APPENDIX 1: EVIDENCE FOR INTRAPLATE SEISMICITY FROM CALCAREOUS MOUND SPRING DEPOSITS, LAKE EYRE REGION, SOUTH AUSTRALIA

This Appendix is partly based on the following peer-reviewed reports:

Keppel, M., Halihan, T., Love, A., Post, V., Werner, A., and Clarke J., 2013a. Chapter 3: Formation and Evolution of Mound Springs. In Love, A.J, Shand, P., Crossey, L., Harrington G.A. and Rousseau-Gueutin, P. (Editors) Groundwater Discharge in the Western Great Artesian Basin. National Water Commission, Canberra.

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

A1.1 Introduction

As detailed in Chapter 2, calcareous spring deposits are known to have a variety of neotectonic connections, such as formation along faults that act as fluid conduits, formation in transpressive fault step-overs, and as a record of intraplate mantle degassing (Altunel and Hancock, 1993; Brogi and Capezzuoli, 2009; Crossey et al., 2009; Hancock et al., 1999). Many calcareous spring deposits in South Australia are associated with mound springs, which provide important natural discharge locations for the continental scale GAB (Chapter 3; Habermehl, 1980; Habermehl, 1982).

This Appendix presents evidence for the deformation of calcareous spring deposits around active spring systems in the GAB with respect to the previously recognised correlation of springs with regional structures and seismic zones. This evidence increases our understanding of the tectonic influences on mound springs development. If the calcareous springs can be shown to contain a record of modern seismic activity within the central regions of the Australian continent, it will affect our understanding of both styles of intraplate neotectonics deformation and its potential interactions with hydrogeology of the GAB.

A1.2 Study Sites

Two sites were chosen for this study: Warburton Spring located at the Beresford Hill Spring Complex and Freeling Springs (Figure A1.1).

The Beresford Hill Spring complex is located approximately 40 km to the west of Lake Eyre South along the Oodnadatta Track. The Beresford Hill Spring complex is one of a number that occur at approximately 15 km intervals along a regional northwest-southeast lineament, which is observed in regional aeromagnetic data and interpreted to be a northern extension of the Torrens Hinge Zone (Krieg et al., 1991). Warburton Spring is the largest active group of springs at the Beresford Hill spring complex. Freeling Springs is approximately 100 km to the west of Lake Eyre North and approximately 73 km to the southeast of the township of Oodnadatta (Figure A1.1).

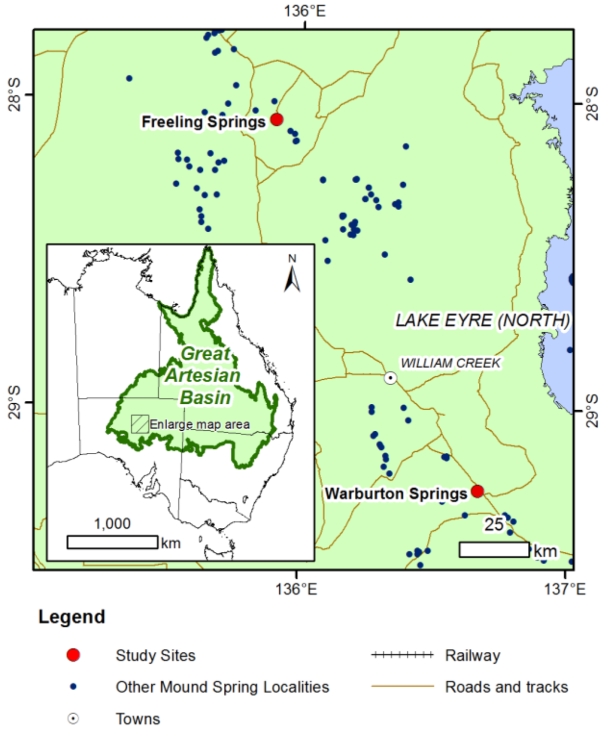

Figure A1.1: Location of study sites.

A1.3 Methodology

Two structural data sets were assessed at Warburton Spring/ Beresford Hill Spring complex. The first data set consists of 460 lineament measurements from the greater Warburton Spring area (Figure A1.4A) that were interpreted from ortho-corrected, 1:10,000 scale, stereoscopic pairs of aerial photographs (e.g. Figure A1.3A); obtained from DEH. The second data set involved 57 field measurements of calcite–filled veins on the outflow platform for Warburton Spring (Figure A1.4B). At Freeling Springs, one structural data set consisting of 797 lineament measurements, also inferred from 1:10,000 scale aerial photographs was used. Field-mapping at both sites was compiled and drafted using the GIS package “ArcMap™”. Rose diagrams of vein and lineament strikes obtained from fieldwork and aerial photography were plotted using the program “OpenStereo” (Grohmann and Campanha, 2010). All measurement data can be found in Appendix 2.

A1.4 Results

A1.4.1 Warburton/ Beresford Hill study site

The Warburton Spring/ Beresford Hill study site is located in the vicinity of the interpreted extension of the Norwest fault between the Willoran Ranges and the Peake and Dennison Inlier. This area has been extensively dated (Prescott and Habermehl, 2008; Priestley et al., 2012.), has both active and inactive spring mound complexes and is therefore an excellent site to examine neotectonic influence in mound spring formations. The Beresford Hill Spring complex has two active spring sites at Beresford Spring and Warburton Spring and two mesas formed from relict carbonate capping 25 m high pedestals of Bulldog Shale (Figure A1.2 and A1.3). The relict and active springs have a northwest-southeast strike that is concordant with the underlying interpreted regional structure. The springs occur in a roughly diamond-shaped basin, approximately 2.75 km in strike and 1.9 km wide, in which a number of ephemeral streams terminate.

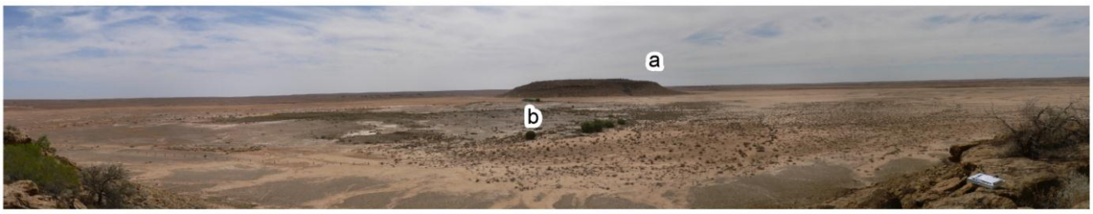

Figure A1.2: View of the Beresford Hill Spring complex from Warburton Hill. The Mesa Beresford Hill (a) is visible in the background, with the modern Warburton Springs (b) located in the foreground.

Aerial photography (Figure A1.3A) shows the main elements of this complex and their ages obtained from Priestley et al. (2012). From southeast to northwest a) Warburton Hill, an extinct mound complex that was active between 100,000 years and ≥1 million years (Sample 6); b) the currently active Warburton Spring (38,000-30,000 years), which is also the focus of detailed fracture measurements (Samples 4 and 5); c) Beresford Hill, a second extinct mound complex that was active between 104,000 years and ≥1 million years (Samples 1 and 2); d) Beresford Spring and its active carbonate-depositing spring (undated); 5) Another calcareous spring deposit is located to the southwest, off the main line of springs and is dated at approximately 100, 000 years (Sample 3).

The geometry and dating of these deposits indicates that discharge of springwaters occurred for 1 million years or more at the two extinct vent sites. Then, after approximately 100,000 years, spring discharge shifted approximately 500 m northwest along the main fault zone (Figure A1.3B).

The most prominent trend consists of northwest-southeast fractures and ridges (Figure 1.4 and Figure A1.5A). On the carbonate platform of Warburton Spring, these are characterised by centimetre to decimetre-high upturned ridges with central fractures and sparry calcite veins. Occurrences of these features extend for approximately 200 m and consist of numerous linked fracture segments (Figure A1.5C). The fractures are parallel with the major regional structure in the vicinity. In two localities in particular, the lineament was associated with the development of a break-away developed in spring-related carbonates and the precipitation of sparry laminated limestone (Figure A1.5A).

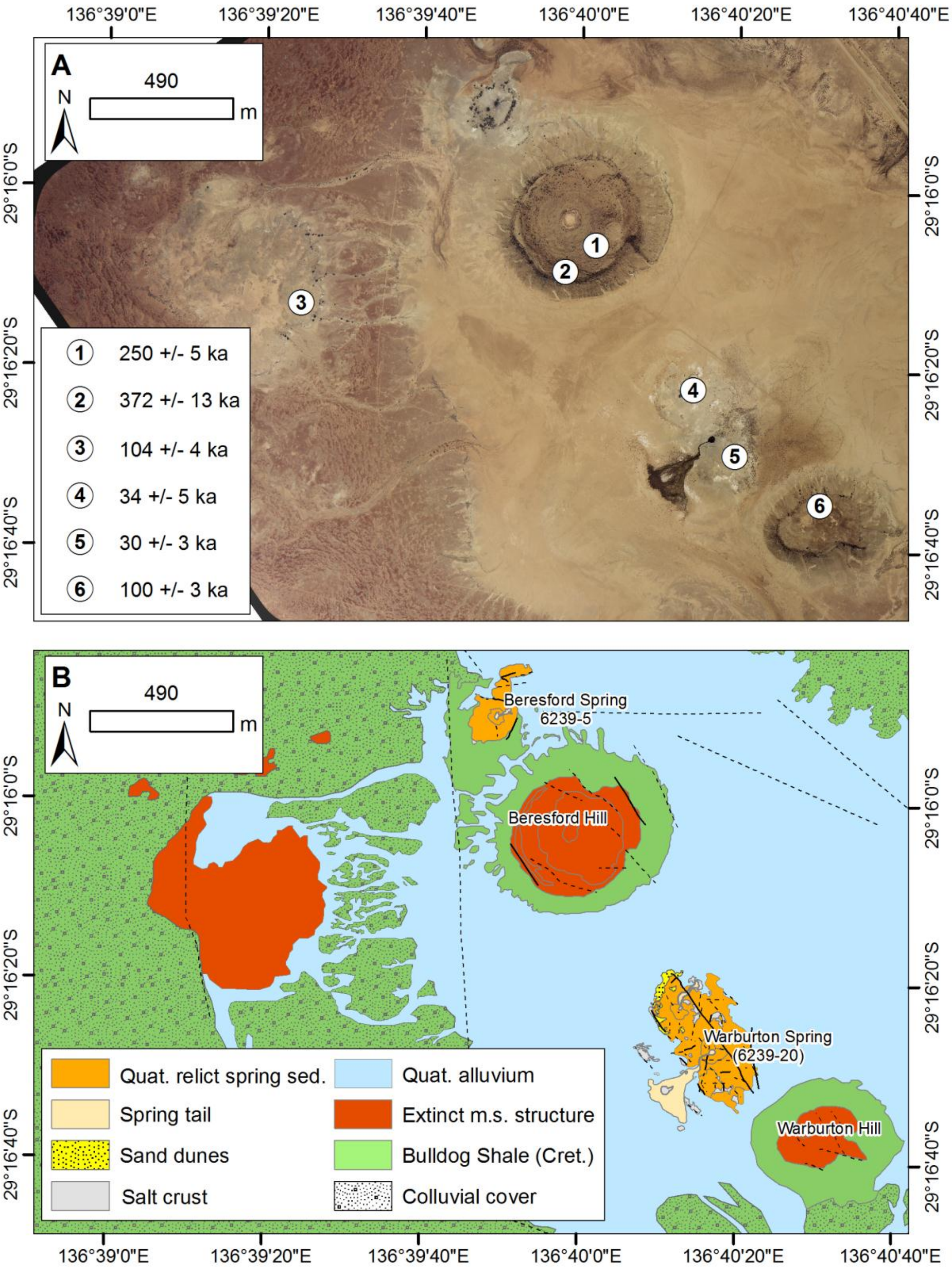

Figure A1.3: Aerial photograph and surface geological interpretation of the Beresford Hill Spring system. (A) Aerial photograph of the Beresford Hill Spring system with locations of age samples from Priestley et al., (2012) Results listed in table in bottom left hand corner. (B) Geologic map of the Beresford Hill Spring system. Note the alignment of modern and extinct springs along a northwest strike. Modern springs are approximately 500 m along strike from extinct spring structures.

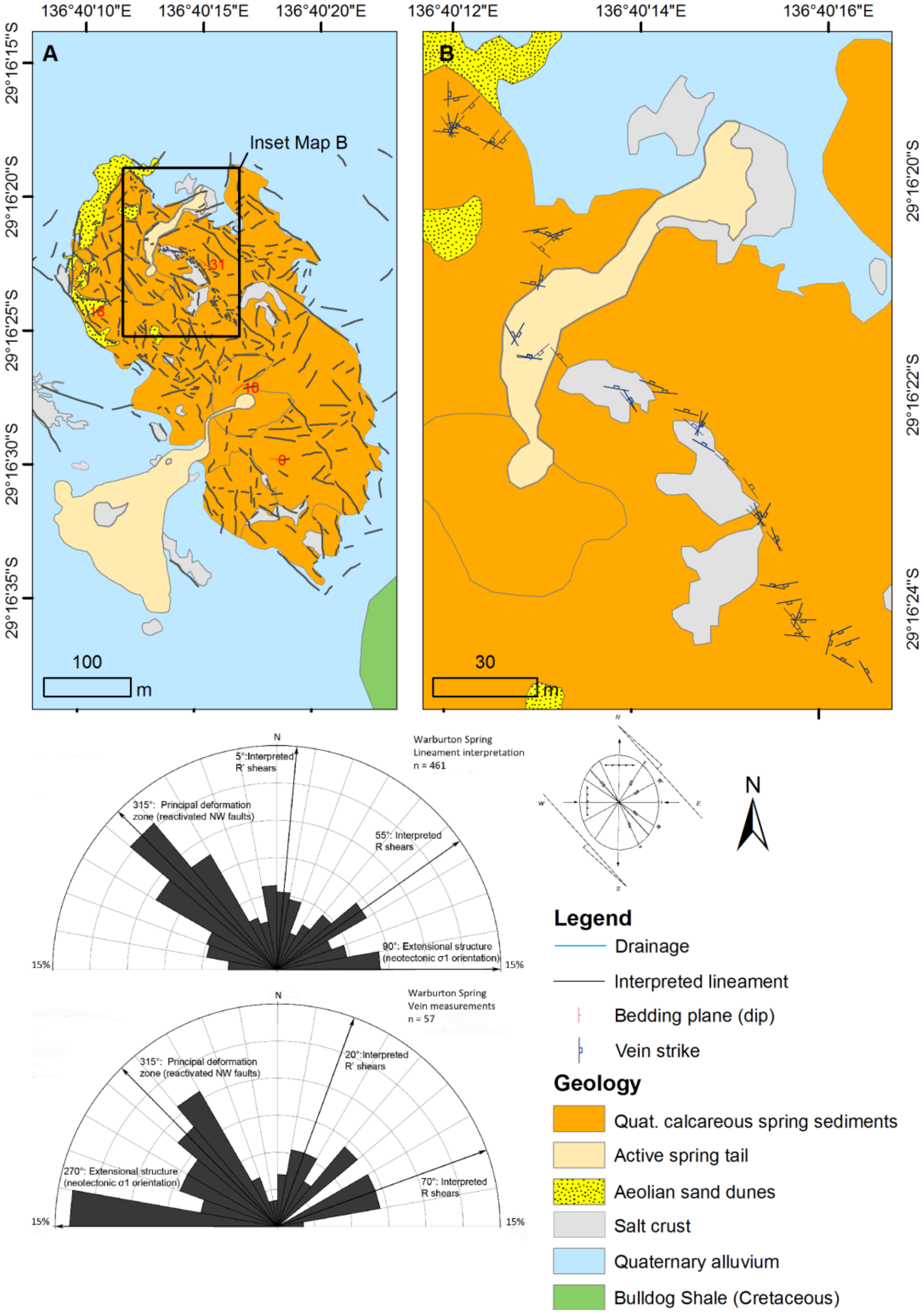

Figure A1.4: Interpreted lineaments and vein orientations derived from the Warburton Spring complex. A) Interpreted lineaments derived from aerial photographs and B) vein orientations from field mapping in area of inset map. Rose diagrams at base of map highlight orientation groupings of lineaments and veins.

Additionally, calcareous spring deposits within a former tail environment have been tilted, with dips of up to 30° towards the centre of the spring complex, suggesting slumping caused by depression near the centre of the complex (Figure A1.5B).

A notable orientation for veins and lineaments was east-west, although it was more common in veins than lineaments interpreted from aerial photographs. This orientation is interpreted to be related to extension fractures that formed parallel to east-to west σ_H far field stress described in Chapter 2 (Figure A1.4B). This veining takes the form of either sparry laminated, steeply dipping carbonate fracture fill veins up to 10cm thick (Figure A1.5C) or stringer veinlets of sparry calcite with manganese and iron oxide staining (Figure A1.5D).

Two other prominent orientations are southeast (125°) and northeast (075°), which are about 60° apart. These are interpreted to be Riedel shears related to the regional-scale northwest-southeast sinistral transpressive shear (Riedel, 1929) (Figure A1.4). Northwest-southeast and north-south orientations for faulting have also been observed by Krieg et al. (1991) in small outcropping inliers of Adelaidean Wilpena Group sediments further to the southeast.

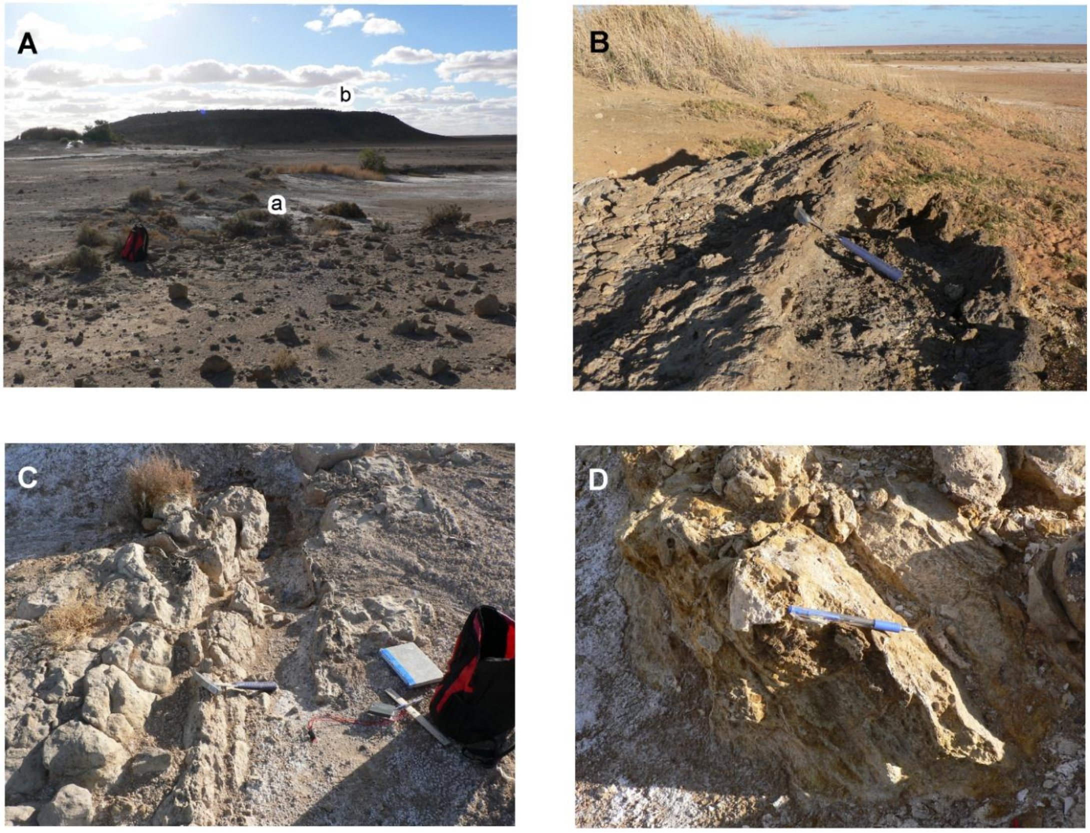

Figure A1.5: Field examples of structural deformation in calcareous spring deposits near Warburton Spring. A) Breakaway development, with orientation of break-away concordant with underlying northwest-southeast regional fault structure. B) Tilted beds of spring-carbonate. The dip of these beds is 30° towards the centre of the spring-carbonate platform. C) Outcrop of sparry fracture fill material with steep (66°) dip and an east-west strike D) Tilted beds of calcareous spring deposits with stringer veinlets of spar and iron oxide impregnation.

A1.4.2 Freeling Springs

Freeling Springs is approximately 100 km to the west of Lake Eyre North and on the eastern edge of the Peake Inlier within the Davenport Ranges (Figure A1.1). The area has a number of small carbonate-depositing springs and associated precipitate deposits occurring over a 1.9 km, north to south strike length. The largest spring and the primary vent for the outflow platform are located near the southern end of the complex (Figure A1.6 and A1.7). Spring vent localities are marked by a number of circular vegetated seeps and spring-related carbonate accumulations that form a series of barrage dams and terraces. Within the general area of interest, Rogers and Freeman (1994) interpret the occurrence of steeply dipping Cretaceous units adjacent to the Levi fault, located approximately 30 km to the south-southeast of Freeling Springs, and dipping Cainozoic units to the east of the Peake and Denison Inlier, as evidence for vertical displacement.

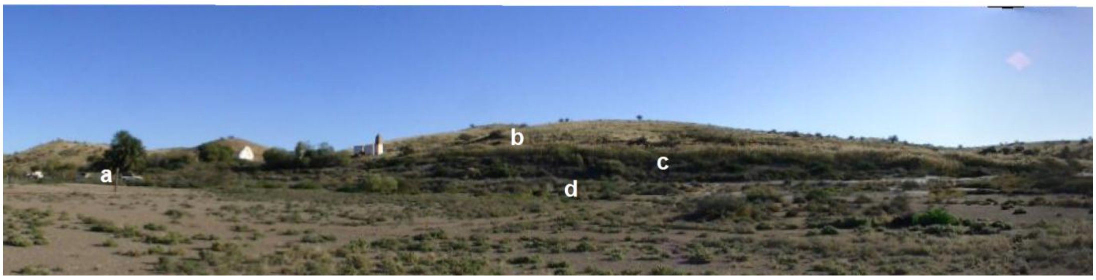

Figure A1.6: Panorama of the Freeling Springs site, looking west. The largest spring (EFS001) (a) located at the far south of the complex. The Peake and Dennison Inlier (b) is composed of up-thrown Adelaidean basement rocks. The Kingston Fault is marked by a large stand of *Phragmites* a*ustralis* that is supported by discharging groundwater (c). Calcareous spring deposits (d) are present in the foreground.

The spring-carbonates form part of the floor of a small alluvium-filled valley that feeds into the larger Peake Creek located a further 1.5 km to the north. The eastern side of the valley is composed of older generations of Quaternary colluvial and alluvial sedimentation and exposures of Mesozoic Bulldog Shale that have been incised during the formation of the valley. The southern end of the spring complex abuts the regionally significant Kingston Fault that forms the western side of the valley (Figure A1.7). The Kingston Fault has a strike of approximately 340° and up-thrown Adelaidean basement rocks on the western side of this fault form highlands (Figures A1.6 and A1.7). Spring discharge from the fault is evidenced by thick stands of *Phragmites australis* and other hydrophytes that grow along the fault, as well as small rivulets of springwater that flow onto the plain to the east (Figure A1.6).

The orientations of aerial photograph-interpreted lineaments at Freeling Springs have a larger variance than those at Warburton Spring. However, a number of specific orientations predominate (Figure A1.7). Similar to Warburton Spring, the most prominent orientation was one parallel to the major regional structure in the vicinity (Kingston Fault), which has a strike of approximately 340°. Lineament orientations at 290°, 65° and 30° are thought to be the equivalent of east-west, northeast-southwest and north-south orientations observed at Warburton Spring, with the difference related to the localised influence of pre-existing fault orientations on the east-west stress field as discussed below.

A1.5 Discussion

Measured veins and fracture systems found in terrestrial carbonate associated with GAB springs display orientations that are compatible with basement fault and fracture networks that have been reactivated under primarily east-west horizontal compressive stress as defined by Hillis et al. (1998), Hillis and Reynolds (2000) and Reynolds et al. (2006). This stress is expressed predominantly as sinistral transpressive shearing (Preiss, 2000). Consequently, the spring systems of the southwest GAB fit within the description of springs associated with “kinematically maintained fracture systems” of Curewitz and Karson (1997) (refer Chapter 2). Conceptually, spring propagation is associated with networks of smaller fractures that are concentrated in zones where basement structures are reactivated to form monoclinal flexures and fault propagation folds. An influence of “dynamically maintained fractures" (Curewitz and Karson, 1997) is also suggested by east-west fractures.

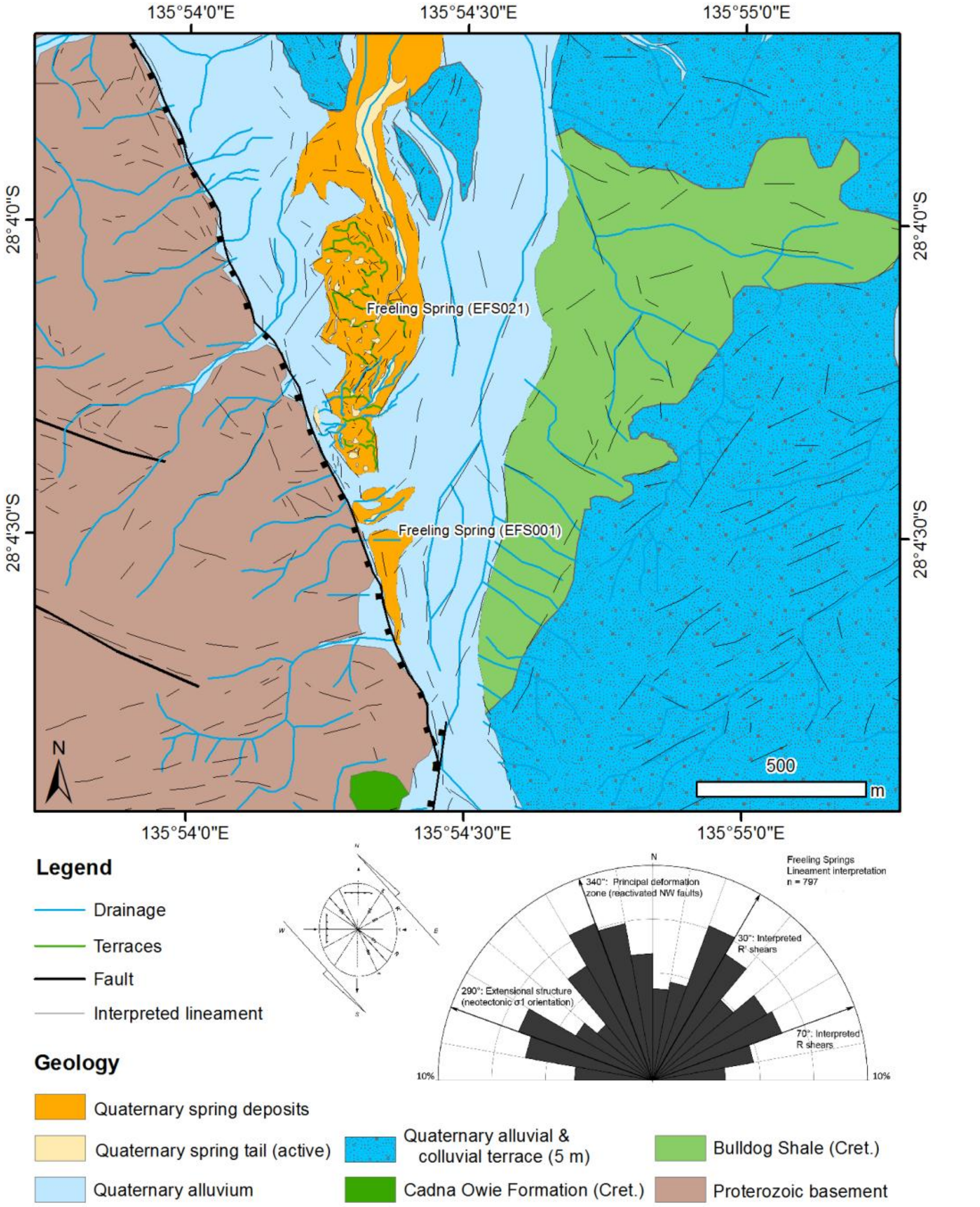

Figure A1.7: Mapped surface geology at Freeling Spring. Note the relationship between calcareous spring deposits and the location of the Kingston Fault. Rose diagrams at base of map highlight orientation groupings of lineaments.

The capacity for faulting to form preferential pathways, impermeable barriers or leaky barriers to groundwater flow in a three dimensional system is important beyond permitting localised natural discharge to surface of GAB groundwater. Mavromatidis (2008) noted that reverse and normal faulting anticlines with variable asymmetry and monoclines are all interpretable in Phanerozoic sediments from seismic sections across the GAB, while Watterson et al. (2000) provided 3D modelling of seismic data in the Lake Hope region of the southwest GAB demonstrating the development of polygonal fault structures that transect a number of GAB aquifer and aquitard units. Consequently, such faulting and related folding are potentially important in causing aquifer partitioning, influencing groundwater flow paths and allowing vertical transfer and mixing of fluids; for example, Radke et al. (2000) and Senior and Habermehl (1980) noted that vertical displacement on GAB aquifer sequence post-deposition is locally up to several hundred metres, which Radke et al. (2000) interpreted to be potentially enough to completely disrupt groundwater flow patterns at a local scale. Additionally, the ability of such structural deformation to produce secondary porosity and permeability regionally has important implications for diffuse discharge of groundwater from the GAB, particularly given that current diffuse discharge estimates are much larger than other forms of groundwater discharge (Armstrong, 2005; SAALNRMB, 2009; Welsh, 2000). These considerations are particularly pertinent in areas of active tectonism where compression or dilation of rock caused by inter-seismic or co-seismic strain can form a dynamic hydrogeology (Muir-Wood, 1993; Muir-Wood and King, 1993).

The prevalence of carbonate-depositing springs suggests that active seismicity may be important in relation to the maintenance of spring conduit systems. Such a situation has international precedent (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; Hancock et al., 1999; Minissale, 1991), although tectonic activity in these regions is generally so active as to cause large-scale geomorphic change. The intraplate activity interpreted in the southwest GAB region appears to leave more subtle geomorphic indicators as detailed in Waclawik (2006). This would also fit with the suggestion of Muir-Wood (1993) that in continental areas where deformation rates are low and the interval between earthquake recurrences long, spring manifestations may be important evidence for the existence of an earthquake hazard. Additionally, the association of mound springs in the southwest GAB and the influence of an intraplate stress field on pre-existing deformation architecture may have parallels elsewhere in the Australian continent. Recently, Davidson et al. (2011) described how springs and associated mound development could occur in the absence of large-scale faulting; springs were associated with a pre-existing fracture set that had been critically stressed by a regional anisotropic stress field that happened to be orientated for dilation at a location in northwestern Tasmania.

Slumping, either by differential erosion or by the weight of surface carbonate accumulation and possible subsurface dissolution, is evident in the vicinity of the springs at the Beresford Hill Spring complexes and is likely to be an important cause of many fractures and lineaments. Dias and Cabral (2002) noted that in regions subject to relatively low rates of tectonic activity, resulting evidence for active structures may be sparse and subtle, thus exacerbating the confusion between tectonic and non-tectonic structures. Dias and Cabral (2002) also suggested that non-tectonic structures are more likely to possess orientations that were not conformable with the local tectonic stress field. However, the orientation of many lineaments with underlying regional structures, combined with the occurrence of laminated sparry calcite fracture fill, tilted bedding, and stringer veins, suggest that many of the mapped lineaments are the result of fault slippage. In these instances, slumping may exacerbate the deformation by preferentially occurring along pre-existing, fault-related points of failure.

Although the frequency with which localised slumping in the vicinity of carbonate-depositing GAB springs occurs is uncertain, the relationship between faulting and GAB springs appears clear. Such a relationship between mound spring structures, faulting and localised slumping may also significantly contribute to the formation of breakout (Chapter 3), by forming a preferential flow pathway through the mound structure to which springwater may deviate and therefore provide a focus for corrosion and erosion of the mound wall. However, the observation of Hancock et al. (1999) concerning the requirement of active tectonism to maintain fracture-related spring conduits against suturing via carbonate precipitation may also have relevance to fracture-related break-out development in mound spring structures. In examples where mound spring pool waters still degas sufficient CO_2 to permit active mound growth, suturing of fracture-related breakouts may be also possible, particularly if flow though the fracture is more turbulent than conditions within the pool.

Localised perturbations in the stress field may occur due to either the impact of pre-existing structure or variations in the elastic properties of rock (Bell, 1996; Homberg et al., 1997). Consequently, Martinez-Diaz (2002) notes that the interpretation of stress fields using micro-tectonic data requires consideration of the local tectonic context; dynamic interaction with nearby faults can produce apparent local stress fields that are highly heterogeneous when compared to the regional stress field. Given the age of many of the regional structures in the southwest GAB and their potential development in tectonic settings different to that presently active, their localised influence on micro and meso-tectonic structure orientations is a possibility. This is particularly pertinent at the Freeling Springs site, where movement along the main Kingston and Levi Faults is interpreted to be oblique strike-slip.

Finally, hydraulic fracturing and subsequent vein development may result in vein structures not conformable with local tectonic stress field. Gudmundsson and Brenner (2001) and Gudmundsson et al. (2002) described hydrofractures as extensional mode I cracks that form in response to internal overpressure of fluids that eventually fill with mineral precipitate. The presence of seismic activity and pressurised, carbonate-bearing groundwater render the development of hydrofractures as a possibility in the GAB. However, Langbein et al. (1993), Sample and Reid (1998) and Uysal et al. (2009) note that hydraulic fracturing is often associated with extensive brecciation. Given the conformance of many measured veins with either the primary shear or the secondary tensional direction, as well as the general lack of well-developed brecciation in outcropping spring-related carbonate deposits, it is thought that hydraulic fracturing is not significant in relation to the development of veining at the study sites chosen.

A1.6 Conclusions

Evidence for recent seismicity was prevalent within spring-related carbonates located within the southwestern GAB. On a regional scale, evidence is provided by the development of springs in close association with regional faults within a previously identified zone of enhanced seismicity (Chapter 2), while at a local scale, evidence is forthcoming by the presence of veins and lineaments conformable with the underlying regional shear. Ongoing re-activation of faults has affected mound spring morphology as evidenced by deformation of mound spring deposits. As many springs are carbonate-depositing, active seismicity may have an important role in relation to the maintenance of the spring conduit systems, given the capacity of $CaCO_3$ precipitation to block spring conduits (Hancock et al., 1999).

The concordance of structural deformation in calcareous spring deposits with that of underlying regional structures indicates that these basement structures have been reactivated and propagated through overlying basin sediments via ongoing intraplate tectonic activity.

The ideas that tectonics imparts, including the development of secondary porosity and permeability that impacts on both direct and diffuse discharge and the interconnectivity between aquifer units via faulting have important implications with respect to our understanding of GAB hydrogeology, particularly in regions of discharge and will therefore necessitate greater consideration in the future with continued demand for groundwater resources from the GAB.