HYDROGEOPHYSICAL EVIDENCE FOR GROUND WATER MIXING AT FREELING SPRING GROUP, SOUTH AUSTRALIA

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2009

Submitted to the Faculty of the
Graduate College of the
Oklahoma State University
in partial fulfillment of
the requirements for
the Degree of
MASTER OF SCIENCE
July 2011

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INTRODUCTION

Springs provide a location where ground water may discharge from a number of different sources as regional flow lines converge at a discharge point. Ecosystems established in these systems may depend not only upon a continuing source of discharging ground water, but also a mixture of discharging waters from multiple sources. Freeling Spring Group located near the Oodnadatta Track in South Australia (Figure 1) offers a study site where two aquifers- the sandstones of the Great Artesian Basin (GAB) in the east and the fractured granite of the Peake and Dennison Ranges (PD) outcropping in the west- meet creating an area where ground water convergence and mixing may occur. This research is part of the Australian National Water Commission's (NWC) project "*Allocating water and maintaining springs in the Great Artesian Basin*" whose objective is to better quantify the GAB aquifer including recharge, discharge, residency time, aquifer properties and basin analysis as it is one of the only sources of water in the Australian Outback (Habermehl, 1980).

The Freeling Springs Group spring site (Figure 2) is both an important historical site as well as a tourist site that relies on the ruins of the former Peake Telegraph Station and Freeling Spring Group springs as its primary attractions. The spring's habitats represent vital, fragile ecosystems that have adapted to modern conditions of flow and water chemistry and maintaining these habitats requires an understanding of the source(s) of water (Fensham *et al.*, 2005). In the event that there are multiple ground water sources mixing or converging, these flows and flow paths must be understood in order to maintain spring flow and spring water chemistry in the area and secure the ecosystem. The loss of one or more of these source waters may impact the site ecosystem as well as animals that depend on the springs during droughts (Greenslade *et al.*, 1985; Ponder, 2002). With concerns over pressure heads decreasing in the GAB, it is important to understand both the flow mechanics and source water(s) for the springs to allow informed management decisions to be made for these systems.

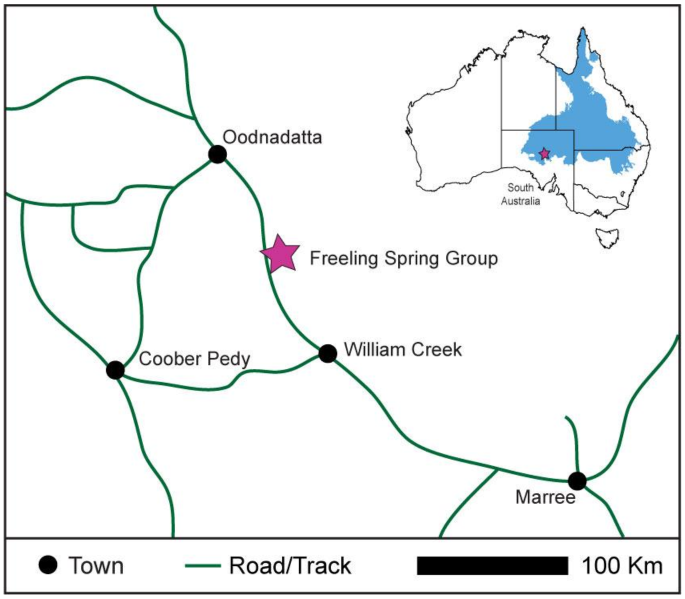

Figure 1: Inset map of Australia overlain with the boundary of the GAB showing the location of Freeling Spring Group, South Australia. Outer map is the location of Freeling Spring Group, nearby towns and roads/tracks in South Australia.

Figure 2: Photograph of the Freeling Spring Group area taken atop the Peake and Dennison Ranges looking east over the Kingston Fault (represented by the dashed white line) onto the flats underlain by the Great Artesian Basin. Visible are the ruins of the former Peake Telegraph Station, the tree line generated by discharge along the Kingston Fault and Freeling Spring (the primary spring of the group marked with a pink star). Freeling Spring Group extends to the north (left) along the fault zone and to the east.

Hydrogeophysical data integration utilizing structural, geochemical, geophysical, biological and hydrogeological data can be used to determine information about the subsurface (Atekwana *et al.*, 2004). The majority of hydrogeological investigations focus on integrating geological and hydrogeological data with either geophysics (Hyndman and Tronicke, 2005; Metwaly *et al.*, 2006; Halihan *et al.*, 2009) or geochemistry (Herczeg and Berry Lyons, 1991; Klein-BenDavid *et al.*, 2005) but not both. Geochemical studies concentrate on determining sources of fluid with fluid signatures such as ionic or isotopic composition whereas geophysical investigations seek to infer subsurface features such as fracture patterns, water table depth or fluid type (oil, gas, contaminants, fresh water, etc.) by inferring rock/fluid properties. This hydrogeophysical investigation will incorporate both geochemical and geophysical data with previously known data from literature including structural mapping and hydrogeology in order to better understand flow paths and source water(s) for Freeling Spring Group. This new, combined hydrogeophysical data set will help better quantify flow paths and source water(s) by using geophysical data to infer flow paths, geochemical data to calibrate geophysical data and geochemical data to evaluate mixing model potentials based on end member source waters. The corroboration of these results will provide a more reliable interpretation that can distinguish the poorly understood flow paths and source water(s) for Freeling Spring Group.

Freeling Spring Group, located on the western margin of the GAB, provides a location where it is possible to test hydrogeophysical data integration in a setting where spring mixing may be occurring on a regional fault between a fractured rock granite basin (PD) and a deformed sandstone aquifer (GAB). This study seeks to answer the question if there is mixing occurring for the source water(s) for Freeling Spring Group? Thus, the purpose of this study is to determine if mixing is occurring for Freeling Spring Group source water(s). The objective of this study was to conduct a hydrogeophysical investigation of the site i.e. gather existing data pertaining to the geology and hydrogeology of Freeling Spring Group, collect additional data including Electrical Resistivity Imaging (ERI) and geochemical samples and examine mixing models to test spring mixing conceptual models.

SITE DESCRIPTION

Freeling Spring Group is located at the old Peake Telegraph Station that was used to relay messages across the Australian Outback. Peake Telegraph Station is now a tourist destination off the Oodnadatta Track that relies on the springs and the ruins of the old telegraph station for its appeal. The springs- considered sacred by the indigenous people- are used as a water source by the wildlife and indigenous peoples crossing the Outback. The springs align with the Kingston Fault where the Peake and Dennison (PD) Ranges jut up against the western margin (boundary) of the GAB. Due to the region's inaccessibility and the inherent difficulty associated with field work in the Outback, previous literature uses the Freeling Spring Group as a benchmark site for the western margin of the GAB because it is more accessible than most places. The site has also been defined as a possible mixing zone (Aldam and Kuang, 1988).

Geology of Freeling Spring Group

The Freeling Spring Group straddles the border between the Peake and Dennison Ranges (PD) and the GAB aquifer on the Kingston (thrust) Fault (Rogers and Freeman, 1994). As part of the NWC GAB project, Keppel (2011) mapped the structure of the boundary of the GAB at Freeling Springs Group (Figures 3 and 4). To the west of the Kingston Fault sits the Peake and Dennison Ranges- which are represented by the fractured Palaeoproterozoic Wirriecurrie Granite (a foliated, coarse-grained, porphyritic fractured granite) (Rogers and Freeman, 1994). To the east side of the fault sits the GAB which is represented by two sandstones with an overlying shale at the site. Aldam and Kuang (1989) characterized the GAB as an artesian, multi-aquifer system comprised of Jurassic and Cretaceous sediments with the main aquifers consisting of the sand and silt of the Algebuckna Sandstone and Cadna-owie Formation. The confining beds consist of the

Bulldog Shale (top) and the Oodnadatta Formation (bottom) (marine silt and clay). The Oodnadatta Formation is not seen at Freeling Springs Group.

The Late Jurassic Algebuckna Sandstone (lower aquifer) has an upper layer consisting of medium to very coarse quartz sandstone and a lower layer being fine to very coarse to conglomeratic quartz sandstone. The Early Cretaceous Cadna-Owie Formation (upper aquifer) is a very fine to medium-grained, micaceous, feldspthic quartz sandstone, siltstone and claystone. The Cretaceous Bulldog Shale is described as claystone with thin lenticular interbeds. Holocene alluivium and Quaternary travertine deposits are also mapped east of the Kingston Fault (Rogers and Freeman, 1994; Keppel, 2011).

Hydrogeology of Freeling Spring Group

Researchers studying springs of the Great Artesian Basin have developed a set of nomenclature related to the structure of the springs in the aquifer. Freeling Spring Group is a *spring group* in the sense that it is a cluster of springs at one location in a single area. Due to the scarcity of water in the Outback, the terms *spring and seep* have been used to describe any amount of water appearing at the surface from depth. This can include a clump of reeds or a single groundwater-dependent plant as well as traditionally defined springs. The *spring orifice* is the surface discharge point of a spring. Many GAB springs also have a *spring tail* which is water that exits the spring orifice and discharges over the surface usually supporting an ecosystem. A s*pring ecosystem* contains many plants that are only able to survive on specific ground water chemistries (Greenslade *et al.*, 1985). Spring tails are often considered only surface runoff from the primary springs, but occasionally springs appear in the tail area adding additional discharge to the surface flow. This is the case for Freeling Springs Group as well.

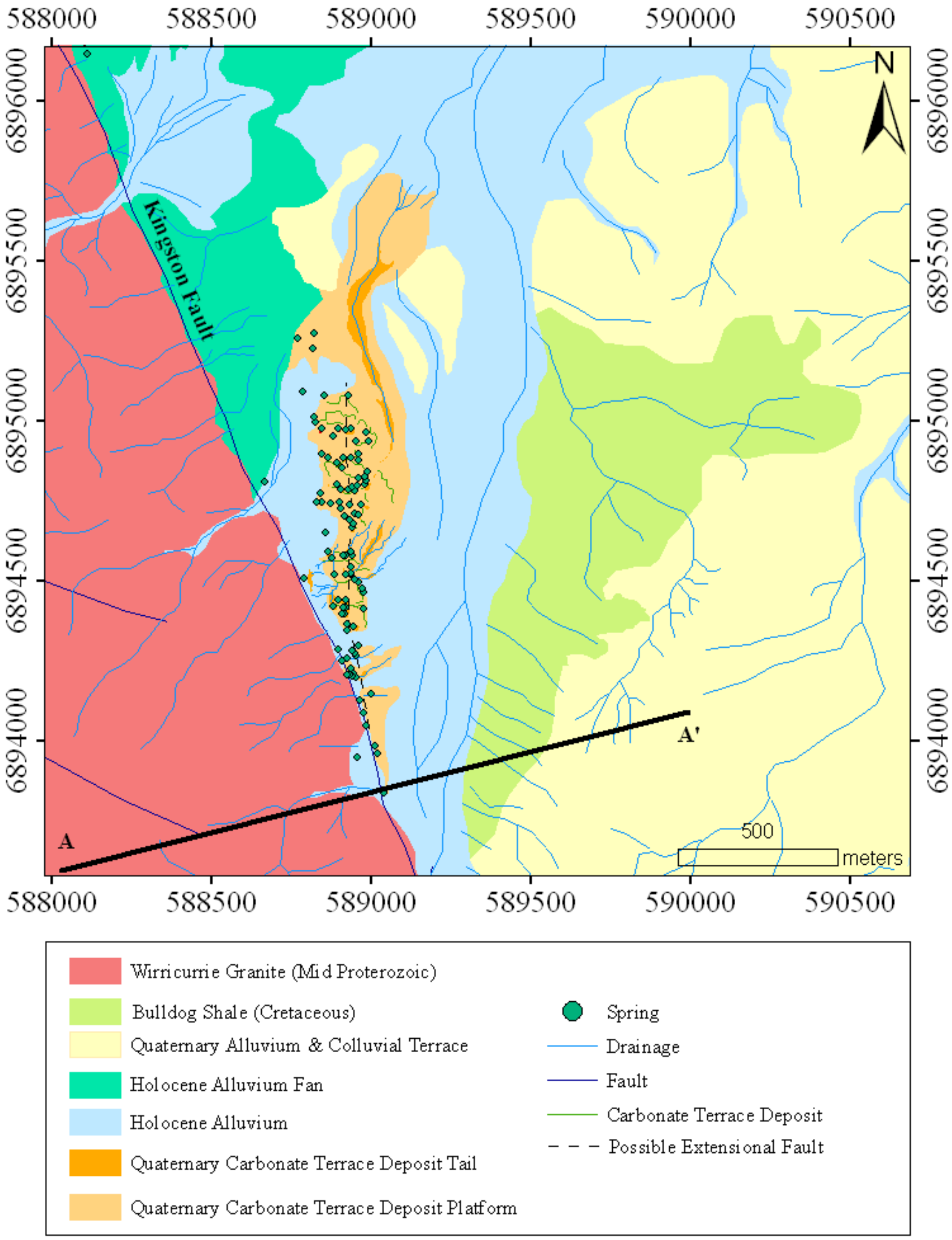

Figure 3: Structural map of Freeling Spring Group area including cross section A to A' across the primary spring- Freeling Spring (see Figure 4) (amended from Keppel, 2011).

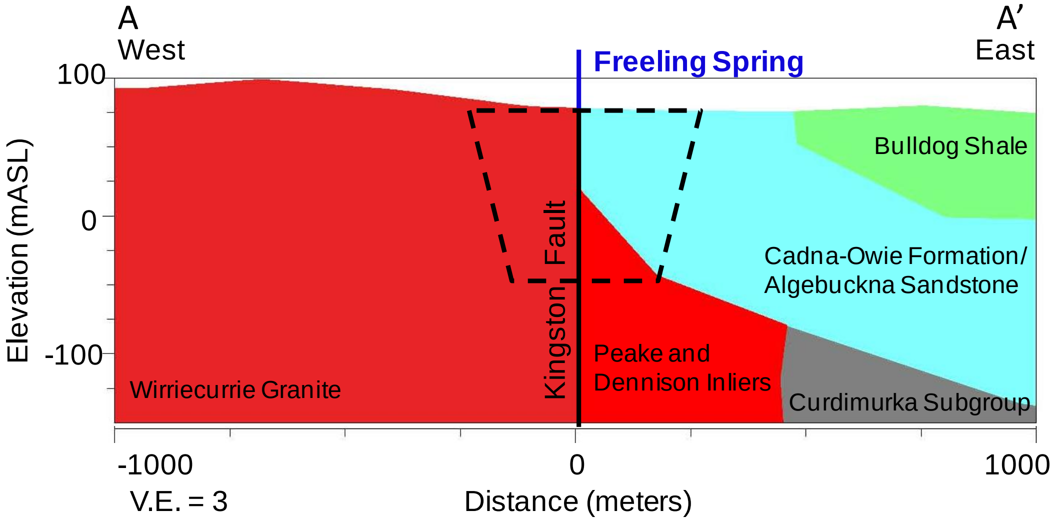

Figure 4: Cross Section A to A' over Freeling Spring Group with the approximate locations of the Kingston Fault and Freeling Spring marked (amended from Rogers and Freeman, 1994). Dashed trapezoid indicates the area imaged using electrical resistivity imaging across the fault.

Freeling Spring Group consists of multiple springs and seeps with the main spring being Freeling Spring located 75 meters to the southeast of the Peake Telegraph Station ruins. Over 130 locations in the Freeling Springs Group have been defined as springs or seeps by the NWC GAB Project. The majority of the springs are located within 500 meters of the Kingston Fault in a line that decreases in elevation towards the north (Figure 3). The occurrence of sprigs can be grouped in a variety of ways. There is a line of springs along Kingston Fault, springs on top of the travertine to the east of the fault and springs in the Freeling Spring tail orthogonal to the fault. There are also waters coming from the fractured granite within 500 m west of the fault with some of them being orthogonal to the fault on the same plane as the Freeling Spring tail but west of the fault. The springs currently have sufficient discharge to support a diverse ecosystem including a range of vegetation, kangaroos, goannas, spiders, snakes and gobies- all of which were observed in the field. Flow rates measured for the Freeling Spring Group range from below 14.4 L/min to over 61 L/min. Potentiometric levels at Freeling Springs Group are 10-40 meters above the land surface.

Previous literature indicates that Freeling Spring Group is a discharge feature of the GAB (Habermehl, 1986; Aldam and Kuang, 1988, 1989), but that the area’s flow mechanics are poorly understood and need further investigation (Aldam and Kuang, 1988, 1989). There is also evidence (Habermehl, 1986) suggesting that Freeling Spring Group could be a mixing zone between a bicarbonate source and a sulfate source within the GAB.

Freeling Spring Group’s setting would allow for a convergent flow system setting along the Kingston Fault (Aldam and Kuang, 1989) (Rogers and Freeman, 1994), but little discussion has been included in the literature regarding the potential contribution from the Peake and Dennison Ranges.

FREELING SPRING GROUP CONCEPTUAL MIXING MODELS

Aldam and Kuang (1988) stated that determining the source of the water is important both to maintain current ground water needs and to maintain the springs in the Outback. The hypotheses for the Freeling Springs Group conceptual mixing models evaluate the source(s) of water and the shallow subsurface lateral migration of groundwater. The source(s) of water needs to be determined- possibilities include the PD (sourced from the Wirricurrie Granite) and the GAB (sourced from the Algebuckna Sandstone and the Cadna-Owie Formation). Structurally, both of these are possible. Deeper formations were discounted as potential sources as the springs do not have temperatures above 30 ˚C. Geophysically, conductive electrical zones could be expected where brackish spring waters (Drever, 1982) are moving near the fault zone. End members of PD and GAB waters are available from other sites in the area to allow the source(s) of the water to be evaluated based on a regional analysis of the basins.

Both PD waters and the GAB aquifers water could be present at the fault and either could be a spring source. Lateral migration of water away from Kingston Fault is also unclear. Possibilities include water only moving upward along the fault zone with shallow subsurface water migrating away from the fault to the east. This would cause the entire spring group to discharge waters similar to the fault zone waters. An additional possibility is that water is sourced east of the fault zone by waters moving upward from the GAB near the fault due to the absence of the Bulldog shale confining unit. These issues of spring sources become more unclear in the spring tail for Freeling Spring. Along the spring tail, located orthogonal to the fault and east of Freeling Spring, surface water are flowing towards the east away from the fault while subsurface flow is originating in the tail in additional springs. Surface water along the spring tail can be traced from Freeling Spring while at the same time individual subsurface flow springs inside the tail can be found and isolated from the surface flow.

A set of possible hypotheses for mixing conceptual models for the Freeling Spring Group have been generated based on the hydrogeologic setting discussed above.

Hypothesis I: Water discharging at Peake Telegraph Station is from a single source of water from the PD or the GAB (Figure 5- Arrow 1 or 3).

Hypothesis II: Water discharging at Peake Telegraph Station is from two water sources (PD and GAB). The waters are discharging but not mixing as seen in two independent water chemistries (Figure 5- Arrows 1 and 3).

Hypothesis III: Water discharging at Peake Telegraph Station is from two water sources (PD and GAB). The waters are discharging and mixing as seen in water chemistries that reflect a mixture of both PD and GAB waters. Springs more than 50 meters east of the fault exhibit 100% GAB water chemistry (Figure 5- Arrows 1, 3, 2 and 4).

Hypothesis IV: Water discharging at Peake Telegraph Station is from two water sources (PD and GAB). The waters are discharging and mixing as seen in water chemistries that reflect a mixture of both PD and GAB waters. Springs more than 50 meters east of the fault exhibit chemistry influenced by both the PD and GAB waters (Figure 5- Arrows 1, 3, 2 and 5).

The structural, geophysical, hydrogeological and geochemical data collected for the site should allow adequate differentiation between these four hypotheses regarding the origin and flow of water for the Freeling Spring Group.

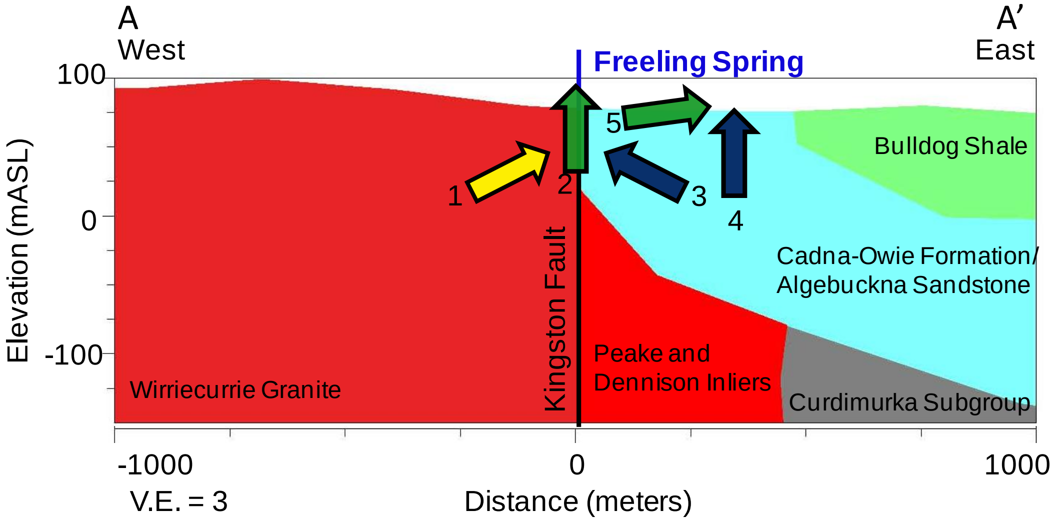

Figure 5: Cross section A to A' showing inferred flow paths. The yellow arrow represents PD water, the blue arrows represent GAB water and the green arrows represent mixed PD and GAB water.

METHODS

A hydrogeophysical investigation on Freeling Spring Group at Peake Telegraph Station was conducted to test the conceptual models for the springs. Three ERI lines were obtained over Freeling Springs and geochemical samples were collected from nine springs (Figure 6). Mixing models were then evaluated using the geochemical data. The methods described will include 1) ERI acquisition and processing, 2) geochemical sampling and analyses and 3) geochemical mixing models.

ERI

The multi-electrode surface resistivity method is used to examine horizontal and vertical discontinuities in the electrical properties of the ground as well as being used in the detection of three-dimensional bodies of anomalous electrical conductivity (Kearey *et al.*, 2002). The method uses direct current or low-frequency alternating currents to study the electrical properties (resistivity) of the shallow subsurface. When electrodes are in the subsurface, the method is referred to as electrical resistivity tomography (ERT), but when they are at the surface only the method is referred to as multielectrode resistivity profiling. A more generic term is electrical resistivity imaging (ERI).

The resistivity of a material is defined as the resistance in ohms between the opposite faces of a unit cube of the material in Ohm-meters and conductivity is the inverse of resistivity in units of mhos per meters or Siemens per meter. Resistivity is one of the most variable physical properties and is influenced by lithology, fluid properties, porosity structure and bioactivity (Telford *et al.*, 1990; Kearey *et al.*, 2002). ERI surveys are widely used in hydrogeological investigations due to the low cost and low environmental impact of the surveys coupled with a high amount of data recovered such as geologic structure, lithologies, subsurface water resources and plume migration (Simmons and Nur, 1968; Paterson, 1983; Knight, 1991; Chelidze and Gueguen, 1999; Binley *et al.*, 2002; Halihan *et al.*, 2009).

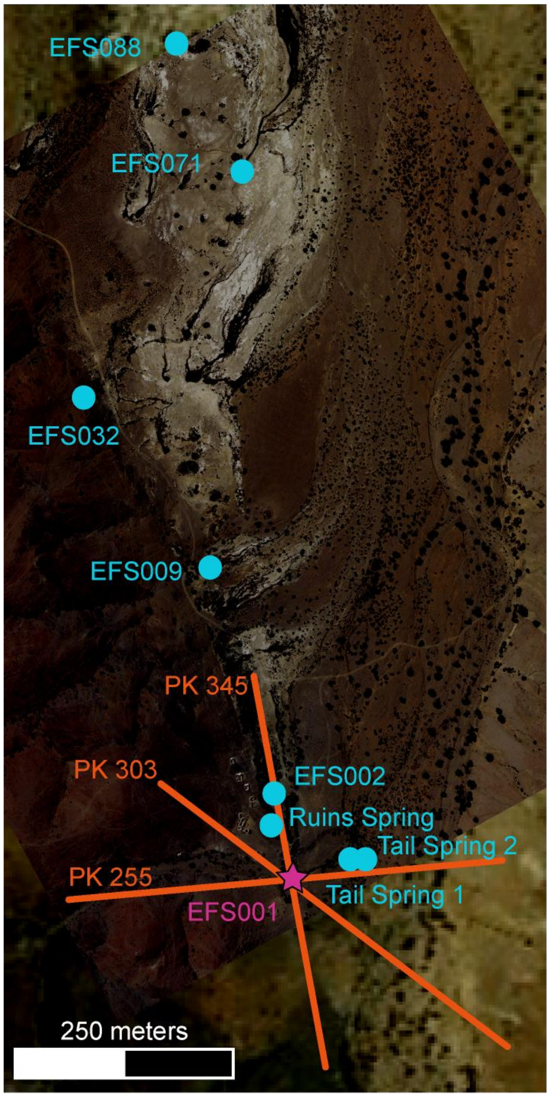

Figure 6: Google Earth images overlain with the 3 ERI lines (orange lines), geochemical sampling locations (blue dots) and Freeling Spring (pink star). The whiter portions of the map are the travertine platform and the dark vegetation directly to the west/ under PK 345 is the location of Kingston Fault. The Peake and Dennison Ranges can be seen on the west side of the map while the gibber plane over the GAB can be seen on the east side of the map.

Expected electrical resistivity values

As reported in Telford *et al* (1990) resistivity values of rocks vary greatly due to porosity, age and fluid content (Table 1). Small changes in fluid content of the rock can decrease resistivity exponentially (Table 1). Field and lab studies (Simmons and Nur, 1968; Urish, 1983; Frohlich and Parke, 1989; Knight, 1991; Lane *et al.*, 1995; Frohlich *et al.*, 1996; Roberts and Lin, 1997; Taylor and Barker, 2002; Sharma and Baranwal, 2005; Halihan *et al.*, 2009) show that resistivity decreases with increased porosity and/or fluid saturation. A compiled range of values from the above sources will be used to evaluate the ERI images and their resistivity values in relation to what is predicted for fractured granite and sandstone and what is measured for Freeling Spring Group. Resistivity values for granite are predominately above 1000 Ω-m, sandstones (SS) are predominately below 200 Ω-m and fluids are below 5 Ω-m.

Material	% Fresh Water	~Electrical Resistivity (Ω-m)
Medium Grained SS	0.10	1.4×10^{8}
Medium Grained SS	1.00	4.2×10^{3}
Coarse Grained SS	0.18	1.8×10^{8}
Coarse Grained SS	0.39	9.6×10^{5}
Granite	0.00	1.0×10^{10}
Granite	0.19	1.8×10^{6}
Granite	0.31	4.4×10^{3}

Table 1: Approximate electrical resistivity with respect to percentage of fresh water in rocks (amended from Telford et al. (1990).

Electrical resistivity survey

Three ERI lines extending 550 meters laterally and penetrating 110 meters vertically were collected in May 2009 using an Advanced Geosciences, Inc. (AGI) SuperSting© R8/IP using 56 stainless steel stakes with 10 meter spacing. Small amounts of salt water were poured in the granitic areas to decrease contact resistance between the ground and the stakes. The ERI lines were collected along the fault (ERI line PK 345), perpendicular to the fault (ERI Line PK 255) and off the fault (ERI Line PK 303) with Freeling Spring as the approximate midpoint of each line (Figure 8). Handheld and differential GPS units as well as standard survey equipment were used in order to collect spatial data for the three ERI lines.

ERI data acquisition and processing were completed using the proprietary Halihan-Fenstemaker method (Halihan and Fenstemaker, 2004). Data exceeding a repeatability error of 2% were eliminated from the dataset as well as data that had inversion model misfits of greater than 50%.

Geochemical Analysis

Nine water samples were collected along the ERI lines and around the Peake Telegraph Station during December 2010. The nine Freeling Spring Group water sampling points (Figure 6) were Freeling Spring (Figure 7.a), a historic well to the northwest of Freeling Spring, two samples of springs along the tail section of Freeling Spring, two samples on the travertine platform, a sample under a travertine lid (Figure 7.b) and two samples on top of or near the Kingston Fault. Regional chemical data that were available included a PD spring water sample and GAB spring water samples collected in 2008 for the NWC GAB Project. Waters sampled for this study were taken from sources with flows greater than 250 L/day.

Figure 7: Field pictures showing a) Freeling Spring sampling and b) Glory sampling site under a travertine deposit.

All water samples were filtered through a 0.45 μm filter during collection or in the laboratory for one sample that was turbid. The samples were collected and stored in HDPE bottles that were unacidified for anions and acidified to a pH <2 with high purity HNO_3 for cations and metals. The samples were cooled on ice in the field and transported to the laboratory where they were stored at 4^{o}C until analyses. The samples were not refrigerated for ten days while in transit from Australia to Oklahoma in the mail.

Temperature, electrical conductivity, pH and DO were measured using a Yellow Springs Instrument (YSI) multiprobe prior to sample collection. Alkalinity was measured by acid titration in the field. Water analyses were conducted at Oklahoma State University School of Geology chemical laboratories, Stillwater, Oklahoma. Major anions (chloride, bromide, nitrate and sulfate) and major cations (sodium, potassium, ammonium, magnesium and calcium) were measured using a Dionex ICS 3000 ion chromatograph.

Regional end member water samples for PD and GAB spring fluids were analyzed by the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Adelaide, South Australia.

Mixing Model Analyses

Genereux and Pringle (1997) define mixing models as using naturally-occurring differences in chemical concentrations (for at least one solute) to quantitatively determine the proportions in which different waters contribute to flow. Mixing models are commonly used to determine source water and determine contamination sources in surface and ground water. Common inputs include temperature, electrical conductivity, isotopes, rare earth elements and cations/anions- especially chloride and bromide (Pinder and Jones, 1969; Arnórsson, 1985; Hem, 1985; Genereux and Pringle, 1997; Uliana and Sharp, 2001).

Geochemical data- chloride and sodium concentrations and electrical conductivity- were input into mixing models to determine if the Freeling Spring Group was a mixture of PD water and GAB water or if they were 100% of one or the other. Modifying an equation from Genereux and Pringle (1997) and using the basic equation for a line, the following mixing model was applied to the geochemical data:

$$\% PD = \frac{C_n - C_{GAB}}{C_{PD} - C_{GAB}} \qquad (1)$$

where % PD is the percentage the sample is PD, C_n is the concentration of the variable for a particular sample, C_{GAB} is the concentration of the variable for a mean GAB sample and C_{PD} is the concentration of the variable for the PD sample.

Chloride and electrical conductivity were chosen as the variables for the first mixing model evaluation due to the conservative nature of chloride and the varying values for electrical conductivity seen across the site using the ERI data (Uliana and Sharp, 2001). Sodium and chloride were used for the second mixing model (Genereux and Pringle, 1997). Sodium and chloride are considered conservative ions as they are not a affected by biogeochemical reactions at aquifer and surface conditions.

RESULTS

Results of this study including geophysical data (ERI), geochemical data (cations, anions, EC and temperature) and mixing models are reported below.

ERI

The ERI data were similar in the three images. The RMS errors for the three datasets ranged from 7.8 to 10.4 percent. The lowest errors and easiest data collection were along the fault as the electrode contact in the granite was more difficult to achieve. The areas west of the Kingston Fault were more resistive than the areas east of the fault. The range of inverted resistivity values were 0.1 ohm-meters to 2500 ohm-meters. Along the fault ERI values had a much smaller range of 0.3-84 ohm-meters. These values are significantly lower than those of undeformed granite. Significant color breaks were established for the datasets at 5, 15 and 100 ohm-meters. These were used in an attempt to evaluate areas that would not have significant fault fluids (>100 ohm-meters), and areas that would likely be strongly influenced by fault fluids (<15 ohm-meters). The lowest break was used to evaluate more saline versus less saline fluids (5 ohm-meters). The results for each dataset are described in detail as follows.

PK 255

ERI survey line PK 255 (Figure 8) is perpendicular to the Kingston Fault with the fault lying at the approximate location of Freeling Spring. The line runs approximately along and close to a joint that is orthogonal to the Kingston Fault. West of the fault the line runs along an east-west valley in the granite and east of the fault the line runs along one of the tails for Freeling Spring. The west side of the Kingston Fault (LHS) shows resistive zones ranging from 5 Ω-m (green) to 2500 Ω-m (red) with the majority of the LHS having a resistivity greater than 15 Ω-m. There is a conductive vertical feature on the west side of the fault ranging from 5-15 Ω-m which extends from the bottom of the domain to an area just east of the Freeling Spring orifice. The east side of the fault (RHS) shows resistive zones ranging from 0.1 Ω-m (blue) to 900 Ω-m (red) with the majority of the RHS having a resistivity less than 15 Ω-m. Two prominent conductive features are a 0.1 to 15 Ω-m resistive zone along the top of the RHS east of the fault and one vertical feature coming from the bottom of the image.

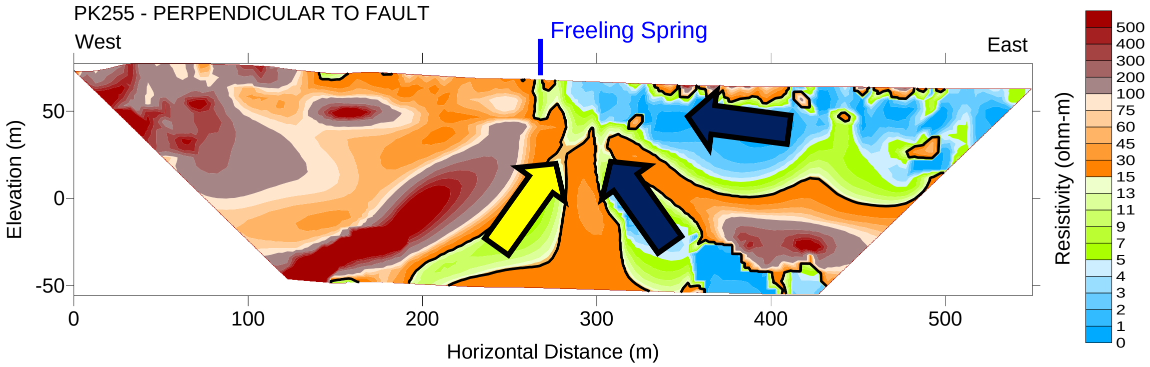

Figure 8: PK 255 ERI image showing resistivity values ranging from 0.1 - 2500 Ω-m. Three prominent conductors exist in the image that converge just east of Freeling Springs. The less conductive of these three features is on the west side of the fault. The yellow arrow represents an inferred PD flow path while the blue arrows represent inferred flow paths from the GAB possibly showing both the Algebuckna Sandstone (lower) and the Canda-Owie Formation (upper).

PK 303

ERI survey line PK 303 (Figure 9) is off the Kingston Fault and the orthogonal joint. PK 303 shows higher resistive zones ranging from up to 1110 Ω-m (red) on the west side (LHS) of Kingston Fault and less resistive zones ranging from as low as 0.2 Ω-m (blue) on the east side (RHS) of Kingston Fault. Some signatures of the three conductive zones observed in PK255 are present in this image as well, but they are not clearly separated and do not all reach the surface.

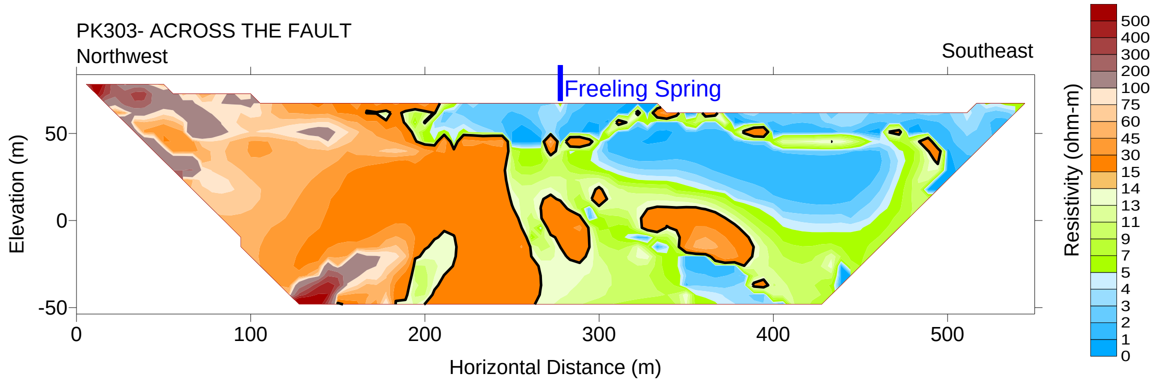

Figure 9: PK 303 ERI image showing resistivity values ranging from 0.2 - 1110 Ω-m.

PK 345

ERI survey line PK 345 (Figure 10) is along the approximate location of the Kingston Fault and shows less resistive zones ranging from 0.3 Ω-m (blue) to 84 Ω-m (orange/white) along the line with the top 50 m of the image and the central portion being predominately 0 to 15 Ω-m. Electrically conductive areas below 5 ohm-meters are constrained to the upper portions of the image. Although the conductive portion in the center of the image may represent an area of upwelling, the image may also depart from the fault zone and thus have higher resistivity due to the location of the line instead of fluid changes.

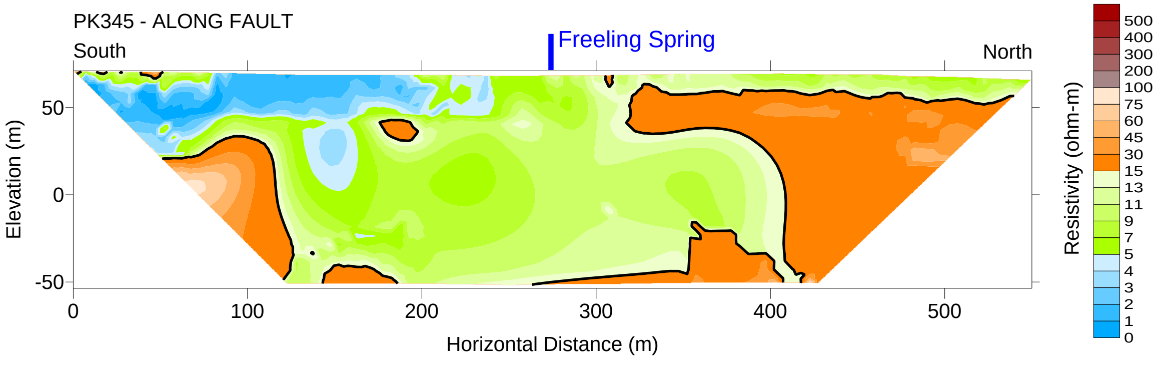

Figure 10: PK 345 ERI image showing resistivity values ranging from 0.3 - 84 Ω-m.

Geochemical Analysis Results

The regional water samples collected by the NWC GAB project for the Peake and Dennison Ranges sample (Tarlton Spring (ATS006)) has an electrical conductivity of 3559 μS/cm, a chloride value of 15.2 mM/L and a sodium value of 19.3 mM/L (Table 2). The GAB is represented by two samples from Billa Kalina (KBK001 and KBK002), and Bakewell Spring (KBK1004) with electrical conductivity values of 8685-8969 μS/cm, chloride values of 60.5-64.0 - mM/L and sodium values of 73.2-77.96mM/L (Table 2). The water samples for the Freeling Spring Group have electrical conductivities that range from 1454 to 7087 μS/cm, chloride values ranging from 25.7 to 45.1 mM/L and sodium values ranging from 34.77 to 62.47 mM/L.

Mixing Model Analyses

The two mixing models were analysed for source water potential for the Freeling Spring Group. The chloride versus conductivity provided insight into the fluid composition versus fluid electrical properties. The chloride versus sodium model provided insight into the fluid composition.

Sample ID	NWC GAB Project ID	UTM_X	UTM_Y	SPC	Cl^-	Na^+	EC vs Cl^- Mixing Model		Cl^- vs Na^+ Mixing Model	
		(m)	(m)	(uS/cm)	(mM/L)	(mM/L)	%GAB	%PD	%GAB	%PD
Peake Telegraph Station										
Freeling Spring	EFS001	589045	6893838	3968	26.63	35.96	8	92	24	76
Ruins Spring		589019	6893915	5073	36.90	48.38	28	72	46	54
Date Palm	EFS002	589027	6893959	1454	36.61	48.34	NaN	NaN	45	55
Glory	EFS032	588791	6894509	7087	45.13	62.47	65	35	63	37
Freeling Tail Spring#1		589124	6893868	4039	27.76	38.46	9	91	26	74
Freeling Tail Spring #2		589138	6893868	4024	27.77	38.26	9	91	26	74
Peake N1	EFS071	588996	6894823	4155	25.75	34.77	11	89	22	78
Peake N2	EFS088	588907	6895002	4785	29.61	41.35	23	77	30	70
Ruins Flat	EFS009	588949	6894273	3952	27.33	37.21	7	93	25	75
Peake and Dennison										
Tarlton Spring	ATS006	607439	6843714	3559	15.23	19.30	0	100	0	100
Great Artesian Basin										
Billa Kalina A	KBK001	644869	6740071	8685	64.00	77.95	95	5	103	-3
Billa Kalina B	KBK002	644890	6739980	8165	60.49	73.19	85	15	95	5
Bakewell Spring	KBK1004	641768	6734295	8969	62.70	77.60	100	0	100	0

Table 2: Geochemical analysis results used for mixing models as well as mixing model results. A comprehensive analysis is available in Appendix I.

Chloride/Fluid Conductivity Mixing Model

The PD sample has an EC value of 3559 μS/cm, the median GAB EC value is 8685 μS/cm and the PTS Spring Group samples range from 3852 to 7087 μS/cm. The best fit line between the end members and the Freeling Spring Group sample has a R^2 value of 0.96. Using these values in Equation 1 the Freeling Spring Group samples average value is 20 % GAB waters with the only sample above 30 % being Glory Spring at 65 %. The majority of samples are dominated by fluids from the Peake and Denison Ranges based on this model. No spatial trends were observed in the model relative to the distance from the fault zone.

Sodium/Chloride Mixing Model

The PD sample has a chloride concentration of 15.2 mM/L, the median GAB chloride concentration is 62.7 mM/L and the PTS Spring Group samples range from 26.6 to 45.1 mMol/L. The mixing model has a best fit R^2 value of 0.99. Using these values in Equation 1 the Freeling Spring Group samples average value is 35 % GAB. Once again, the mixing model suggests the strongest signature is fluid from the Peake and Denison Ranges. There is no spatial trend in the data relative to the distance away from the fault.

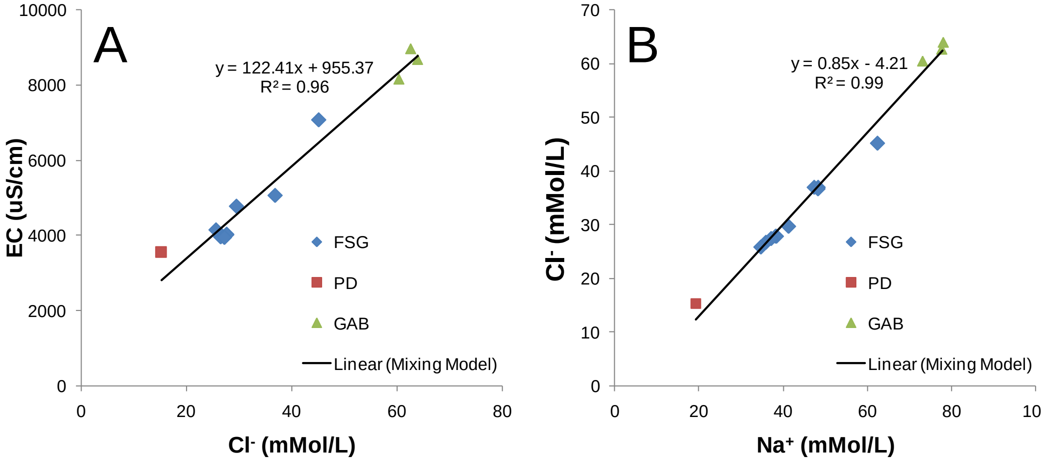

Figure 11: Mixing model results for A) chloride versus electrical conductivity and B) sodium versus chloride.

DISCUSSION

ERI

Relative to literature values for unsaturated rocks, resistivity values are lower than expected over Freeling Spring Group. Over 50% of the dataset has resistivity values under 15 Ω-m which is interpreted as the result of fresh to brackish fluids in the underlying formations. The west side of the Kingston Fault over the Wirriecurrie Granite (MB) would have resistivity values exceeding 5000 Ω-m if no significant fluid were present, however the mean value is less than 500 Ω-m, which is interpreted as evidence for the presence of fluids in the granite. The east side of the images over the GAB is predominately under 15 Ω-m implying that the rock is fully saturated with fresh to brackish fluid.

PK 255 and PK 303

ERI survey lines PK 255 (Figure 8) and PK 303 (Figure 9) may be inferred as basement rocks (PD) on the west side of Kingston Fault (LHS) and the GAB (saturated sandstone) on the east side (RHS). PK 255 is interpreted as demonstrating three fluid flow paths coming from depth (marked with arrows) - one from the MB (yellow arrow) and two from the GAB (blue arrows) discharging at Freeling Spring. Based on geological mapping of the area, the less resistive blue in the top 50 m of the east side of PK 255 may be inferred to be the Cadna-Owie Formation (GAB) aquifer flowing to Freeling Spring beneath the spring tail while the lower, additional fluid path may be inferred to be the Algebuckna Sandstone (GAB).

PK 345

ERI survey line PK 345 (Figure 10) along the Kingston Fault does not have ERI values normally associated with an underformed granite. The values seen under the fault imply that the fault is mostly fluid filled. This helps support the idea that water is coming up from depth along the fault zone and discharging along the surface.

Mixing Model and Geochemical Analysis

The mixing models show that the Freeling Spring Group samples lie between the PD and the GAB samples with all but one of the samples (Glory) being over 50 % PD water. The only sample to not follow this trend, the Glory water sample, did not have an outflow and its composition could have been partially influenced by rain water. This would suggest that PD water is coming across the fault from the Wirricurrie Granite and feeding the springs along the fault, on the travertine platfrom and in the Freeling Spring tail that are orthogonal to the fault. This also suggests that the GAB is not the most influential water source on the springs even though many of the springs sit directly on top of the aquifer.

Hydrogeophysical Evaluation

This study uses a hydrogeophysical approach to study the fluid flow/source(s) for Freeling Spring Group. This approach integrates the geochemical, geophysical, structural and hydrogeological data for the site. As part of the integrated approach, the structural data helped plan a geophysical investigation that could better map the spring system subsurface, the geophysical investigation allowed a superior understanding of where to conduct geochemical sampling and geochemical sampling helped calibrate the geophysical data. All of the data were then combined to test the hypotheses of ground water mixing for the Freeling Spring Group. Alone, these data sets provide an incomplete answer regarding the fluid source(s) for the Freeling Spring Group, but together each data set can help validate the other data sets to improve the final interpretation.

Although the geophysical and geochemical methods agree that multiple waters are exiting the Freeling Spring Group, a possible disagreement exists in the quantity of each source. The chemical mixing models show a clear dominance of PD fluid exiting the spring group, but the ERI data sets show only a small conductor leading to the fault from the west in PK 255 relative to large conductors east of the fault in the GAB. There are two possible explanations for this discrepancy. The first possible explanation is that the two conductors to the east are the two distinct layers in the GAB- the lower Algebuckna Sandstone and the upper Cadna-Owie Formation. These conductors, possibly having two distinct chemistries, could be mixing in proportions that are not seen in the regional GAB samples used for the mixing model evaluation and therefore actually play a much larger role in the composition of the spring group chemistry than currently considered. The second, more likely, explanation is based on structural mapping of the area. Structural mapping indicates the majority of the Freeling Spring Group sits atop the Kingston Fault, orthogonal to the fault (both east and west of the fault) and along a possible extension fault to the northeast (the travertine platform). A juxtaposition of fractured aquifer PD source against a porous media GAB source could allow the PD water to be the dominant fluid source observed in the chemical dataset. At the same time, the ERI data sees this fracture rock source as a smaller less conductive source than the strong wide conductors present in the GAB. This appears to be the interpretation that satisfies all of the datasets.

CONCLUSIONS

The Freeling Spring Group offers a unique study site that allows an evaluation of the boundary of two aquifers- fluids from the Peake and Dennison Ranges and fluids from the Great Artesian Basin. This boundary, the Kingston Fault, is clearly influencing electrical resistivity images and is supported by the geochemical signatures of local and regional waters. The ERI results indicate converging waters with potentially two to three waters mixing under and around Freeling Spring. Geochemical analysis results including electrical conductivity and cations/anions indicate at least two distinct water types around the Freeling Spring Group.

Structural evidence, vegetation, geochemical analysis and ERI all provide evidence that there is flow *along the fault*. The location of the fault is easily recognizable. There are an extensive number of plants along the fault that have been shown to only survive on ground water (Greenslade *et al.*, 1985). The ERI data also indicate that there is water along the fault as the majority of the fault is underlain by low resistivity values associated with fresh and brackish fluid saturated rock. The geochemical signatures of Freeling Spring directly on top of the fault indicates that the spring is a mixture of PD and GAB waters and therefore not entirely fed by the GAB. These four key pieces of data indicate that there is fluid flow upward along the fault by both the PD and GAB waters.

The mixing models indicate *lateral movement* of water in the shallow subsurface across the fault as well as movement of PD water onto the east side of the fault into the GAB. The geologic signatures of the waters indicate that the springs are a mixture of both PD and GAB waters with the compositions being more predominately PD rather than GAB. The springs on the travertine platform are over 50% PD composition in relation to the mixing models indicating that the PD water is moving significantly east of the fault (at least 500 m). This suggests that the PD aquifer is recharging the top of the GAB at Peake Telegraph Station for the Freeling Spring Group.

Based on the results of the hydrogeophysical investigation of Freeling Spring Group, data suggest that the Freeling Spring Group is a mixture of PD and GAB waters with the PD waters heavily influencing the springs in the group including springs east of the Kingston Fault.

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ELECTRONIC APPPENDICES

Two electronic appendices are included as part of this thesis.

Appendix I: Full geochemical analysis of Freeling Spring Group samples
Appendix II: ERI location and resistivity values.

VITA

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Abstract:

The Great Artesian Basin (GAB) is an aquifer system that extends across Australia covering over 22% of the continent and is a vital support system for ecosystems in the region. As part of the Australian National Water Commission's (NWC) GAB Project, research is being conducted to understand the aquifer including studying the discharge of springs and determining flow paths of the aquifer. Water sampling at springs that are a part of the Freeling Spring Group were used along with Electrical Resistivity Imaging (ERI) data to evaluate evidence of mixing between the GAB aquifer and waters from the adjacent basement aquifer in the Peake and Dennison Ranges (PD). Nine springs were used to evaluate fluid chemistry of the Freeling Spring Group. ERI data were collected along three orientations over the Freeling Spring site. The ERI data, which extend for 550 meters laterally and 110 meters vertically, indicate three possible flow lines providing mixing at the spring orifice similar to what would be predicted from traditional conceptual models. Regional water samples of springs were used as end members to evaluate chemical mixing models for waters at the site. The chemistry of spring water samples indicates that the water emanating from the Freeling Spring Group is a mixture of waters from both the GAB and the PD, which confirms the ERI evidence for mixing at the site. The data suggest the mixing occurs along a structural feature in the Peake and Dennison Ranges and that the spring water maintains a strong PD signature even well east of the fault zone.

ADVISER'S APPROVAL: Dr. Todd Halihan