Evidence for groundwater mixing at Freeling Spring Group, South Australia

Todd Halihan¹ · Andrew Love² · Mark Keppel³ · Meghan K. M. Dailey¹ · Volmer Berens³ · Daniel Wohling⁴

Received: 18 March 2019 / Accepted: 18 October 2019 / Published online: 4 December 2019
© The Author(s) 2019

Abstract

Water sampling at springs that are a part of the Freeling Spring Group, South Australia, was used along with electrical resistivity imaging (ERI) data to evaluate the sources and pathways for groundwater to the springs and to find evidence of mixing between the Great Artesian Basin (GAB) aquifer system (Algebuckina Sandstone, Cadna-owie Formation and lateral equivalents) and waters from the adjacent mountain block basement (MB) aquifer. Five springs and a well were used to evaluate spring chemistry; multi-electrode resistivity data were collected along three orientations over the Freeling Spring site. The resistivity data indicate three independent electrically conductive curvilinear features connected to the spring. These features are evidence of mixing at the spring vent similar to what would be predicted from traditional hydraulic flownets. The chemistry of the spring water samples indicates that the water emanating from the Freeling Spring Group is a mixture of waters from both the GAB and the MB aquifers, supporting the geophysical evidence. The data suggest mixing occurs along a fracture in the body of the MB and porous media flow in the GAB beds, but the system is dominated by the GAB flow, which provides approximately 90% of the discharge.

Keywords Australia · Fractured rocks · Geophysical methods · Groundwater mixing · Electrical resistivity imaging

Introduction

Springs occur where regional flowlines intersect the ground surface. Regional flow lines that occur at the same point may originate in different lithologies or groundwater facies. Ecosystems established in these systems may depend not only upon a continuing source of discharging groundwater but also the mixture of these discharging waters (Harvey et al. 2007). Freeling Spring Group, located near the Oodnadatta Track in

South Australia (Fig. 1), offers a study site where two distinctly different lithologies meet, the sandstones of the Great Artesian Basin (GAB) in the east and the fractured mountain block granite (MB) of the Peake and Dennison Inliers outcropping in the west, creating an area where groundwater convergence and mixing may occur (Habermehl 1980). This site is important for understanding the historical and future use in a remote part of Australia that is of interest to stakeholders in indigenous communities, ranchers, and mining companies.

Published in the special issue “Advances in hydrogeologic understanding of Australia’s Great Artesian Basin”

✉ Todd Halihan
todd.halihan@okstate.edu

Andrew Love
andy.love@flinders.edu.au

Mark Keppel
mark.keppel@sa.gov.au

Meghan K. M. Dailey
watermd@ymail.com

Volmer Berens
volmer.berens@sa.gov.au

Daniel Wohling
daniel@innovativegroundwater.com.au

¹ Boone Pickens School of Geology, Noble Research Center, Oklahoma State University, Stillwater, OK 74074, USA

² School of the Environment, Flinders University, GPO Box 2100, Adelaide 5001, Australia

³ Department for Environment, Water and Natural Resources, South Australian Government, 81–95 Waymouth Street, Adelaide 5001, Australia

⁴ Innovative Groundwater Solutions, Unit 2, 162 Hindmarsh Road, Victor Harbor, SA 5211, Australia

The site is limited in accessibility and in the inability to do invasive subsurface investigations in a set of protected springs. The objective of the project is to better quantify the sources of groundwater to the Freeling Springs Group in the western GAB as the springs may be influenced by the adjacent igneous aquifer.

Previous work on evaluating mixing at springs has usually taken a chemical approach and evaluated major ions, isotopes, or both (Lyons et al. 1995; Uliana and Sharp 2001; Wang et al. 2006). If the mixing is a complex blend of waters, statistical or multitracer approaches are utilized to determine endmember water composition and their relative proportions (Plummer et al. 2001; Crossey et al. 2006; Doctor et al. 2006; Moore et al. 2009). In addition, geophysical approaches are utilized to find flow paths and to understand the underlying structure of the system. These approaches utilize seismic or electrical methods to determine preferential pathways and find hidden structures but may not observe mixing phenomenon (Halihan et al. 2013). Integrated hydrogeophysical approaches are useful when evaluating spring mixing problems (Povinec et al. 2006; Gary 2010; Petitta et al. 2015). These approaches utilize the geophysical data to look at the geometry of the flow system and the chemistry to test flow hypotheses.

This hydrogeophysical investigation incorporated both geophysical and geochemical data with previously known data from literature, including structural and hydrogeologic mapping, in order to better understand flow paths and source water(s) to the Freeling Spring Group. The integrated hydrogeophysical data can potentially quantify flow paths and source water(s) by using geophysical data to infer flow paths and geochemical data to calibrate geophysical data, and to evaluate mixing models based on end member source waters. The integration of these datasets was used to provide an improved interpretation of spring water sources and distinguish the poorly understood flow paths and source water(s) for the Freeling Spring Group.

Site description

Freeling Spring Group is located at the Peake Overland Telegraph Station ruins on the Oodnadatta Track, South Australia, and has been suggested as a possible mixing zone between GAB waters and waters from the granitic basement (Aldam and Kuang 1988). The springs and the ruins of the nearby former overland telegraph station are a focus for tourism. The springs are considered to be sacred sites as well as important natural resources by the local indigenous people. The springs' habitats represent vital fragile ecosystems that have adapted to modern conditions of flow and water chemistry. These habitats include not just permanent wetland water sources for aquatic species but phreatophytes living near the

Fig. 1 Map of Australia (inset) overlain with the boundary of the GAB and Western GAB showing the location of Freeling Spring Group, South Australia. Locality map of the Freeling Spring Group, nearby towns and roads/tracks in South Australia. Roads in study area (orange lines) are unpaved graded tracks except for the Stuart Highway through Coober Pedy. The potentiometric lines for the GAB (blue lines) are in units of meters based on the Australian Height Datum (m AHD) (Love et al. 2013). The location of the MB endmember water, spring MB002, is shown

springs and migrating species using the springs to cross through the arid area where it exists.

In the event of multiple groundwater sources mixing or converging, these flows and flowpaths must be understood in order to maintain spring flow and spring water chemistry in the area and to secure the ecosystem (Fensham et al. 2005; Keppel et al. 2011). The loss of one or more of these source waters may impact the site ecosystem and animals depending on the springs during droughts (Greenslade et al. 1985; Ponder 2002). With concerns over pressure heads decreasing in the GAB due to groundwater use and natural long-term resource decline, 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 (Love et al. 2013).

Geology of Freeling Spring Group

The Freeling Spring Group straddles the border between the Peake and Dennison Inliers to the west, and the GAB aquifer to the east of the Kingston Fault (Rogers and Freeman 1996; Sampson et al. 2012; Keppel 2013; Keppel et al. 2019, this issue; Figs. 2 and 3). The Kingston Fault is interpreted as a steeply dipping boundary fault for the Inliers but is poorly understood. The inlier portion of Proterozoic granite is approximately 10 km wide from east to west. The Peake and

Fig. 2 Geology map of the Freeling Spring Group area including cross-section A–A' across the largest spring, Freeling Spring, EFS001 (see Fig. 3 and Keppel et al. 2019, this issue). Map dimensions are in UTM coordinates and the map has the same boundary as Fig. 4

Dennison Inliers is composed of the fractured mid-Proterozoic Wirricurrie Granite: a foliated, coarse-grained porphyritic fractured granite (Rogers and Freeman 1996). This side of the fault has a rugged topography with significant slopes and

an overall higher elevation than the east side of the fault. To the east of the fault is the western portion of the GAB aquifer, composed of Algebuckina Sandstone and the Cadna-owie Formation (Rogers and Freeman 1996). The Late Jurassic Algebuckina Sandstone (lower aquifer) has an upper layer consisting of medium to very coarse quartz sandstone and a lower layer of fine to very coarse conglomeratic quartz sandstone. The Early Cretaceous Cadna-owie Formation (upper aquifer) is a very fine to medium-grained micaceous, feldspathic quartz sandstone, siltstone and claystone. The overlying confining unit is the Cretaceous Bulldog Shale and is described as claystone with thin lenticular interbeds. Holocene alluvium and Quaternary travertine deposits are also mapped east of the Kingston Fault (Rogers and Freeman 1996). The younger Oodnadatta Formation is not seen at the Freeling Springs Group. The underlying Curdimurka Subgroup is composed of sandstone, shales and dolomites. The topography of the east side of the fault is flat with flow towards the northeast and lower elevations than the west side of the fault.

Hydrogeology of Freeling Spring Group

Researchers studying springs of the GAB have developed a set of nomenclature related to the geometry 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 plant that is dependent on the groundwater source but does not occur in a traditional spring wetland habitat. The “spring vent” is the surface discharge

Fig. 3 Cross section A–A' over the Freeling Spring Group with the approximate locations of the Kingston Fault and Freeling Spring marked (amended from Rogers and Freeman 1996; Keppel 2013) (see Fig. 2). Dashed trapezoid indicates the area imaged using electrical resistivity imaging across the fault on ERI line PK255. The yellow arrow represents a MB water flowpath, while the blue arrows represent GAB water flowpaths for the Algebuckina Sandstone (A) and the Cadna-

owie Formation (C). The green arrows represent mixed MB and GAB waters, one moving upward along the Kingston Fault (KF) and one moving outward along and under the travertine deposits downgradient from the fault. Shallow geology of the alluvium and the Bulldog Shale may cover more of the cross section than indicated by Rogers and Freeman (1996). Deeper geological interpretation of Rogers and Freeman (1996) was not confirmed by drilling data

point of a spring. Many GAB springs also have a “spring tail” which is water that exits the spring vent and discharges over the surface, usually supporting a spring wetland. Spring tails are often considered to be surface runoff from the primary spring vent, but recent work has shown that additional small springs may appear in linear spring tails, adding additional discharge and mixing processes to the surface flows and acting as a line source of groundwater over a fault zone (Halihan et al. 2013). These additional sources of native groundwater in the tails are apparent in geophysical and geochemical data but are not apparent from visual inspection making water sampling to determine water evolution complex (Halihan et al. 2013; Keppel et al. 2012; Keppel 2013).

The Freeling Spring Group consists of multiple springs and seeps with the largest spring in the southern portion of the complex being Freeling Spring (spring No. EFS001) located 75 m to the southeast of the Peake Telegraph Station ruins. Photos of the site can be seen in Keppel et al. (2019). The largest discharge spring (Freeling Spring, EFS001) has the highest flow location from a diffuse area in a zone of high reeds (*Phragmites australis*). The Freeling Spring primary spring tail is located in a lineament perpendicular to the Kingston Fault and is likely composed of a number of small springs discharging along the fault orientation as it occurs near the fault intersection (Karlstrom et al. 2013; Keppel et al. 2019). The spring tail for Freeling Spring is smaller and oriented to the east of the spring along the cross-section line A–A' (Figs. 2 and 3). It is not the larger downgradient spring tail originating further northeast in the spring group (Fig. 2).

Over 130 locations in the Freeling Springs Group have been defined as springs or seeps. The majority of the springs are located within 500 m of the Kingston Fault, in a northeast trending line that decreases in elevation away from the fault (Fig. 2). There is a line of individual springs along the Kingston Fault; these are individual springs on top of the travertine to the east and downgradient of the fault. The spring group has sufficient discharge to support a diverse ecosystem including a range of flora and fauna. Flow rates measured for the Freeling Spring Group as part of this investigation range from just seepage to over 61 L/min. Groundwater potentiometric levels at the Freeling Spring Group are 5–25 m above the land surface (Love et al. 2013; Fig. 1). The potentiometric surface in the granitic areas is poorly characterized due to limited available monitoring locations.

Published literature indicates that the Freeling Spring Group is a discharge feature of the GAB (Habermehl 1986; Aldam and Kuang 1988, 1989), but the area's flow mechanics are poorly understood and need further investigation (Aldam and Kuang 1988, 1989). The Freeling Spring Group's setting would allow for a convergent flow system setting along the Kingston Fault, (Aldam and Kuang 1989; Rogers and Freeman 1996) but little discussion has been included in the literature regarding the potential contribution from the Peake and Denison Inliers.

Freeling Spring Group conceptual mixing models

The hypotheses for the Freeling Springs Group conceptual mixing models evaluate the source(s) of water to the main spring and the shallow subsurface lateral migration of groundwater. The source(s) of water needs to be determined; possibilities include the MB (sourced from the Wirricurrie Granite) and the GAB (sourced from the Algebuckina Sandstone and the Cadnaowie Formation). Deeper formations were discounted as potential sources as the springs do not have temperatures above 30 °C. Additional work would be needed to test this assumption. Geochemically, end members of MB and GAB waters are available from other springs and wells in the region to allow the source(s) of the water to be characterized based on a regional analysis of the basin (Fig. 1). The end member of the MB waters is represented by spring MB002 which is located 50 km to the south-southeast on private land (Figs. 1 and 4; Table 1). This is the closest a clear representative sample could be found in this remote area but the exact location is not given based on the request of the landowner (Love et al. 2013). The GAB waters are represented by the nearby Centenary Well, which likely samples both the Cadnaowie and Algebuckina. The well is a 207-m-deep private stock well located 7.7 km to the northeast of Freeling Spring (Fig. 4; Table 1). Geophysically, electrically conductive zones in the bedrock could be expected where brackish spring waters are moving near the fault zone.

The lateral migration of water away from Kingston Fault also has a number of possible configurations (Sampson et al. 2012). One possibility includes water moving upward along the fault zone with shallow subsurface water migrating away from the fault, down the topographic gradient to the north and east. This would result in the entire spring group discharging waters similar to the fault zone waters. Another possibility is that water is sourced east of the fault zone by waters moving upward from the GAB near the Kingston Fault through additional faults in the Bulldog Shale confining unit, like many other springs in the area (Keppel et al. 2011; Halihan et al. 2013). This would result in springs of the GAB having chemistry of GAB fluids and would potentially be different from the fault fluid chemistry. These issues of spring sources may become further complicated in the channels that form the spring tails. Along the channel for discharge from Freeling Spring, located orthogonal to the Kingston Fault and east of Freeling Spring, surface water flows toward the east, away from the fault, while subsurface flow is potentially originating in the channel in additional upwelling springs (Halihan et al. 2013). Surface water along the spring tail can be traced from the main Freeling Spring (EFS001); at the same time, individual subsurface flow springs inside the tail can be found and isolated from the surface flow. This may result in more complex mixing of spring waters.

Based on an interpretation of seismic data, Aldam and Kuang (1988) hypothesized that the source of fluid along the Kingston

Fig. 4 Geophysical line and water sampling locations. Google Earth image overlain with the two ERI lines (blue lines), geochemical sampling locations (yellow dots) and Freeling Spring (EFS001). The dimensions of the figure are in UTM coordinates and directly correlate with the geologic map of Fig. 2. The coordinates are given in Table 1. The relative directions and distances of the endmember mixing models are illustrated as black arrows. The cross-section A–A' is illustrated in Fig. 3

Fault could be a mixture of MB (Fig. 3, arrow MB) and GAB waters (Fig. 3, arrows C and A). This should be evident in both the electrical resistivity imaging data and the geochemical data. If the springs are only sourced from the MB, it should be evident in the geochemistry, even if it is ambiguous in the geophysical data, as a small fracture in the granite may not be a significant electrical signature. If the springs are only sourced from the GAB aquifer, it should be evident in both datasets as the electrical signature of the sandstone beds should be distinctive regardless of whether the fluids they contain provide significant contrast. Additional evidence of a potential MB source is the presence of the former Peake Telegraph Station at the spring which may have been located due to the availability of fresher water from a granitic source.

For the lateral and/or vertical transport east of the fault, waters are hypothesized to be a mixture of fault waters from the GAB or MB moving up the Kingston Fault (Fig. 3, arrow KF), then down the topographic gradient to the northeast (Fig. 3, arrow T). This hypothesis should be supported by both geochemical and geophysical evidence. If the spring discharge east of the Kingston fault is purely GAB fluids from depth, the geophysical data may not be clear as a lack of mixing would not alter the electrical signature. The geochemistry data would be clear with regard to the water source and a lack of evaporation along the surficial flowpath (Fig. 3, arrow T).

Methods

A hydrogeophysical investigation was conducted to test the conceptual models for the springs. Three multi-electrode surface resistivity lines or electrical resistivity images (ERI) were obtained over Freeling Springs and geochemical samples were collected from four spring vents (Fig. 4). Mixing models were evaluated using the geochemical data with endmembers from a GAB well and an MB spring. The methods described include resistivity data acquisition and processing, geochemical sampling and analyses, and geochemical mixing models. These data were evaluated in a context of regional potentiometric data (Fig. 1; Sampson et al. 2012).

Electrical resistivity survey

Three ERI lines extending 550 m laterally and penetrating 110 m vertically were collected in May 2009 with an Advanced Geosciences, Inc. (AGI) SuperSting R8/IP using 56 stainless steel stakes with 10-m 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 PK345), perpendicular to the fault (ERI Line PK255) and off the fault (ERI Line PK303) with Freeling Spring as the approximate midpoint of each line (Fig. 5). Handheld and differential global positioning system (GPS) units along with standard survey equipment were used in order to collect spatial data for the topography of the three ERI lines. The results of PK303 will not be reported as they were similar to PK255 (Dailey 2001). ERI data acquisition and processing were completed using the same procedures as other locations in the basin (Halihan et al. 2013). The acquisition utilized 12-V deep cycle batteries with a 400-V signal generated by the instrument at 350 milliamps of current. Acquisition and processing protocols were identical for all datasets. As the location was remote, no electrical noise features were present; the only field management issue was watering electrodes to obtain contact resistance below 2,000 Ω in some locations.

Geochemical analysis

Four water samples were collected along the ERI lines and around the Peake Telegraph Station during December 2010 (Dailey 2001). The Freeling Spring Group water sampling points (Fig. 4) were Freeling Spring (EFS001), and three samples at individual discharging spring vents away from the main spring (EFS017, EFS071, and EFS088). Samples were collected from locations that appeared to be the first surface occurrence of groundwater at the locations, but sample chemistry from these vents is variable in composition as reactions

Table 1 Geochemical analysis data used for the mixing models and mixing model results. Specific conductance of water or fluid electrical conductivity of water is denoted as *EC*

Parameter	Site name (site ID number)					
	MB002 (MB002)	Centenary well (6041-36)	Freeling Spring (EFS001)	Ruins Flat (EFS017)	Peake N1 (EFS071)	Peake N2 (EFS088)
UTM location (m)						
Easting	Private	596,082	589,043	588,949	588,985	588,899
Northing		6,897,042	6,893,839	6,894,276	6,894,816	6,894,980
Field readings						
EC ($\mu\text{S}/\text{cm}$)	1,295	3,971	3,968	3,952	4,155	4,785
pH	6.5	7.9	7.55	7.78	7.99	7.95
Temp ($^{\circ}\text{C}$)	n.a.	n.a.	27.0	20.8	23.5	18.8
Measured chemistry (mmol/L)						
Cl	4.2	27.9	26.6	27.3	25.7	29.6
Alk (pH 4.5)	6.5	4.4	3.8	3.2	3.2	3.5
SO ₄	0.7	3.7	3.7	3.8	3.6	4.1
Na	5.4	35.9	36.0	37.2	34.8	41.4
K	0.37	0.20	0.42	0.43	0.39	0.46
Ca	1.64	1.02	1.34	1.57	1.46	1.36
Mg	1.83	0.25	0.35	0.39	0.29	0.30
Parameters normalized to chloride						
EC/Cl	306.1	142.5	149.0	144.6	161.4	161.6
Na/Cl	1.3	1.3	1.4	1.4	1.4	1.4
SO ₄ /Cl ($\times 100$)	17.7	13.5	13.8	14.0	14.0	13.8
K/Cl ($\times 100$)	8.6	0.7	1.6	1.6	1.5	1.6
Ca/Cl ($\times 100$)	38.7	3.7	5.0	5.8	5.7	4.6
Mg/Cl ($\times 100$)	43.2	0.9	1.3	1.4	1.1	1.0
Percent mountain block water - linear mixing model						
EC/Cl	100%	0%	4.0%	1.3%	11.6%	11.7%
SO ₄ /Cl	100%	0%	8.0%	11.9%	13.5%	8.2%
K/Cl	100%	0%	10.6%	10.7%	9.8%	10.4%
Ca/Cl	100%	0%	3.9%	5.9%	5.7%	2.7%
Mg/Cl	100%	0%	1.0%	1.3%	0.6%	0.3%
Avg	100%	0%	5.5%	6.2%	8.2%	6.6%

happen immediately upon the water reaching the surface (Keppel et al. 2012). Available regional chemical data included a MB spring water sample (MB002) and a nearby well in the GAB (well ID 6041-36; Fig. 4).

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 HNO₃ for cations and metals with no headspace in the sample bottles. The samples were cooled on ice in the field and transported to the laboratory where they were stored at 4 $^{\circ}\text{C}$, for storage in Australia. The samples were not refrigerated for 10 days while in transit from Australia to Oklahoma (USA) for analysis.

Temperature, electrical conductivity (EC), pH and dissolved oxygen (DO) were measured using a calibrated 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 geochemical 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 MB and GAB spring fluids were analyzed by the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Adelaide, South Australia.

Mixing model analyses

Geochemical data were input into mixing models to determine if the Freeling Spring Group was a mixture of MB water and GAB water or if they were 100% of one or the other. The data were normalized based on chloride

concentration due to evapotranspiration, as much of the spring system was vegetated (Table 1). Each molar concentration of each ion was normalized by dividing the concentration by the concentration of chloride to compensate for any evaporation that may have occurred. Modifying an equation to have the correct variables for the GAB from Genereux and Pringle (1997) and using the basic equation for a line, the following mixing model was applied to the geochemical data:

$$\%MB = \frac{C_n - C_{GAB}}{C_{MB} - C_{GAB}} \quad (1)$$

where % MB is the percentage the sample that is MB waters, 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_{MB} is the concentration of the variable for the MB sample.

Each ion was evaluated separately for mixing as the surface processes that may be affecting some data were not clear. A normalized EC was also evaluated, due to the conservative nature of chloride and the varying values for EC seen across the site using the ERI data (Uliana and Sharp 2001; Table 1). Other normalized parameters were tested for mixing percentages as well (Genereux and Pringle 1997). These analyses were attempting to confirm the geophysical results of a flowpath from the mountain block side of the fault (Fig. 5).

Results

Results of this study, including geophysical data (ERI), geochemical data (cations, anions, electrical conductance (EC) and temperature) and mixing models are reported in the following subsections. The geophysical results affect the interpretation of the chemical data and are presented first.

Fig. 5 ERI data for Freeling Springs with interpreted fluid flow directions. The location of Freeling Spring (EFS001) and the spring tail extent is shown. **a** PK345 ERI image showing resistivity values in the fault plane of the Kingston Fault. The conductive values in green from 5 to 15 Ω-m make up much of the data (interpreted as MB fluids), extending northward toward the additional springs in the complex. The more conductive fluids in the upper left are interpreted as GAB fluids heading towards Freeling spring from the Cadna-owie Formation. **b**

PK255 ERI image showing three prominent conductors in the image converging just east of Freeling Spring orthogonal to the fault plane. The least electrically conductive of these three features is on the west side of the fault. This inferred MB flow path contains fresher water than the GAB fluids, confirmed by geochemical data. The flowpaths on the right side represent inferred flow paths from the GAB inferred as fluids from the Algebuckina Sandstone (lower conductor) and the Cadna-owie Formation (upper conductor)

Electrical resistivity image (ERI) results

Survey line PK255 results

ERI survey line PK255 (Fig. 5b) 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 orthogonal to the Kingston Fault, apparent from the topography to the west and the flow of the spring tail to the east. West of the fault, the line runs along an east–west valley in the granite, and east of the fault, the line runs along the primary tail for Freeling Spring (EFS001). The west side of the Kingston Fault shows resistive zones ranging from 5 Ω -m (green in Fig. 5) to over 200 Ω -m (gray), with the majority of the granitic domain having a resistivity greater than 15 Ω -m. There is a conductive vertical feature on the west side of the fault ranging from 5 to 15 Ω -m (green), extending from the bottom of the domain approximately 100 m west of the fault to an area just east of the Freeling Spring vent. The feature mimics the pattern of the conductor between 15 and 100 Ω -m (orange) that extends from the edge of the dataset at 100 m laterally and angles upward towards Freeling Spring.

The east side of the fault over the GAB shows resistive zones ranging from 0.1 Ω -m (blue) to over 200 Ω -m (gray); with the majority of the east side having a resistivity less than 30 Ω -m. Two prominent conductive features are a 0.1–15 Ω -m resistive zone along the top of the east side of the fault, and one vertical feature coming from the bottom of the image approximately 100 m east of the fault. The trend of the conductive features mimics the pattern in the cross sectional interpretation of the site (Fig. 3). The tail of the spring corresponds with the strongest conductor (<5 Ω -m in blue) from the shallow lateral conductor.

Survey line PK345 results

ERI survey line PK345 (Fig. 5a) 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 0–15 Ω -m. Electrically conductive areas below 5 Ω -m 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. The 5–15 Ω -m (green) zone does complement the same zone beneath Freeling Spring in image PK255 with the same resistivity range.

Geochemical analysis results

The regional water sample for the Peake and Dennison Inliers MB sample (Spring 2: MB002) has an EC of 1,295 μ S/cm, a

chloride value of 4.2 mmol/L and a sodium value of 5.4 mmol/L (Table 1). The regional GAB is represented by a sample from the Centenary Well (6041-36) with an EC value of 3,971 μ S/cm, a chloride value of 27.9 mmol/L and sodium value of 35.9 mmol/L (Table 1). The water samples for the Freeling Spring Group have electrical conductivities ranging from 3,952 to 4,785 μ S/cm, chloride values ranging from 25.7 to 29.6 mmol/L and sodium values ranging from 34.8 to 41.4 mmol/L (Dailey 2001).

Mixing model analyses

The mixing models were analyzed for source water potential for the Freeling Spring Group (Table 1). The normalized EC model is detailed followed by the other mixing models.

Fluid conductivity mixing model

The MB spring sample has an EC value of 1,295 μ S/cm, while the GAB well EC value is 3,971 μ S/cm and the Freeling Spring Group samples range from 3,952 to 4,785 μ S/cm (Table 1). The Freeling Spring Group samples' EC mixing-model values range from 1.3 to 11.7% MB fluids (88.3–98.7% GAB fluids). The model indicates that the mixing percentage increases to the north of the primary spring vent, consistent with the lack of a high bulk electrical conductivity (low bulk resistivity <5 Ω -m) path to the north in the ERI data (Fig. 5a).

Other mixing models

Other parameters used to evaluate mixing often include sodium, but normalized sodium parameters were identical across the springs and they all had higher than normalized sodium values at the endmember locations. Thus, they are not used for the analysis. The other parameters indicated between 0.3 and 13.5% MB fluids exiting from the springs. Normalized potassium provides the smallest variability in mixing estimates with an average estimate of 10.4% MB waters (89.6% GAB waters) exiting the springs (Table 1). The average of all models is 6.7% MB fluids exiting the springs, or 93.4% GAB waters. The average values increased from the primary vent similar to what was seen in the fluid conductivity mixing model implying that MB water was migrating north to the east of the fault.

Discussion

ERI

Relative to literature values for unsaturated rocks, resistivity values are lower than expected over the Freeling Spring Group (Eberhart-Phillips et al. 1995). Over 50% of the dataset have resistivity values under 15 Ω -m, which are interpreted as

the result of fresh to brackish fluids in the underlying formations. This is based on the comparison between the measured fluid EC values at the springs along the ERI lines, and ERI bulk resistivity at those locations. The west side of the Kingston Fault over the Wirriecurrie Granite (MB) would be expected to have resistivity values exceeding 1,000 Ω -m if no significant fluid were present and the rock was unfractured (Palacky 1987; Fig. 5b). The mean value is less than 500 Ω -m which is interpreted as evidence for the presence of fluids in fractures in the granite. The east side of the images over the GAB is predominately under 15 Ω -m, this implies the sandstone is fully saturated with fresh to brackish fluid.

PK255

ERI survey line PK255 (Fig. 5b) may be inferred as basement rocks (MB) on the west side of Kingston Fault and the GAB (saturated sandstone) on the east side. PK255 is interpreted as demonstrating three fluid flow paths coming from depth (marked with arrows), one from the MB (5–15 Ω -m vertical green feature) and two from the GAB (1–15 Ω -m vertical and horizontal blue and green features) discharging at Freeling Spring (Fig. 5b). The 5–15 Ω -m vertical conductor to the west of the fault starts approximately 100 m to the west of the fault at the bottom of the dataset and has a distinct curve at an elevation of approximately 0 m relative to the Australian Height datum (AHD) when it heads nearly vertically in the image. As the Kingston Fault is thought to be near vertical, this is interpreted to be a MB flowpath instead of a feature of the fault damage in the rock body. The similar pattern of the conductive feature to the conductive (orange) and resistive (gray) trends on the west side of the fault suggest that the conductive trend is following the pattern of the rest of the rock body. As the zone is in an area of known deformation, this could be a folding pattern or other pattern in the lithology, but no drilling data are available to test the dataset further. The correlation between the interpreted MB flowpath and the granitic portions of the dataset as well as the correlation with the same range of resistivity in PK345 in the fault zone suggest a distinct conductive signal of fluid migration as opposed to a noise feature or simply part of the Kingston Fault damage zone.

Based on geological mapping of the area, the less resistive (blue) values centered at approximately 75 m AHD of the east side of PK255 may be inferred to be the Cadna-owie Formation (GAB) aquifer flowing to Freeling Spring beneath the spring tail. The lower fluid path on the east side of the Kingston Fault may be inferred to be generated by the fluids of the Algebuckina Sandstone (GAB; Fig. 5b). The uppermost layer in the shallow surface east of the Kingston Fault is interpreted as fractured Bulldog Shale or alluvium that has fluids moving upward similar to imaging conducted on other springs exiting the Bulldog Shale (Halihan et al. 2013).

PK345

ERI survey line PK345 (Fig. 5a) along the Kingston Fault does not have ERI values normally associated with an undeformed granite. The values seen under the fault imply the electrical properties of the fault is dominated by fluid signatures. This helps support the idea of water coming up from depth along the fault zone and discharging along the surface. The more resistive fluids at the 5–15- Ω -m range are inferred to come from the MB system as it coincides with the values in the perpendicular line at PK255. The shallower more conductive features below 5 Ω -m are interpreted as fluids from the GAB Cadna-owie sandstone (Fig. 5a). If drilling were possible in this area, a borehole into the fault or to the west of the fault would assist in strengthening the interpretation.

Mixing models and geochemical analysis

The mixing models show the Freeling Spring Group samples lie between the MB and the GAB samples with a small noticeable contribution from the MB system. These data would suggest MB water is coming to the fault from the Wirriecurrie Granite and feeding the springs along the fault and on the travertine platform in the Freeling Spring tail. This also suggests the GAB provides the most influential water sources on the springs but they are likely influenced by contributions from MB water. If this influence was greater in the past, it may be the cause of the siting of the telegraph station on the site in 1870 compared with other potential more brackish spring locations. Additional monitoring of the springs over time may also provide insight over mixing percentages over time.

Due to the remote site location, the choice of endmember water samples is limited. The authors have a range of experience in the area to select locations that appeared representative of the respective aquifer while being located as close as possible to the springs. Other investigations of springs in the area found degassing to strongly affect chemistry with an increase in pH and a decrease in alkalinity (Keppel et al. 2012). While this study's results see this increase in pH, a strong decrease in alkalinity in the samples is not evident. While the system is called a spring group, there is also uncertainty as to whether the vents that were sampled were all related to each other on a single subsurface flowpath. Additionally, the vent locations were commonly vegetated, and finding the exact vent from the groundwater system has uncertainty. Subsurface investigations using borings would aid at improving the understanding of the springs, but cultural factors limit this approach.

Although the geophysical and geochemical methods agree that multiple waters are exiting the Freeling Spring Group, it is difficult to interpret more than two waters contributing to the spring in the chemical data. The chemical mixing models show a clear contribution of MB fluid exiting the spring group, in agreement with the ERI data showing a more

electrically conductive interpreted pathway leading to the Kingston Fault from the west in PK255 relative to two conductors east of the fault in the GAB leading up to Freeling Spring (Fig. 5b). One consistent interpretation is that the two electrically conductive pathways to the east are the two distinct layers in the GAB: the lower Algebuckina Sandstone and the upper Cadna-owie Formation (Fig. 5b). These electrical conductors, possibly having two distinct chemistries, could be mixing in proportions not seen in the regional GAB samples used for the mixing model evaluation. So while the chemistry data have some scatter but indicate a fluid mixing at the springs from the MB waters, the geophysical data suggest the major GAB fluid contribution comes from two fluids of different conductances and thus somewhat varying chemistry. This interpretation appears to satisfy all of the datasets, and illustrates why the chemical analysis can determine that at least two waters are mixing while the geophysical data indicate three waters are actually mixing at the springs.

Considering the remote location and the required sampling limitations at the site, further investigation was not possible at this time. Further clarification of the chemistry could be achieved with targeted borings on both sides of the fault in an effort to obtain independent samples of the three potential water sources to the spring. This could eliminate the issue of mixed and/or reacted chemical samples caused by evaporative processes, microbial processes, precipitation of minerals, and potential reactions caused by the vegetation at the spring vents (Keppel et al. 2012). Lithologic analysis of new borings and additional seismic data could provide further information on the fault structure controlling the location of the springs and the mixing processes that are interpreted. While this additional data would provide more insight into the mixing process, the historical use of the site and the existing hydrogeologic, geophysical, and geochemical datasets still indicate that mixing of fresher waters from the MB side of the fault have an influence on the springs.

Conclusions

The Freeling Spring Group offers a unique, although remote, study site which allows an evaluation of the boundary of two aquifers of differing lithologies, fluids from the Peake and Dennison Inliers MB aquifer, and fluids from the Great Artesian Basin aquifer. This boundary, the Kingston Fault, is apparent in electrical resistivity images and is supported by the geochemical signatures of local and regional waters. The ERI results indicate converging waters with potentially three waters mixing under and around Freeling Spring. Geochemical analysis results, including simple mixing models, indicate at least two distinct water types around the Freeling Spring Group.

Geological mapping, vegetation, geochemical analysis and ERI all provide evidence of flow along the fault. The location

of the fault is easily recognizable. The ERI data indicate there are fluids flowing in the fault, as the majority of the fault is underlain by low resistivity values associated with rock saturated by fresh to brackish waters in the fault plane and the orthogonal dataset illustrates a completely different electrical geometry. The geochemical signatures of Freeling Spring directly over the fault indicate that the spring is a mixture of approximately 10% MB and 90% GAB waters, and therefore not entirely fed by the GAB.

The MB waters influence the springs in the group, including springs east of the Kingston Fault. What is uncertain is whether that the balance changes significantly over time, as the MB aquifer has a higher topography and a history of settlement around these springs in the past. While it is difficult to determine if the system was fresher during the 1800s, additional investigations may determine how much the relative contributions of each aquifer may vary over time.

Acknowledgements Dr. Eliot Atekwana and CSIRO is thanked for geochemical data.

Funding information The authors wish to thank the Australian National Water Commission, Flinders University, and Oklahoma State University for funding.

Compliance with ethical standards

Conflict of interest It is here noted that Dr. Halihan has a managed conflict of interest with regard to ERI developments.

Open Access This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (<http://creativecommons.org/licenses/by/4.0/>), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

References

- Aldam R, Kuang KS (1988) An investigation of structures controlling discharge of spring waters in the South Western GAB. Department of Mines and Energy, Adelaide, South Australia
- Aldam R, Kuang KS (1989) An investigation of structures controlling natural discharge of artesian waters in the southwestern Great Artesian Basin. *Q Geol Notes South Aust* 109:2–9
- Crossey LJ, Fischer TP, Patchett PJ, Karlstrom KE, Hilton DR, Newell DL, Huntoon P, Reynolds AC, De Leeuw GA (2006) Dissected hydrologic system at the Grand Canyon: interaction between deeply derived fluids and plateau aquifer waters in modern springs and travertine. *Geology* 34(1):25–28. <https://doi.org/10.1130/G22057.1>
- Dailey MK (2001) Hydrogeophysical evidence for ground water mixing at Freeling Spring Group, South Australia, MSc Thesis, Oklahoma State University, Stillwater, OK
- Doctor DH, Alexander EC Jr, Petrič M, Kogovšek J, Urbanc J, Lojen S, Stichler W (2006) Quantification of karst aquifer discharge components during storm events through end-member mixing analysis

- using natural chemistry and stable isotopes as tracers. *Hydrogeol J* 14(7):1171–1191. <https://doi.org/10.1007/s10040-006-0031-6>
- Eberhart-Phillips D, Stanley WD, Rodriguez BD, Lutter WJ (1995) Surface seismic and electrical methods to detect fluids related to faulting. *J Geophys Res* 100(B7):12919–12936
- Fensham R, Fairfax RJ, Ponder WF (2005) Recovery plan for ‘The community of native species dependent on natural discharge of groundwater from the Great Artesian Basin 2006–2010’. Australian Government, Canberra
- Gary MO (2010) Karst hydrogeology and speleogenesis of Sistema Zacatón, Tamaulipas, Mexico. PhD Thesis, University of Texas, Austin, TX, 114 pp. AMCS Bull 21, Association for Mexican Cave Studies, Austin, TX
- Genereux D, Pringle C (1997) Chemical mixing model of streamflow generation at La Selva Biological Station, Costa Rica. *J Hydrol* 199:319–330. [https://doi.org/10.1016/S0022-1694\(96\)03333-1](https://doi.org/10.1016/S0022-1694(96)03333-1)
- Greenslade J, Joseph L, Reeves A (eds) (1985) South Australia’s Mound Springs. Nature Conservation Society of South Australia, Adelaide
- Habermehl MA (1980) The Great Artesian Basin, Australia. *BMR J Geol Geophys* 5:29
- Habermehl MA (1986) Regional groundwater movement, hydrochemistry and hydrocarbon migration in the Eromanga Basin. In: Gravestock DI, Moore PS, Pitt GM (eds) Contributions to the geology and hydrocarbon potential of the Eromanga Basin. Geological Society of Australia, Hornsby, NSW, pp 353–376
- Halihan T, Love A, Keppel M, Berens V (2013) Analysis of subsurface mound spring connectivity in shale of the western margin of the Great Artesian Basin, South Australia. *Hydrogeol J* 21(7):1605–1617. <https://doi.org/10.1007/s10040-013-1034-8>
- Harvey FE, Ayers JF, Gosselin DC (2007) Ground water dependence of endangered ecosystems: Nebraska’s eastern saline wetlands. *Papers in Natural Resources* 131. <https://www.ncbi.nlm.nih.gov/pubmed/17973752>. Accessed November 2019
- Karlstrom KE, Keppel MN, Love AJ, Crossey L (2013) Structural and tectonic history, chap 4. In: Keppel MN, Love AJ, Karlstrom KE, Priestley S (eds) Hydrogeological framework of the western margin of the Great Artesian Basin, Australia. National Water Commission, Canberra
- Keppel MN (2013) The geology and hydrochemistry of calcareous mound spring wetland environments in the Lake Eyre South region, Great Artesian Basin, South Australia. PhD Thesis, Flinders University, Adelaide, South Australia
- Keppel MN, Clarke JDA, Halihan T, Love AJ, Werner AD (2011) Mound Springs in the arid Lake Eyre south region of South Australia: a new depositional tufa model and its controls. *Sediment Geol.* <https://doi.org/10.1016/j.sedgeo.2011.08.001>
- Keppel MN, Post VEA, Love AJ, Clarke JDA, Werner AD (2012) Influences on the carbonate hydrochemistry of mound spring environments, Lake Eyre south region, South Australia. *Chem Geol.* <https://doi.org/10.1016/j.chemgeo.2011.12.017>
- Keppel MN, Karlstrom K, Crossey L, Love AJ, Priestley S (2019) Evidence for intra-plate seismicity from spring-carbonate mound springs in the Kati Thanda–Lake Eyre region, South Australia: implications for groundwater discharge from the Great Artesian Basin. *Hydrogeol J.* <https://doi.org/10.1007/s10040-019-02049-1>
- Love AJ, Wohling D, Fulton S, Rousseau-Gueutin P, DeRitter S (eds) (2013) Allocating water and maintaining springs in the Great Artesian Basin, vol II: groundwater recharge, hydrodynamics and hydrochemistry of the Western Great Artesian Basin. National Water Commission, Canberra
- Lyons WB, Tyler SW, Gaudette HE, Long DT (1995) The use of strontium isotopes in determining groundwater mixing and brine fingering in a playa spring zone, Lake Tyrrell, Australia. *J Hydrol* 167(1):225–239. [https://doi.org/10.1016/0022-1694\(94\)02601-7](https://doi.org/10.1016/0022-1694(94)02601-7)
- Moore PJ, Martin JB, Screation EJ (2009) Geochemical and statistical evidence of recharge, mixing, and controls on spring discharge in an eogenetic karst aquifer. *J Hydrol* 376(3):443–455. <https://doi.org/10.1016/j.jhydrol.2009.07.052>
- Palacky GL (1987) Resistivity characteristics of geologic targets. In: Nabighian MN (ed) Electromagnetic methods in applied geophysics: theory, vol 1. SEG, Tulsa, OK, pp 53–129
- Petitta M, Caschetto M, Galassi DM, Aravena R (2015) Dual-flow in karst aquifers toward a steady discharge spring (Presciano, central Italy): influences on a subsurface groundwater dependent ecosystem and on changes related to post-earthquake hydrodynamics. *Environ Earth Sci* 73(6):2609–2625. <https://doi.org/10.1007/s12665-014-3440-1>
- Plummer LN, Busenberg E, Böhlke JK, Nelms DL, Michel RL, Schlosser P (2001) Groundwater residence times in Shenandoah National Park, Blue Ridge Mountains, Virginia, USA: a multi-tracer approach. *Chem Geol* 179(1):93–111. [https://doi.org/10.1016/S0009-2541\(01\)00317-5](https://doi.org/10.1016/S0009-2541(01)00317-5)
- Ponder WF (2002) Desert Springs of the Australian Great Artesian Basin. In: Sada DW, Sharpe SE (eds) Spring-fed wetlands: important scientific and cultural resources of the Intermountain Region, Las Vegas, USA. In: Conference proceedings, Las Vegas, NV, May 2002, DHS Publ. 41210, Desert Research Institute, Reno, NV
- Povinec PP, Aggarwal PK, Aureli A, Burnett WC, Kontar EA, Kulkarni KM, Moore WS, Rajar R, Taniguchi M, Comanducci JF, Cusimano G (2006) Characterisation of submarine groundwater discharge offshore south-eastern Sicily. *J Environ Radioact* 89(1):81–101. <https://doi.org/10.1016/j.jenvrad.2006.03.008>
- Rogers PA, Freeman PJ (1996) Explanatory notes for the Warrina geological map. Department of Mines and Energy, Adelaide, South Australia
- Sampson L, Wohling D, Jensen-Schmidt B, Fulton S (2012) South Australia and Northern Territory Great Artesian Basin (Eromanga Basin) hydrogeological map, part 2. Department of Environment, Water and Natural Resources, South Australian Government, Adelaide
- Uliana MM, Sharp JM (2001) Tracing regional flow paths to major springs in Trans-Pecos Texas using geochemical data and geochemical models. *Chem Geol* 179:53–72. [https://doi.org/10.1016/S0009-2541\(01\)00315-1](https://doi.org/10.1016/S0009-2541(01)00315-1)
- Wang Y, Guo Q, Su C, Ma T (2006) Strontium isotope characterization and major ion geochemistry of karst water flow, Shentou, northern China. *J Hydrol* 328(3):592–603. <https://doi.org/10.1016/j.jhydrol.2006.01.006>