# CHAPTER 2: OVERVIEW OF STUDY AREA

*This chapter is based on the following peer-reviewed report:*

*Keppel, M. Karlstrom, K., Love, A., Priestley, S., Wohling, D., De Ritter, S. (Eds.), 2013 b. Hydrogeological Framework of the Western Great Artesian Basin, 1. National Water Commission, Canberra.*

## 2.1 Climate

Allan (1990) and McMahon et al. (2005) describe the climate of the Lake Eyre region as arid, while Stern et al. (2000), using a modified version of the Koppen climate scheme, describes the region as “desert”.

Kotwicki and Allan (1998) and McMahon et al. (2005) assert that these arid conditions are largely attributable to the El Nino/Southern Oscillation (ENSO) weather system. The mean daily maximum temperature of the nearest town (Marree) is 28.4°C, while the mean temperature is 18.8°C (Figure 2.1).

Central Australian weather is dominated by persistent high pressure systems; the location of the dominant high pressure system is an important influence on temperature within the region. Rainfall events are primarily sourced from weak winter cold fronts; typical annual precipitation is estimated at approximately 120 mm/year, although actual rainfall amounts from year to year may vary significantly (Allan 1990; McMahon et al., 2005) (Figure 2.2).

Kotwicki and Kundzewicz (1995) state that the modern Lake Eyre drainage basin mean annual runoff of 4 $km^3$ is the lowest of any major drainage basin in the world. Kotwicki and Kundzewicz (1995) also compared the yield of the Lake Eyre drainage basin (10 $m^3 \cdot km^2$/day) to that of the much higher value for River Nile drainage basin in Egypt (115 $m^3 \cdot km^2$/day) and described this as a good demonstration of the Lake Eyre region's aridity. McMahon et al. (2005) also noted that precipitation in the Lake Eyre Basin is more variable than 65% of equivalent arid regions internationally, while the Australian Bureau of Meteorology (BoM. 2011c) suggests that the region has extreme rainfall variability when compared to the rest of continental Australia (Figure 2.2). Finally, Hamilton et al. (2005) measured average pan evaporation rates in the Cooper Creek region of central Australia of 2.5 m/year, while Tetzlaff and Bye (1978) reported an evaporation rate of approximately 3 m/year in the Lake Eyre region.

Given the arid climate, the region is generally very sparsely vegetated except in the vicinity of drainage channels and springs. Particularly around springs, vegetation may become very dense. An overview of vegetation found within the mound spring wetlands studied is provided in section 3.2.3 of Chapter 3.

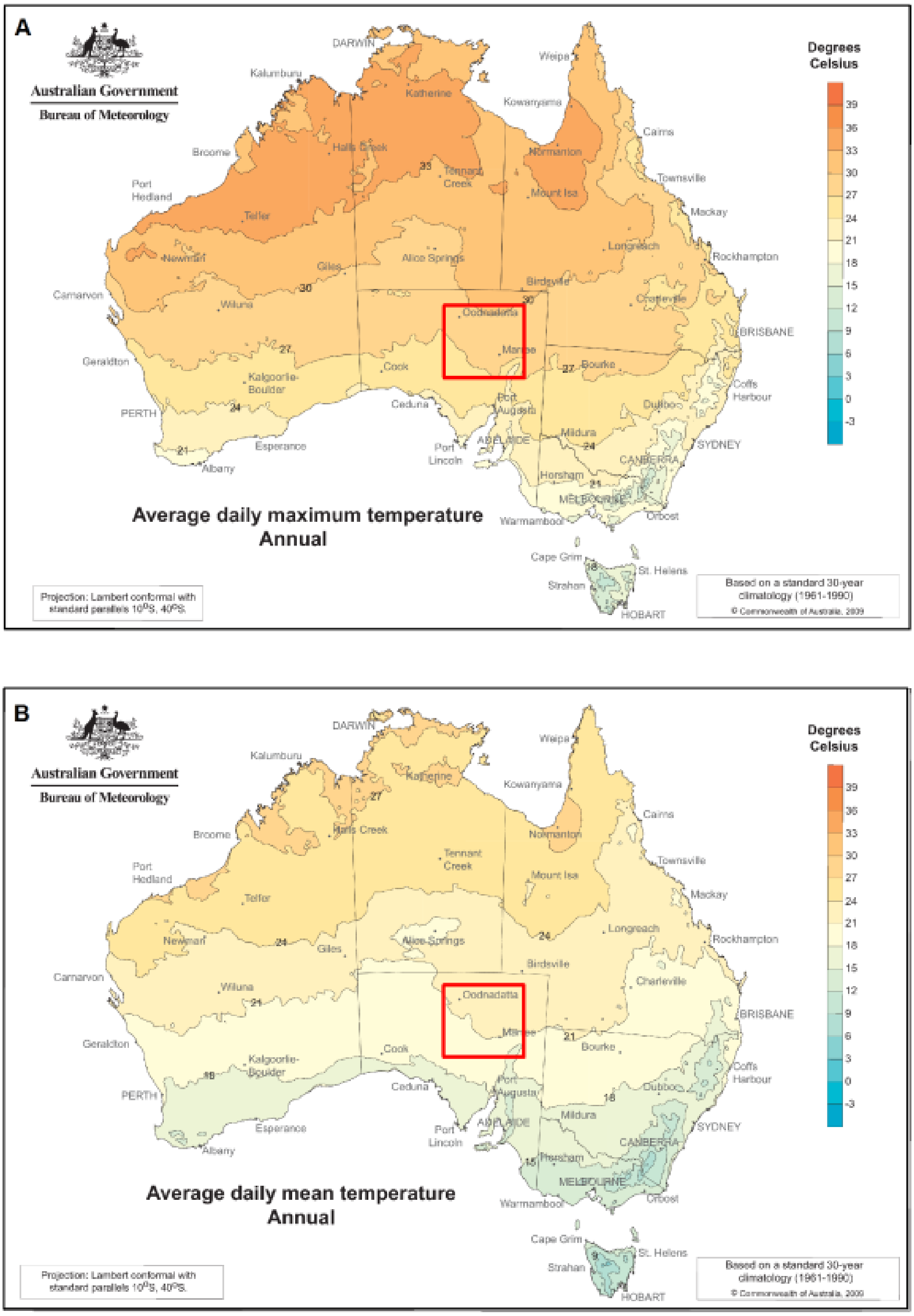


Figure 2.1: Average daily maximum annual temperature (A) and average daily mean annual temperature (B) for continental Australia. The regional study area shown in Figure 2.3 is highlighted in red. Data and images courtesy of the Australian Bureau of Meteorology (BoM) (2011a).

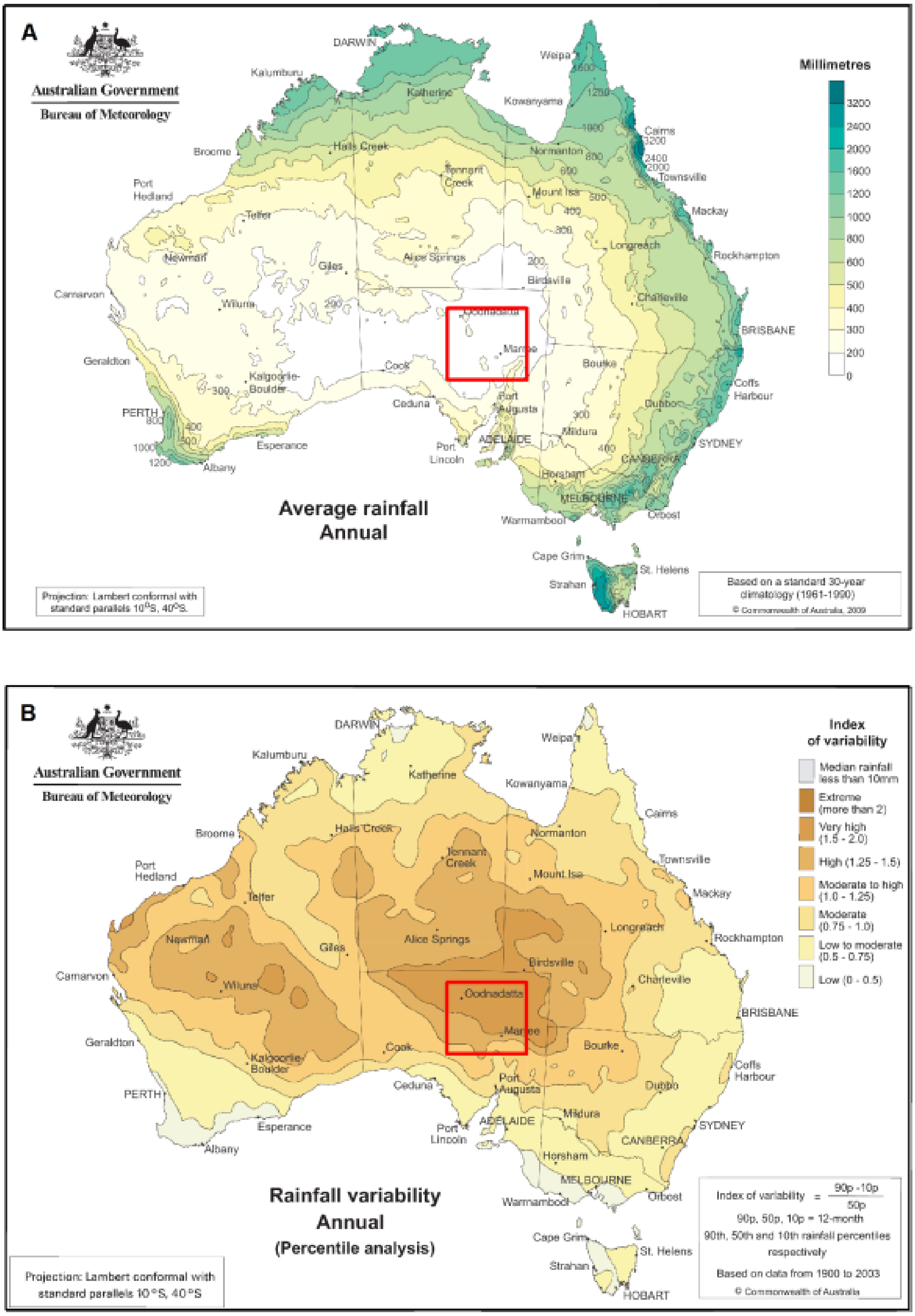


Figure 2.2: Average annual rainfall (A) and annual rainfall variability (B) for continental Australia. The regional study area shown in Figure 2.3 is highlighted in red. Data and images courtesy of BOM. (2011b and c).

## 2.2 Hydrology and geomorphology

### *2.2.1 Surface hydrology*

A number of ephemeral rivers and creeks with headwaters in the Stuart Range to the east of the GAB and Northern Flinders Ranges to the south provide surface water drainage to the region (Figure 2.3). Major ephemeral drainage channels within the study area include the Frome, Macumba, Warburton and Neales Rivers as well as the Peake, Warriner, Margaret, Cooper and Gregory Creeks (Figure 2.3). Kotwicki (1986) reports that the major rivers draining into Lake Eyre have a typical fall of between 200-300 m between headwaters and their discharge point. Additionally, Silcock (2010) noted that permanent surface water-bodies are rare in this region and are generally associated with springs or rock holes in discrete locations.

At approximately 9,500 $km^2$, Lake Eyre North and South provide the largest drainage termination in the region. Other important playas that occur near the GAB boundary include Lake Frome (2,596 $km^2$), Lake Torrens (5,700 $km^2$) and Lake Gardiner (4,300 $km^2$). Lake Torrens and Lake Gardiner occur outside the basinal extent of the GAB, while the others occur within the boundary of the GAB.

Flow events are highly episodic and heavily reliant on the erratic precipitation events. The majority of events are short lived, relatively small and occur on either an annual or bi-annual basis (Northern Territory Government (NTG), 2011). Kotwicki and Allan (1998) states that given the arid climate, stream flow conditions are only experienced after either heavy summer monsoonal rains or heavy winter rains that are typically caused by La Niña Southern Oscillation events in the Pacific Ocean.

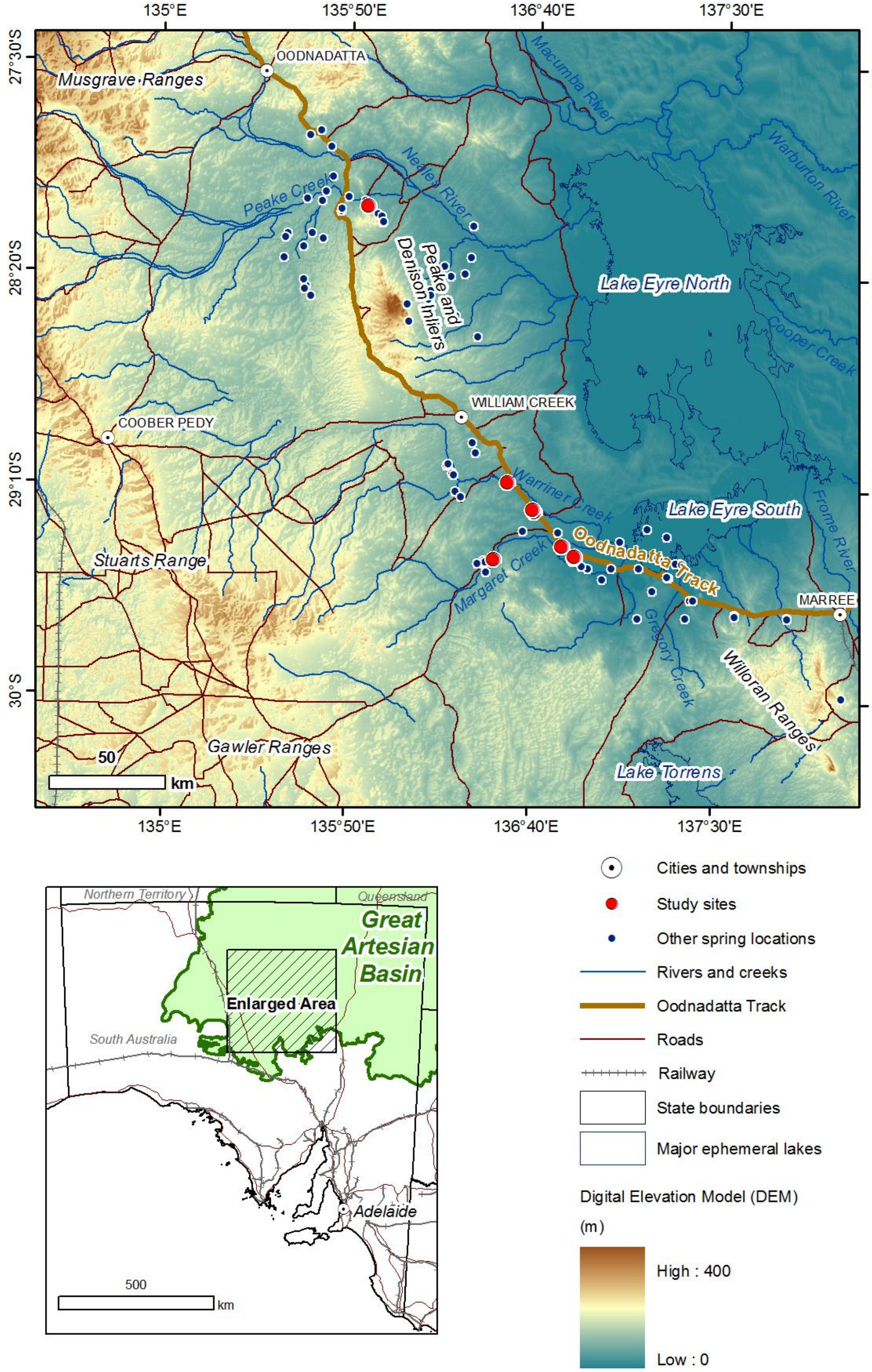


Figure 2.3: Location map of study areas, geographic features and Digital Elevation Model (DEM) (NASA 2011) of the region.

Armstrong (1990) states that erosion by ephemeral streams often incise GAB aquitard units such as the Bulldog Shale. Consequently, springs that form as a result of this incision may provide localised sources of surface flow (Aldam and Kuang, 1988; Boyd, 1990). However, Habermehl (1980) states that stream flow beyond the headwaters and middle reaches of rivers is rare due to the impact of low gradients and high evaporation and infiltration rates. In support of this, Allan (1990) suggests that precipitation levels in excess of 400 % greater than the long term annual average are required to provide sufficient floodwaters for the Frome and Clayton Rivers to reach their terminations in Lake Eyre. Consequently, the South Australian Arid Lands Natural Resources Management Board (SAAL NRMB) (2006) has characterised the surface water resources of the western margin of the Great Artesian Basin (GAB) as displaying a “boom and bust” cycle, where years of drought may be interspersed with a few weeks of intense rainfall and flooding.

Groundwater in shallow aquifers in the vicinity of ephemeral lakes may be recharged during periods of inundation, however may also become areas of diffuse groundwater discharge via evaporation during dry times, leading to salination of the soil profile. Highly saline shallow groundwater in the vicinity of such lakes may be a consequence of variations in soil profile flushing in response to wet and dry inter-annual periods of river discharge (Costelloe et al., 2009).

### *2.2.2 Geomorphology*

The region between the Stuart Range and the western shore of Lake Eyre is typically very flat; topographic variability present in the region is predominantly provided by drainage and playa development, which forms anastomosing rivers and creeks and associated gently sloped valleys, swales, floodplains and salt flats. Breakaways or escarpments (Figure 2.4a) also form as a consequence of headward drainage erosion. River and creek terminations are normally either, basins, playas or delta shaped sink zones (Figure 2.4c). The other major contributor to topographic development is the arid climate, which has resulted in extensive sand dune development (Figure 2.4b). Minor but visually prominent contributors to topography are mesas formed from the limestone caps of relict mound springs (Figure 2.4c).

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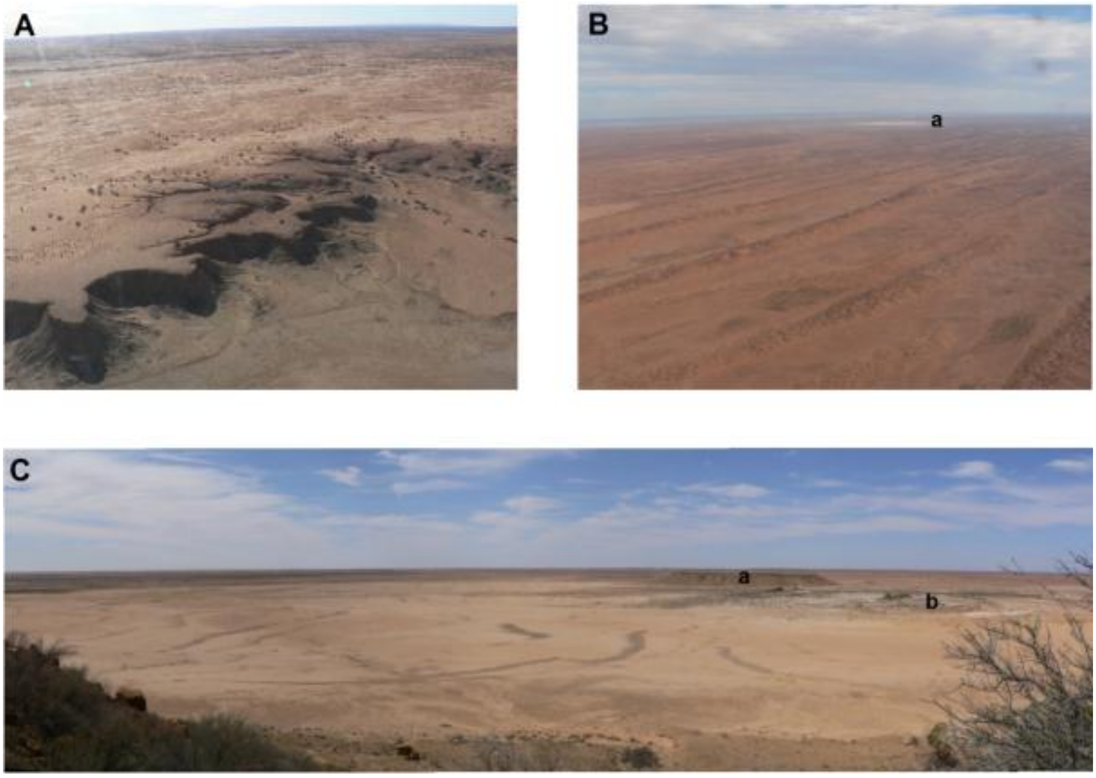


Figure 2.4: Typical geomorphological characteristics of the Lake Eyre South region. A) Breakaways formed by headward erosion of surface drainage. Note generally flat terrain behind the breakaway. B) Longitudinal sand dunes with drainage basin (a) located in background. C) View of Warburton Spring study area from Beresford Hill. Mesa formed from a pedestal of fossiliferous mound spring limestone on Bulldog Shale substrate (a) in background. Platform composed of calcareous spring deposits associated with modern spring activity (b) is located to right of image. Foreground of image composed of alluvium deposited in shallow basin.

The margins of the GAB in the vicinity of the study area are commonly marked by a series of highlands and plateaus that define the margins of the basin and are largely a consequence of either gentle up-warping or faulted uplift of Proterozoic basement sequences (Figure 2.3). Such highlands areas include the Willoran, Flinders, Gawler and Stuart Ranges to the south and southwest and the Musgrave Ranges to the northwest.

The tallest peak in the Musgrave Ranges is Mount Woodroffe (1,435 m); such heights are comparable to those found within the Great Dividing Ranges along the eastern margin of the GAB. On the southwest margin, the Stuart Range is a low-rising escarpment that borders the western margin of the GAB for approximately 170 km near the township of Coober Pedy and is composed of silcrete capped Cretaceous sediment (Simon Coincon et al., 1996). To the south of the Stuart Range, the Gawler Range occurs on the eastern margin of the Gawler Craton and is composed of volcanolithic deposits (Drexel et al., 1993). The highest point is Nukey Bluff at 465 metres above height datum (mAHD). The southern margin of the GAB is defined by the Northern Flinders Ranges, the western arm of which is called the Willoran Range.

According to Quigley et al. (2010), the Flinders Ranges formed in response to lithospheric folding caused by intraplate compression during the Cainozoic. The Northern Flinders is composed of Proterozoic Adelaidean metasediments, while the highest peak (St Mary’s Peak) is 1,170 m. The Peake and Denison Inlier is also an important mountain range within the region (Figure 2.3). The Peake and Denison Inlier are composed of up-faulted, outcropping crystalline Proterozoic and Archaean basement units that are also known as the Denison and Davenport Ranges (Wopfner and Twidale, 1967). The central part of the ranges consists of a north-sloping plateau with an elevation between 400-420 metres above sea level (msl).

Simon Coincon et al. (1996) interprets the Peake and Denison Inlier to be the remnant of a former drainage divide that existed during a large part of the Cainozoic and states that migrating headwater erosion by the eastward flowing drainage system formed the flat erosion scarp between the Stuart Range and Lake Eyre that currently exists (Figure 2.3). Combined with deflation, this headward erosion has removed at least 20 m of Cretaceous pediment since the end of the Pliocene and has captured former streams draining the western side of the Peake and Denison Inlier.

Mabbutt (1977) described deflation as the dominant process shaping the physiology of the region, although as previously discussed evidence for water-related denudation is also pervasive. On average, 5 dust storms per year are reported at Oodnadatta, 60 km west of Lake Eyre, and they become more frequent during drought (SAAL NRMB, 2006). Waclawik (2006) describe typical gale force winds in the vicinity of Lake Eyre are between 40-50 knots, although may reach as high as 60-70 knots. Consequently, longitudinal sand dunes in the plains and lunette dunes in the vicinity of playas are important sources of topographic variance in the region. In particular, the longitudinal dunes of the Simpson Desert region in the vicinity of the South Australia/ Northern Territory border can extend for several hundred kilometres and are up to 40 m high (Ambrose, 2006).

### 2.3 Geology and hydrogeology of the southwestern GAB

The GAB is the primary source of artesian groundwater in the region and is therefore currently considered the primary source of springwater to the springs in the Lake

Eyre South area. Krieg et al. (1995) describe the GAB as a non-marine to marine Triassic-Jurassic-Cretaceous hydrogeological super basin. Although it includes sediments from three large epi-continental depressions, namely the Carpentaria Basin, the Surat Basin and the Eromanga Basin, the Eromanga Basin is the largest of the three volumetrically and is also coincident with the western margin of GAB in South Australia (Figure 2.5). Consequently, a discussion concerning the geology of the GAB in the general area of investigation is synonymous with a discussion about the Eromanga Basin.

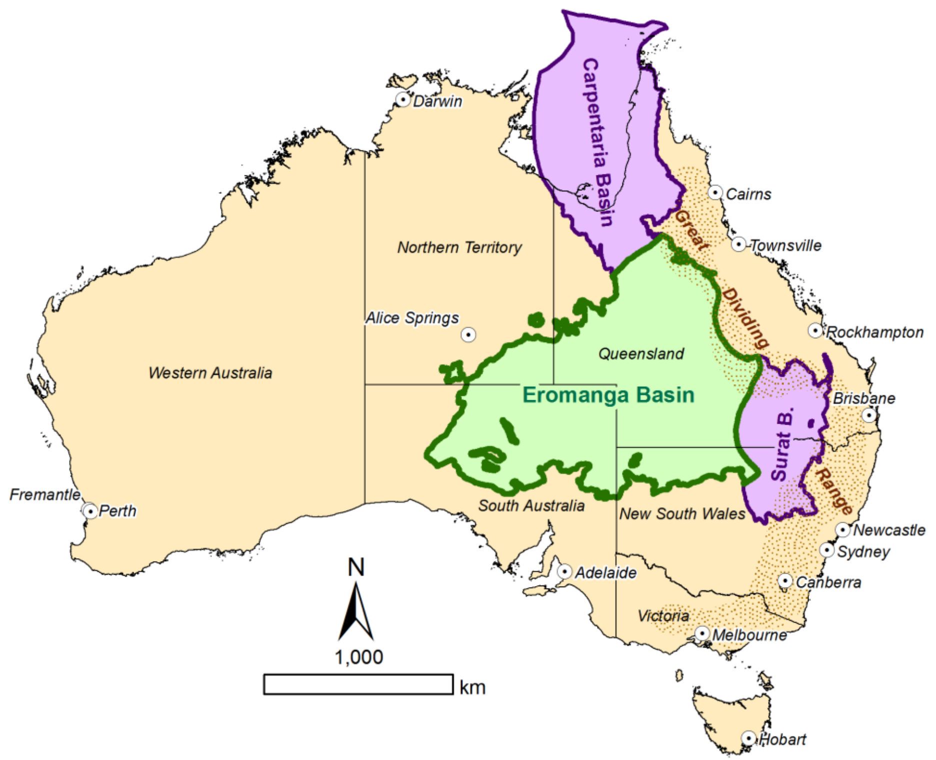


Figure 2.5: Major sub-basins within the GAB and the location of the Great Dividing Range. Basin data from Geoscience Australia (2011).

Krieg et al. (1995), Ollier (1995), Toupin et al. (1997) and Wopfner and Twidale (1967) described the formation of the Eromanga Basin being triggered after general uplift within South Australia during the Triassic coincided with continental down-warping to the northeast. Consequently, variations in basin subsidence or up-warp and global sea level changes during the Mesozoic led to the development of a series of transgressional alluvial, fluvial and marine sequences that form the basin sediments. (Krieg et al., 1995; Wopfner and Twidale, 1967).A detailed summary of the hydrostratigraphy of the Western margin of the GAB compiled from Drexel and Preiss (1995), Krieg et al. (1995), Radke et al. (2000) and Shepherd (1978) is provided in Table 2.1, while a cross-section through the southwestern portion of the GAB is provided as Figure 2.6.

In South Australia, the Cadna-owie Formation and the Algebuckina Sandstone aquifer units supplies the GAB groundwater used for environmental and industrial purposes (Figure 2.6). Wopfner et al. (1970) describes the Algebuckina Sandstone as being composed of relatively high permeability Jurassic sand and conglomerate units deposited in fluvial and alluvial environments. Overlying the Algebuckina Sandstone, the Cadna-owie Formation is a thinner marine transgressional unit of inter-layered siltstone and sandstone deposited in the Cretaceous. Units of coarser sandstone contemporaneous with the Cadna-owie Formation are named in their own right within the wider GAB. In relation to their hydrogeological properties, the Algebuckina Sandstone and the Cadna-owie Formation are normally treated as a single unit (Radke et al., 2000; Welsh, 2000) and are referred to as the J aquifer (Habermehl, 1980; Seidel, 1980). These aquifer units are overlain by a grey marine shaly mudstone aquitard unit of low permeability that was deposited in a deep water marine environment called the Bulldog Shale (Freytag, 1966). The Bulldog Shale outcrops extensively within the general region of investigation, while outcrops of aquifer units are largely restricted to exposures in drainage channels and on the flanks of uplifted basement inliers (Figure 2.7).

Kellett et al. (1999) described typical bore yields from the J aquifer in South Australia of between 0.1 L/sec to 6.0 L/sec. Radke et al. (2000) reported that the salinities range between 550 mg/L in the Finke River region to > 3,500 mg/L along the southwest margin of the GAB. Audibert (1976) provided 61 porosity and storage coefficient estimates obtained from petroleum exploration wells calculated from sonic logs: A mean porosity of 0.21 and a mean storage co-efficient of 2.5 $x10^{-4}$ were determined. Further, a compilation by Berry and Armstrong (1995) of various hydraulic conductivity measurements for the Algebuckina Sandstone in the vicinity of Lake Eyre South ranged between 0.3 to 17.0 m/day, while transmissivities ranged between 5 and 380 $m^2$/day.

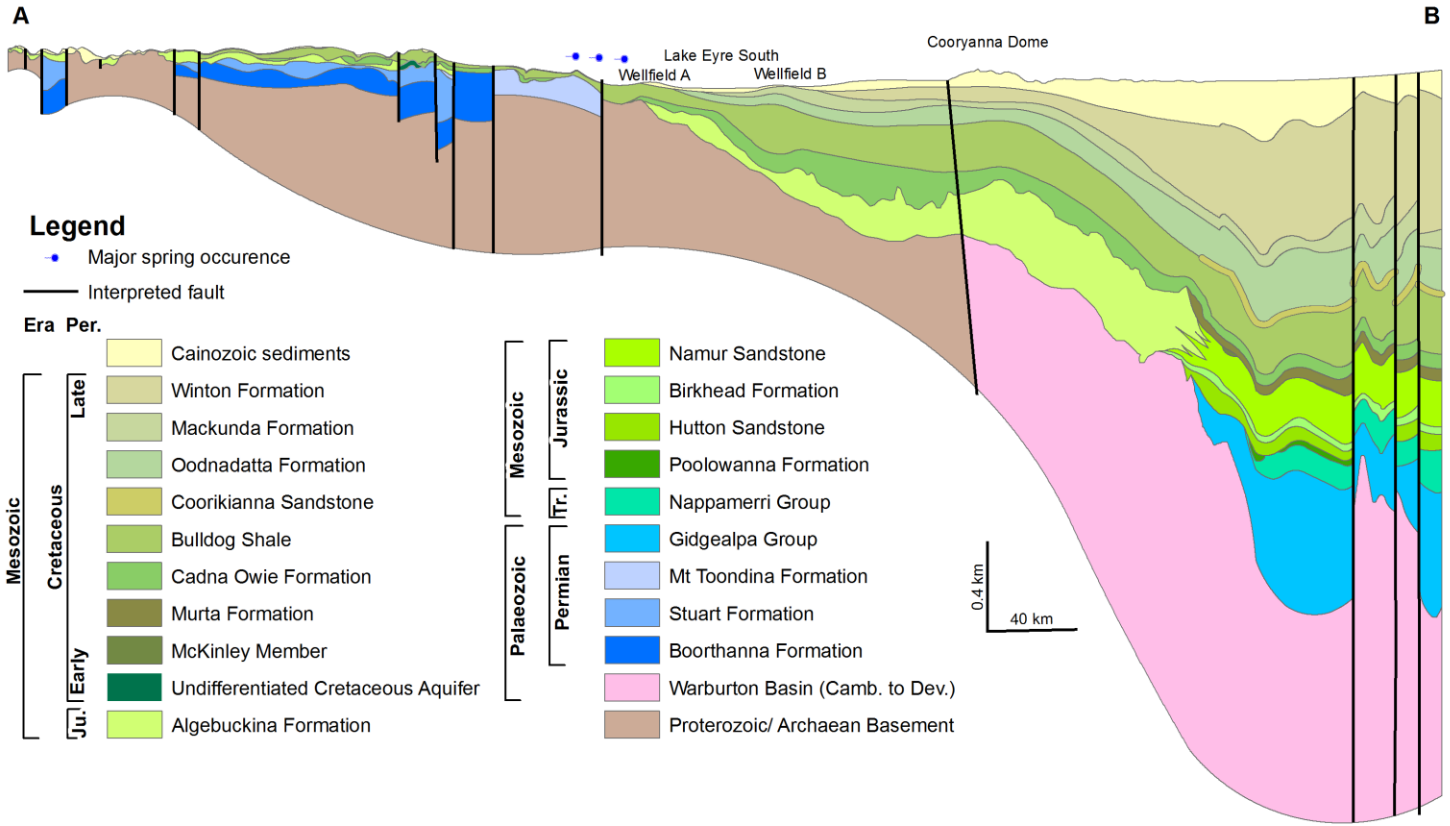


Figure 2.6: Cross section through Lake Eyre South region showing various aquifer and aquitard units of the GAB. Section based on drilling data, mapping and compiled seismic data provided by the South Australian Department for Water (DFW) and Primary Industries and Resources (PIR SA). Location of the cross section is shown on Figure 2.8. Tr.: Triassic, Ju.: Jurassic.

Table 2.1 Summary of hydrostratigraphy of the Western margin of the GAB: Cretaceous to Quaternary (From Keppel et al, 2012b after Drexel and Preiss, 1995; Radke et al., 2000; Shepherd, 1978).

| Period | Formation Name | Lithology Description | Depositional Environment | Av. Thick. and range | Hydrological Characteristics | Extent |
|---|---|---|---|---|---|---|
| Cainozoic | Eyre Fm, Etadunna Fm, Tirari Fm, Simpson Sand | Aeolian sands, gibber, terrestrial silts and clays | Terrestrial conditions ranging from freshwater lacustrine to aeolian (arid). Generally low relief. | - | A number of discrete unconfined and confined aquifers can be found through-out the Tertiary units. | Covers all areas except basin margins. Part of overlying Lake Eyre Basin |
| Cretaceous | Winton Fm | Non-marine shale, siltstone, sandstone, and minor coal seams. | Low energy, fluvial, lacustrine, and paludal | 500; 200-1200 | Confined lenticular aquifers, discharge in eroded anticlines | Outcrop on basin margins but much of it is covered by younger sediments |
| | Mackunda Fm | Partly calcareous, fine grained sandstone, siltstone and shale. Marks transition from marine to freshwater. | Sub-tidal marine and shore faces | 60; 30-250 | Confined minor aquifer, no known natural discharge | Outcrops along in northern Eromanga Basin. |
| | Oodnadatta Fm | Laminated, claystone and siltstone, with inter-beds of fine-grained sandstone and limestone. | Low energy, shallow marine | 150-300 | Oodnadatta Fm is a confining bed with minor aquifers | Oodnadatta Fm outcrops on southwest margin. |
| | Toolebuc Fm | Carbonaceous clayey mudstone and calcareous shale | Low energy, shallow marine | 15; 5-75 | Confining layer | Extends over most of the Eromanga Basin |
| | Coorikiana Sandstone | Predominately carbonaceous, clayey, fine grained sandstone and siltstone. | High energy, marine, shore face and gravel bars | <20 | Confined minor aquifer | Outcrops around Maree and Dalhousie anticline |

Table 2.1 Summary of hydrostratigraphy of the Western margin of the GAB: Cretaceous to Quaternary (From Keppel et al., 2012b after Drexel and Preiss, 1995; Radke et al., 2000; Shepherd, 1978) (cont.).

| Period | Formation Name | Lithology Description | Depositional Environment | Av. Thick. and range | Hydrological Characteristics | Extent |
|---|---|---|---|---|---|---|
| Cretaceous | Bulldog Shale | Grey marine shaly mudstone, micaceous silt and pyrite are also present, with very minor silty sands. Occasional lodestones | Low energy, marine, cool climate | 200-340 | Main confining bed for the Jurassic-Cretaceous aquifers | Large exposures in the southwest Eromanga |
| | Cadna-owie Fm | 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 | 15; 10-100 | Upper part is a good aquifer, high yields and good water quality. Many bores as first major GAB aquifer encountered in many areas | Extends over most of the Eromanga, with extensive outcrops in the southwest |
| | Murta Fm | Dark grey siltstone, shale and fine sandstone | Lacustrine and paralic | - | Confined minor aquifer | Central Eromanga |
| | McKinlay Fm | Sandstone and siltstone | Fluvial and lacustrine | - | Confined minor aquifer | Central Eromanga |

Table 2.1 Summary of hydrostratigraphy of the Western margin of the GAB: Cretaceous to Quaternary (From Keppel et al., 2012b after Drexel and Preiss, 1995; Radke et al., 2000; Shepherd, 1978) (cont.).

| Period | Formation Name | Lithology Description | Depositional Environment | Av. Thick. and range | Hydrological Characteristics | Extent |
|---|---|---|---|---|---|---|
| Jurassic | Namur / Hooray Sst | White to pale grey sandstone, minor inter-bedded siltstone and mudstone. Minor coal seams | Braided fluvial. | 150; 45-400 | Major GAB aquifer, high yielding bores. | Entirely subsurface. East of Birdsville Track Ridge. |
| | Westbourne Fm | Fine-grained sandstone with minor siltstone and claystone. | Lacustrine, fluvial and shallow marine. | 100; 60-200 | Confining layer with minor aquifers. | Entirely subsurface. |
| | Adori Sandstone | Fine to coarse grained sandstone, calcite cement. | Braided fluvial. | 50; 20-70 | Confined aquifer. | Entirely subsurface. East of Birdsville Track Ridge. |
| | Birkhead Fm | Siltstone and mudstone. | Shallow lacustrine and braided fluvial. | 100; 30-150 | Confining Bed, with some minor aquifer layers. | Poorly exposed. Generally lies between the Hutton and Adori/Hooray Sst and inter-tongues with Algebuckina Sst. |
| | Algebuckina Sandstone | Fine to coarse grained sandstone, with granule and pebble conglomerates. | Low gradient fluvial including rivers, floodplain. Both arid and wet climates. | 25; 20-800 | Major GAB aquifer, high yielding bores. | Major unit within Eromanga in South Australia. Large exposures in the southwest Eromanga, especially around Finniss Springs. |
| | Hutton Sandstone | Fine to coarse grained sandstone, with minor siltstone, shale and pebble conglomerates. | High energy braided fluvial. | - | Major GAB aquifer, high yielding bores of low TDS. | Confined to deep depths in central Eromanga Basin, integrates into Algebuckina Sandstone. |
| | Poolowanna Fm | White –pale grey sandstone, inter-bedded with dark grey and brown siltstone and shale. Minor coal seams. | Fluvial and floodplain. | 50-200 | Confining Bed. | Entirely subsurface around Cooper Basin and Poolowanna Trough. Lenses out west of Birdsville Track Ridge. |

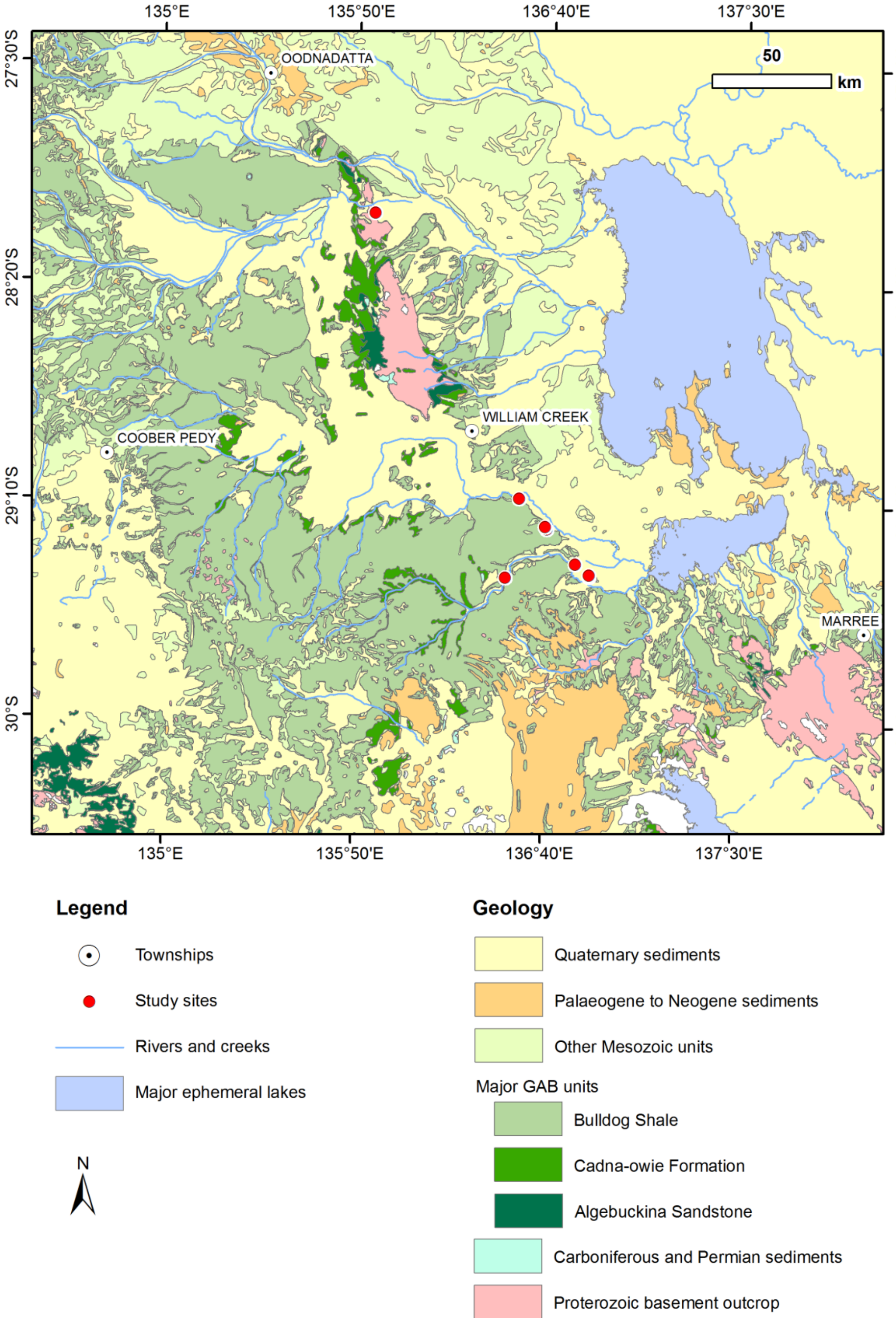


Figure 2.7: Outcrop geology of the regional study area. Geological data from Whitaker et al. (2008).

These hydraulic conductivity and transmissivities for the Lake Eyre South region are comparable to the wider GAB: Audibert (1976) describes a range of hydraulic conductivities for GAB aquifers in the range of 0.02 to 82 m/day with a mean of 3.7 and a median of 1.1 m/day, while Habermehl (1980) reports transmissivities in the range of 1 to 2,000 $m^2$/day, with a predominance of recorded values in the range of 10 to 20 $m^2$/day in the eastern and south-central regions of the GAB and higher values up to the 100's $m^2$/day within the northern and southern parts of the basin. Habermehl (1980) suggested that aquifer permeability across the basin varied between 1 and several 10's m/year.

Jack (1923) was the first researcher to note that groundwater within the main GAB aquifer has two potential sources; a highly alkaline groundwater migrating from the Great Dividing Range (Figure 2.5) and a sulfate-rich groundwater originating from the western margin of the GAB, located in South Australia and the Northern Territory, while Habermehl (1980) noted that a major zone of natural groundwater discharge via springs to the south and west of Lake Eyre South coincides with a groundwater mixing zone within the GAB. More recently, Herczeg and Love (2007) and Radke et al. (2000) published potentiometric surfaces of the study area which described groundwater flow; flow west of Lake Eyre is predominantly from the north and west to the southeast, while in regions to the east and inclusive of Lake Eyre, flow is predominantly from the north and east to the southwest (Figure 2.8). A recent influence on the potentiometric surface within the general region of this study is the Well field A and B areas in the vicinity of Lake Eyre South; these are associated with the Olympic Dam mining operation. Groundwater extraction from these well fields has resulted in a lowering of groundwater head in the vicinity of these areas (Figure

2.8), which lead to the cessation of flow from Priscilla and Venables springs (Mudd, 2000).

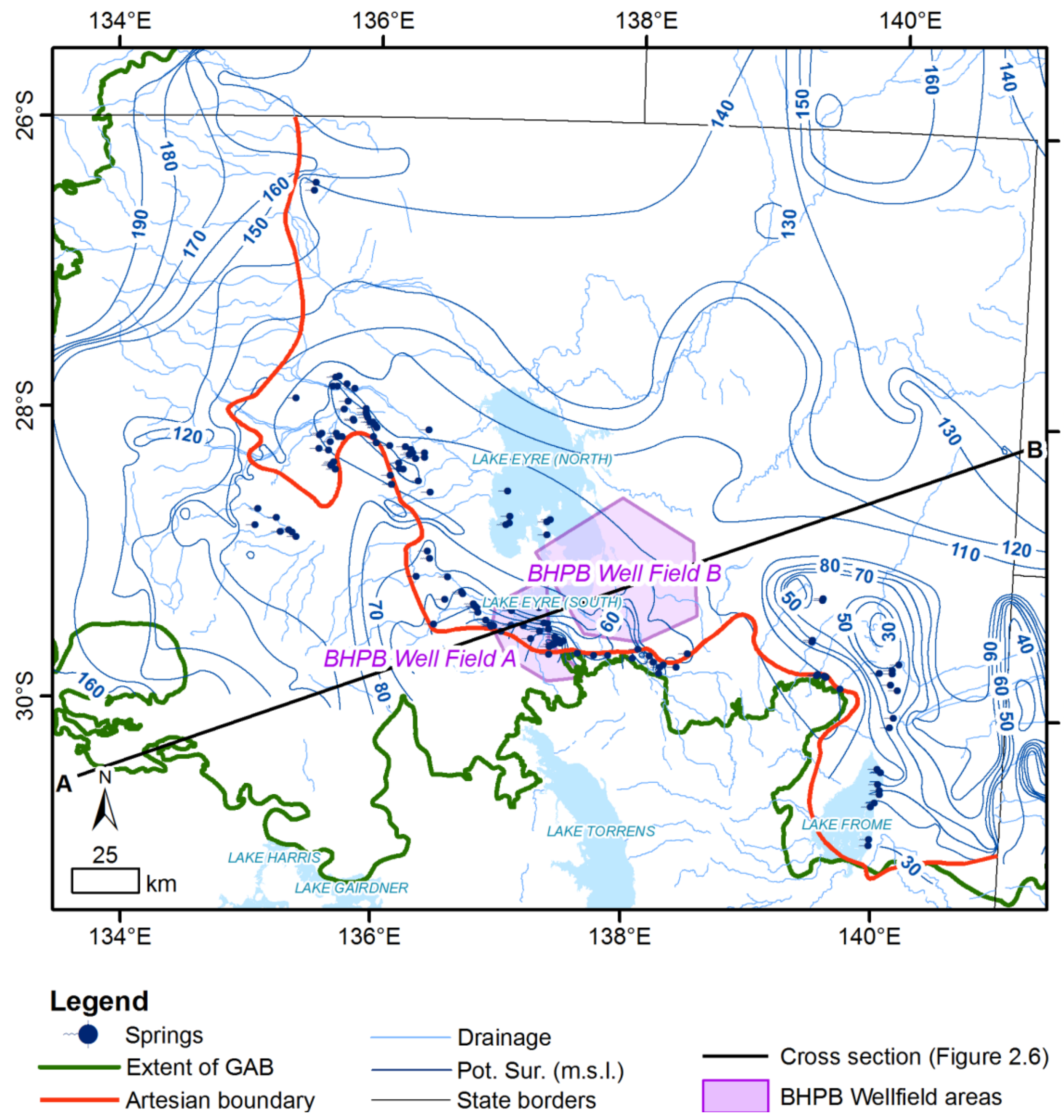


Figure 2.8: Potentiometric surface (Pot. Sur.) msl contours for GAB aquifer interpreted from data provided by DFW.

Airey et al. (1979) noted that all groundwater within the GAB aquifer systems was meteoric based upon the $\delta^{18}O$ concentrations. In relation to “groundwater age”, Torgersen (1994) estimated residence times of between 900,000 years and 1.5 million years using $^{36}Cl$ data for groundwater flowing from the recharge areas on the eastern seaboard of Australia, while Lehmann et al. (2003) estimated residence times of between 230,000 and 400,000 years using $^{36}Kr$ data for groundwater flowing from the western recharge areas of southern Northern Territory and central South Australia. Finally, Love et al. (2000) estimate groundwater velocities from the western recharge areas of approximately 0.24 +/- 0.03 m/yr.

GAB groundwater discharge primarily occurs via springs, bores, diffuse discharge (the discharge of groundwater by molecular movement from zones of high head to zones of low head) or discharge into the Gulf of Carpentaria. While spring discharge and bores are discrete forms of point discharge, diffuse discharge may occur over a large region via vertical leakage into shallow aquifers or via evaporation from a shallow depth (SAAL NRMB, 2006). Armstrong (2005) estimated spring discharge from the South Australian component of the GAB to be approximately 24 GL/year, bore discharge to be approximately 47 GL/year and diffuse discharge via vertical leakage to be approximately 100 GL/year. Microlysimeter and soil water chloride and isotope profiles were used by Costelloe et al. (2006) in the vicinity of observable diffuse discharge in the Neales River catchment on the western side of the Peake and Denison Inlier to estimate a diffuse discharge of 47-192 mm/year.

Costelloe et al. (2005) interprets that groundwater leakage from the GAB into the surface and near-surface environment results in soil salination; this salt may then be transported during infrequent runoff events downstream. Additionally, salt stored in riverbank and floodplain sediments is remobilised during flood recession events, where the contribution to base flow from groundwater within these sediments proportionately increases as surface runoff wanes. Such a cycle partially contributes to the development of saline and hypersaline waterholes in the lower reaches of ephemeral rivers in the Lake Eyre Basin (Costelloe et al., 2005).

## 2.4 Relationship between tectonics and spring formation in the southwestern GAB

A number of recent studies have postulated that central Australia is subject to significant intraplate neotectonic deformation caused by far field plate tectonic stresses (e.g. Sandiford, 2007; Sandiford and Quigley, 2009). This tectonism is well documented by uplifted Precambrian-cored fault blocks and compressional deformation and denudation in the Flinders Ranges of South Australia (Quigley et al., 2007). This is also expressed as a concentration of seismicity and micro-seismicity in this region (Braun et al., 2009; Holford et al., 2011; Leonard, 2008) that includes areas to the north of the Flinders Ranges (Leonard, 2008). Regions to the north of the Flinders Ranges also coincide with many occurrences of GAB springs and their associated calcareous spring mound structures. This section provides a summary concerning the relationship between spring development, seismicity and resultant fault structures and places this in the context of the southwestern GAB.

### *2.4.1 General relationship between springs and seismicity*

In numerous places internationally, seismicity and related faulting has been previously recognised as an important control on the distribution of springs. Curewitz and Karson (1997), Hancock et al. (1999), Muir-Wood (1993), Muir-Wood and King (1993) and Rowland et al. (2008) identified that faults and fractures that intersect artesian groundwater can form spring conduits. Babiker and Gudmundsson (2004) and Barton et al. (1995) suggested that the most likely faults and shear zones to conduct groundwater are those that have most recently been active and Gudmundsson (2000) found that permeability increases substantially once a fault becomes active, leading to changes in the potentiometric surface, yield from fault-connected springs and base flow in affected streams. Babiker and Gudmundsson (2004), Manga and Wang (2007), Muir-Wood and King (1993) and Rojstaczer et al. (1995) established that activity in a fault achieves this maintenance of higher permeability though the creation of new fractures, as well as reopening old fractures within the fault zone. Curewitz and Karson (1997), Davidson et al. (2011) and Leckenby et al. (2005) identified that higher permeability zones tend to be related to extensional strain domains within a given fault architecture and these are most conducive to the development of springs. Where the propagation of fractures related to spring development occurs in fresh rock, such as the breaking “tip” of a fault line or the “breakdown” region between two or more faults in close proximity, this has been described by Curewitz and Karson (1997) as “dynamically-maintained fracture systems”. Conversely, other areas along the trace of pre-existing faults where spring flow is maintained via ongoing failure in response to remote stresses are described by Curewitz and Karson (1997) as “kinematically maintained fracture systems”. The development of springs in the Lake Eyre South region with respect to fracture nomenclature proposed by Curewitz and Karson (1997) is discussed further in Appendix 1.

Calcareous spring deposits often provide evidence for not only the initial formation of faults and fractures, but also evidence of their reactivation. Hancock et al. (1999) established that spring formation associated with faults is dependent upon the permeability of the fault in relation to the confining layer above the aquifer and emphasising that extensional jogs along trans-current fault systems were common locations for calcareous spring deposit accumulation. Curewitz and Karson (1997), Hancock et al. (1999) and Muir-Wood (1993) further stipulated that ongoing fault-deformation is required to maintain spring flow by "re-breaking" faults and fractures acting as conduits. Hancock et al. (1999) interpreted the occurrence of calcareous spring deposits in conjunction with active springs as evidence for active tectonics, as the precipitation of $CaCO_3$ was considered a common cause of conduit permeability reduction. Consequently, springs and their associated carbonate deposits have been used internationally as a means of studying the tectonics and structural architecture of the regions in which they occur (e.g. Altunel and Hancock, 1993; Andreo et al., 1999; Brogi, 2004; Brogi and Capezzuoli, 2009; Crossey et al., 2006; Crossey et al., 2009; Curewitz and Karson, 1997; Minissale, 1991). Further, there is an established link between seismicity with changes in spring discharge and hydrochemistry to the extent that studies have been conducted that attempt to use springwater monitoring to predict earthquake activity (e.g. Chia et al., 2008; Manga and Rowland, 2009; Mogi et al., 1989; Song et al., 2006; Yechieli and Bein, 2002).

### *2.4.2 Relationship between GAB springs and regional fault structures*

A spatial relationship between GAB springs and major fault structures within the Australian continent has been recognised in a number of previous studies. Such regional structures include aeromagnetic trends interpreted to be a northern extension of the Torrens Hinge Zone and the reverse faults the Norwest and Kingston Faults that dip northeast and southwest under the Flinders Range and Dennison basement uplifts respectively (Krieg et al., 1991).

Kinhill Stearns (1984), Krieg et al., (1985), Krieg et al. (1991) and Sprigg (1957) noted that the springs in the region are located in the vicinity of the marginal faults and highs in the underlying basement, implying an association between spring formation and these basement-related structures. Krieg et al. (1991) suggested that the presence of active, fault-aligned mound springs along with modern seismicity and the low elevation of Lake Eyre were all evidence for intermittently active Holocene tectonism within the Lake Eyre region, while Krieg et al. (1991) and Wopfner and Twidale (1967) used the location of mound springs and the foci of recent earth tremors as evidence for contemporary tectonic movement along the major northwest-southeast faults as responsible for the formation of Lake Eyre itself (Figure 2.9). Waclawik et al. (2008) noted the occurrence of a spring in the vicinity of a neotectonic fault in the Neales River catchment area to the west of Lake Eyre. Habermehl (1982) and Wopfner and Twidale (1967) also suggested that uplift along the western margin of the Lake Eyre Basin within the region of spring activity may have contributed to the extinction of older springs now located in higher landscape positions in the region. The most extensive discussion concerning the relationship between fault architecture and mound springs of the southwestern GAB was provided by Aldam and Kuang (1988) who interpreted seismic profiles collected over a number of spring group systems. In all instances faults were postulated to exist beneath the spring zones and in the majority of instances fault networks were found.

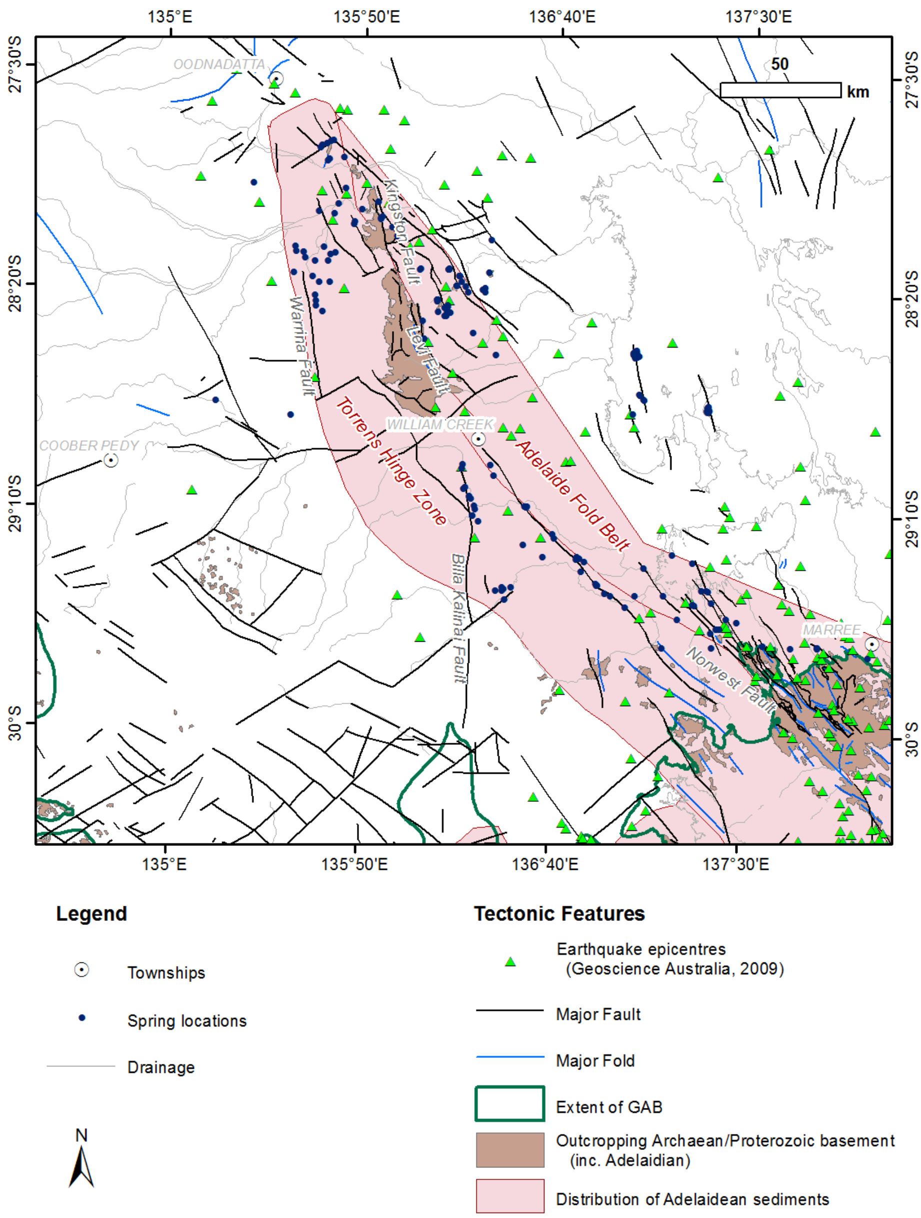


Figure 2.9: Fault network in basement rocks in the vicinity the GAB spring, earthquake epicentres (Geoscience Australia, 2009), outcropping Proterozoic basement and interpreted extent of Proterozoic units. Note mound springs are aligned along northwest-southeast faults (e.g. Torrens Hinge and Norwest fault) related to the normal faults that bound the Neoproterozoic Adelaidean Fold Belt (Preiss, 1987). Faults compiled from the following references and 1:250,000 maps sheets: (Ambrose et al., 1980; Benbow et al., 1985; Callen et al., 1992; Cowley and Martin, 1991; Daly et al., 1985; Drexel and Preiss, 1995; Drexel et al., 1993; Forbes et al., 1965; Freytag et al., 1967; Johns et al., 1966; Pitt and Barnes, 1976; Rogers et al., 1996; Williams, 1973; Williams and Krieg, 1975).

Additionally, Watterson et al. (2000) interpreted polygonal fault structure development transecting a number of GAB aquifer and aquitard units. Polygonal fault systems consist of normal faults with moderate throws that have a crudely polygonal orientation (Cartwright 2003). Fault throws maxima were interpreted at or above the Bulldog Shale. The underlying Cadna-owie Formation was interpreted to contain the most spatially ordered pattern of fault traces with distinct polygonal cellular pattern and the larger faults were observed forming conjugate pairs at or below this unit.

*2.4.3 Tectonic setting of the southwestern GAB*

Based on borehole stress measurements collected from less than 1 km depth, Hillis et al. (1998) and Hillis and Reynolds (2000) interpreted the principal maximum horizontal compressive stress ($\sigma_H$) as orientated east-west and generally larger than the principal vertical stress $\sigma_V$ in the Cooper-Eromanga Basins and southern Australia respectively. Similarly, Reynolds et al. (2005) determined that the orientation for $\sigma_H$ was approximately 101° from borehole breakouts and drillhole-induced tensile fractures at depths of between 700 and 3,300 m obtained from 61 wells across the Cooper Basin region (Figure 2.10). This orientation was found to be largely consistent across the area of study. Although the average orientation of $\sigma_H$ data in central Australia is perpendicular to the absolute plate velocity of the Indo-Australia Plate, numerical modelling by Burbidge (2004), Cloetingh and Wortel (1986), Coblentz et al., (1995), Coblentz et al. (1998) and Reynolds et al. (2002) suggest $\sigma_H$ orientations like those in central Australia can be explained by considering the complexity of the Indo-Australia Plate's northeastern boundary.

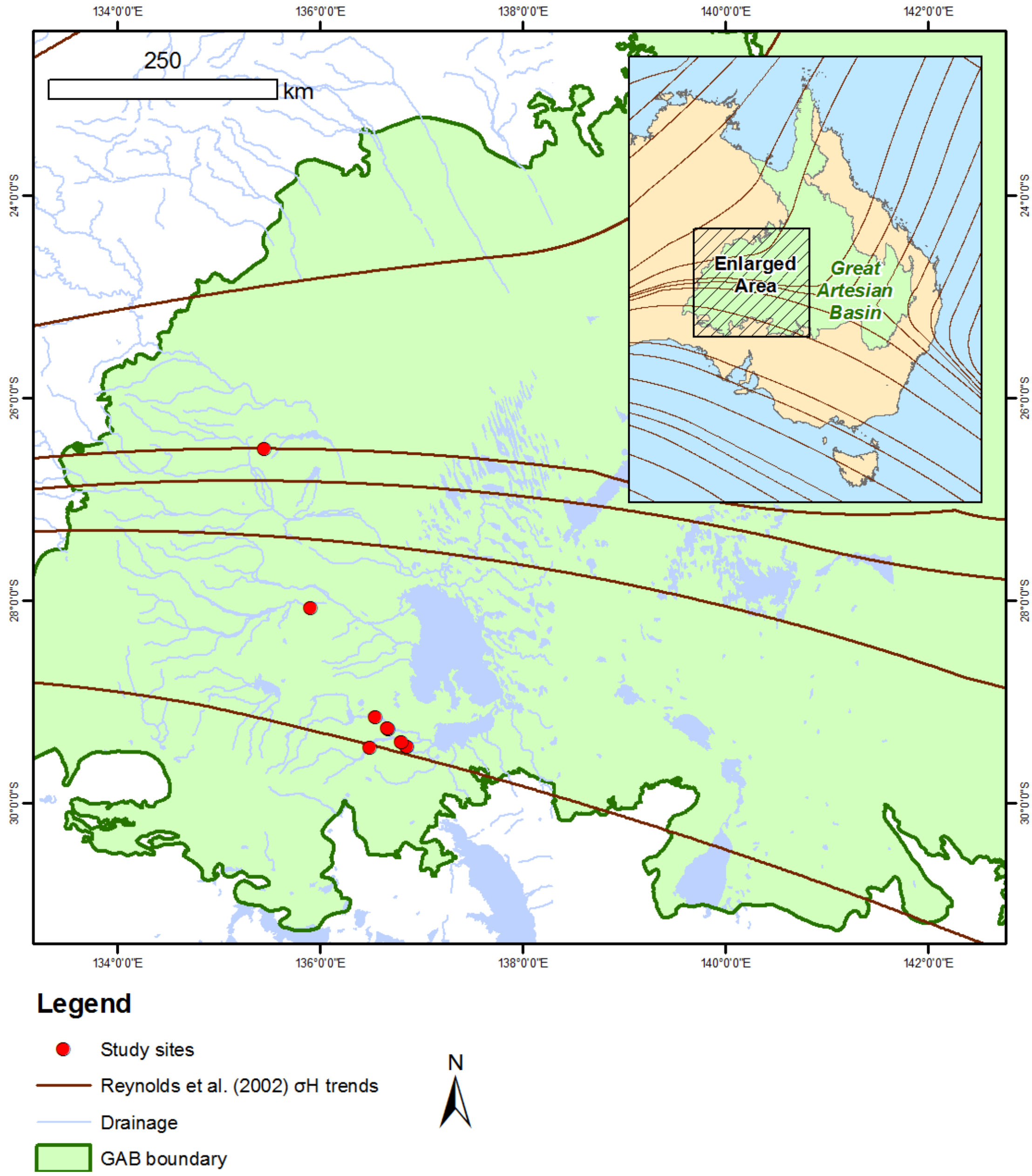


Figure 2.10: Modelled stress trajectory trends for maximum horizontal stress (σH), obtained from Reynolds et al. (2002). Note the interpreted east-west trajectory in the vicinity of the study sites.

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In relation to the magnitude of stress regimes, Hillis et al. (1998) and Hillis and Reynolds (2000) observed that $\sigma_H$ and $\sigma_V$ are often similar in magnitude, while Hillis et al. (1998) also noted that the minimum horizontal stress regime ($\sigma_h$) in the Cooper-Eromanga Basins region is approximately 60-70% that of $\sigma_V$, resulting in a stress regime largely associated with strike-slip movement. In contrast and using a database covering approximately 40 years of petroleum exploration, Reynolds et al. (2006) determined that $\sigma_H$ is significantly greater in magnitude than both $\sigma_h$ and $\sigma_V$ in a number of wells where the magnitude of $\sigma_H$ could be tightly constrained. Additionally, the stress magnitudes established indicated a predominantly strike-slip fault stress regime ($\sigma_H > \sigma_V > \sigma_h$). Most recently, Klee et al. (2011) used stress data derived from borehole breakouts and core-discing from core obtained from a granite approximately 120 km south of Lake Eyre South at the edge of the GAB suggesting that at depths between 800 and 1,740m, $\sigma_H$ was predominately east-west and that $\sigma_H > \sigma_h > \sigma_V$.

Historical seismic records highlight the Flinders Ranges and Adelaide Fold Belt as an area of high seismic activity when compared to other basement provinces (Quigley et al., 2006; Quigley et al., 2007) (Figure 2.9 and 2.11). Leonard (2008) defines an area inclusive of the Adelaide Fold Belt and regions in the vicinity of springs to the west of Lake Eyre as one of five regions of notably enhanced seismicity in the Australian continent (Figure 2.11). Celerier et al. (2005) describes the part of the Adelaide Fold Belt that occupies the Flinders Ranges to the south of the GAB as one of the most seismically active zones in Australia, with a seismogenic (i.e. capable of generating earthquakes) strain rate of $1.7 \times 10^{-16}$/sec; approximately one order of magnitude greater than that for the rest of the continent. Expression of these far field stresses as an intraplate seismic zone is often attributed to release of stress along weak zones such as pre-existing faults, zone of lithospheric heterogeneity and lithospheric buckling (Louden, 1995; Sandiford and Quigley, 2009).

Sandiford et al. (2009) interpreted current intraplate tectonic activity in Australia to be a consequence of the continent's rapid northward drift that began approximately 43 million years ago. This has also resulted in a tilting, north-down, southwest-up upon collision with the Indonesian Archipelago. Evidence for intraplate deformation pertinent to this study has been highlighted in previous studies and includes reported uplift, doming and development of en echelon folding of Mesozoic sediments along the margins of the Lake Eyre Basin and subsequent incision and erosion of overlying Tertiary sediments (Wopfner and Twidale, 1967) as well as uplift and tilting of GAB sediments along the eastern margin (Ollier, 1995; Toupin et al., 1997). More recently, Sandiford and Quigley (2009) reported intermediate (100-1,000 km) wavelength, 100-200 m landscape "undulations" in the Lake Eyre Basin. Sandiford and Quigley (2009) and Sandiford et al. (2009) suggest that the lake system is progressively migrating southward based on the ~13 m southward tilt of the modern playa floor. Karlstrom et al. (2012) also summarises evidence for mantle $^{3}He$ degassing, associated high $CO_2$ flux, and large mantle velocity gradients in this zone as indicators that the region is neotectonically active.

Despite the recognised correlation between the regional structural architecture and springs, there has been little work determining what impact seismicity may have on mound spring morphologies found in the southwestern GAB or whether the springs and associated sediments in this region can be used to study intraplate deformation. Appendix 1 details evidence of kinematic deformation of spring-related sediments found during this study, suggesting that such sediments can be potentially used for these purposes. This is believed to be the first time such evidence from mound spring-related deposits has presented with respect to a discussion concerning intraplate deformation in central Australia.

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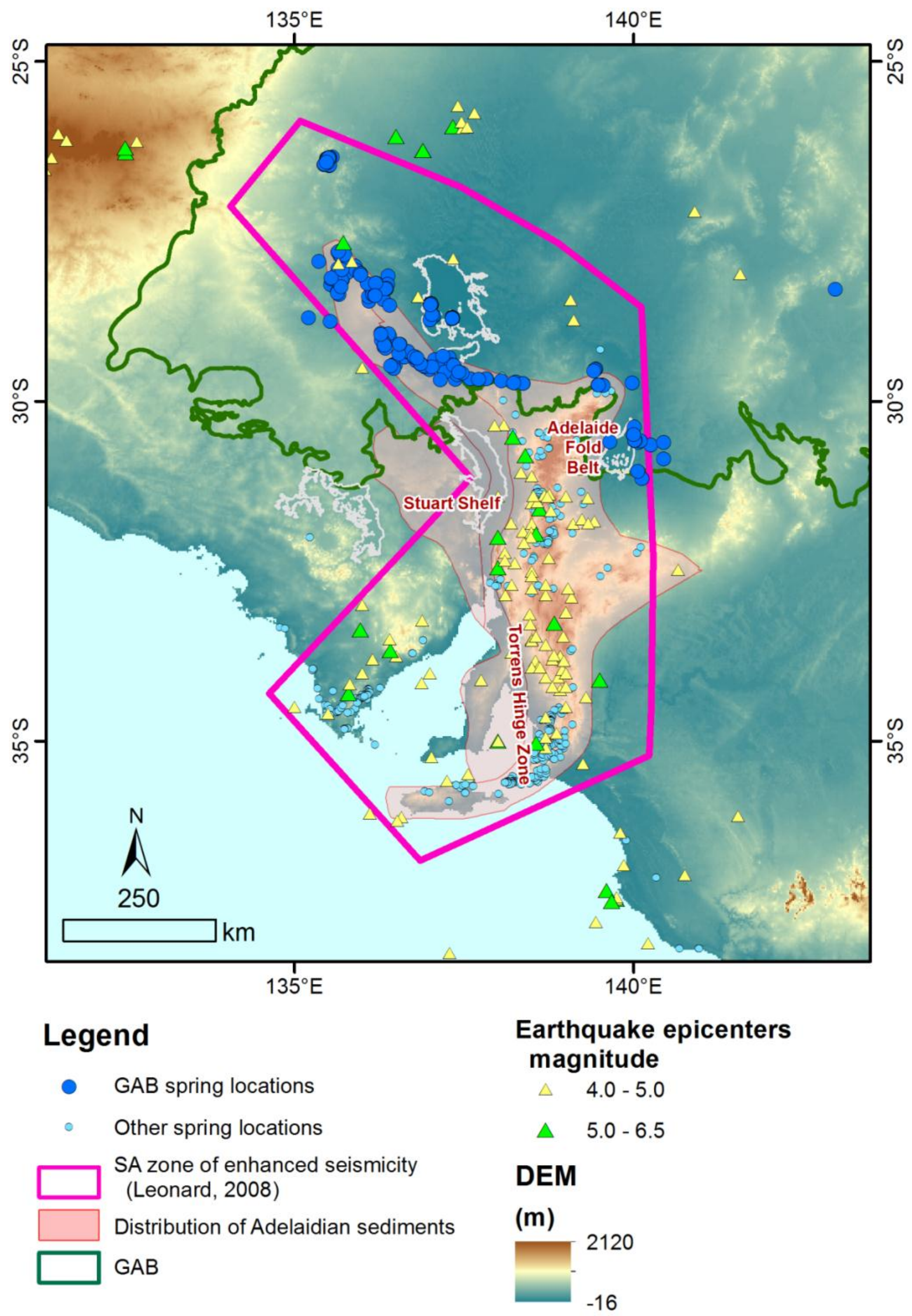


Figure 2.11: Location map of earthquake epicentres (Geoscience Australia, 2009), the South Australian zone of enhanced seismicity (Leonard, 2008), the extent of Adelaidean basinal sediments (Preiss, 1987) and GAB and other springs in South Australia, set on a DEM of the region (Geoscience Australia, 2008).