (Mt Hammersley 1; Witcherie 1; Purni 1 and Mokari 1 – see Figs. 3.1 and 3.2 for well locations)

Aquifer	Depth to top of aquifer (m bgl)	Depth to bottom of aquifer (m bgl)
J–K Aquifer	318–1193	608–1802
Purni formation	605–1803	890–2151
Crown Point formation	714–2153	891–2254

4.3.1.2 Geophysical investigations

Geophysical techniques are often used in hydrogeological investigations to aid in conceptualising lithology, hydrochemistry and groundwater flow. In a study of spring complexes in the south-western GAB, Inverarity (2014) showed that optimal interpretation of geophysical data can be gained by using multiple, complementary geophysical methodologies, such as the techniques of self potential; transient electromagnetics; and audio magnetotellurics. Local-scale surveys at Dalhousie Springs could target key springs to potentially identify shallow groundwater flow paths and infer structurally-controlled spring conduits up to depths of around 1000 m.

4.3.2 Hydrogeological investigations at multiple sites

4.3.2.1 Water well drilling and aquifer testing

The drilling of a regional transect of observation wells in the P aquifer (and J–K Aquifer or adjacent to existing J–K Aquifer wells) between the likely recharge zone on the western margin of basin and Dalhousie Springs is recommended. Locally around the springs, new multiple-completion sites should be drilled to access the J–K Aquifer, P Aquifer, and Finke Group to obtain estimates of aquifer parameters and the degree of inter-aquifer connectivity.

4.3.2.2 Geophysical investigations

In addition to increasing the scope of the proposed geophysical investigations (Sect 4.3.1.2) to the regional transect of observation wells in the P Aquifer, employing the technique of reflection seismology is recommended. Regional seismic surveys could assist in estimating depths to various hydrostratigraphic formations and basement and improve our understanding of basin architecture which would increase our knowledge of hydraulic connectivity.

4.3.2.3 Hydrochemical sampling program

Sampling of the regional transect of wells using age dating techniques will enable the evaluation of groundwater flow paths and the associated hydrochemical evolution that may occur along such flow paths. Hydrochemical sampling from multiple wells will assist in constraining the mixing model outlined in Sect. 4.3.1.1.

4.3.2.4 Shallow coring

Shallow coring of extinct discharge areas (e.g. springs.) provide a discharge chronology.

Appendix

Conceptual hydrogeological model, Pedirka Basin (Wohling *et al.*, 2013b)

	COMPONENT	SUMMARY OF CURRENT INFORMATION	KNOWLEDGE GAPS
Recharge	Recharge Zones	Recharge postulated to occur on the north-west margin of the basin where the Crown Point formation outcrops in the NT (Wells et al., 1970), however, recharge zone is not defined nor is the river reach contributing to ERR	Spatial extent of the potential zone for diffuse recharge is not defined. Recharge reaches of Finke River/Goyder Creek are not defined
	Recharge Mechanisms	Diffuse recharge presumed to occur where Crown Point formation outcrops (Wells et al., 1970). Groundwater flow pattern supports diffuse recharge in this area. Potential for indirect recharge exists where the Finke River intersects the edge of the Pedirka Basin north-west of Finke Community (Love et al., 2013b). Hydraulic head, groundwater chloride and distribution of chemical water types support active recharge from the Finke River and potentially Goyder Creek.	It is unclear if diffuse recharge is still occurring under today's climate or if the head distribution reflects palaeo-recharge from a wetter climate Groundwater data are too limited to comment on the operation of focused recharge in systems other than the Finke River/Goyder Creek. No information available on focused recharge by overland flow
	Recharge Rates	Diffuse recharge rates estimated at between 0.02–0.16 mm/y using groundwater CMB method. The rate of ERR unknown.	High uncertainty surrounding CMB estimates of diffuse recharge The rate of ERR is not known
Aquifer Parameters	Transmissivity	No information available	No estimates of transmissivity or aquifer storage coefficients. Permeability measurements are primarily based on core analysis of small formation intervals and cannot reasonably be up-scaled to estimate formation hydraulic conductivity/transmissivity.
	Storage	No information available	
	Permeability and Hydraulic Conductivity	Purni formation—Permeability estimates for sandstone intervals range from 135–2529 md with a hydraulic conductivity range of 0.11–2.44 m/d. Permeability of the coal measures ranges from 0.2–66.7 md with a hydraulic conductivity range of 1.7x10^{-3}–0.03 m/d.	
		Crown Point formation—Permeability is reported at between 91–1998 md with a hydraulic conductivity range of 0.08–1.66 m/d	
	Porosity	Purni formation —Porosity ranges from 4–32% (16–25% for core analysis)	
		Crown Point formation—Porosity ranges from 3–30% (11–32% for core analysis)	

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

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

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