

DWLBC REPORT

Hydrogeophysical mapping
of fracture orientation and
groundwater flow in the
Eastern Mount Lofty
Ranges, South Australia
2009/09



Government of South Australia

Department of Water, Land and
Biodiversity Conservation

Hydrogeophysical mapping of fracture orientation and groundwater flow in the Eastern Mount Lofty Ranges, South Australia

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**Science, Monitoring and Information Division
Department of Water, Land and Biodiversity Conservation**

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Biodiversity Conservation



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FOREWORD



South Australia's unique and precious natural resources are fundamental to the economic and social wellbeing of the State. It is critical that these resources are managed in a sustainable manner to safeguard them both for current users and for future generations.

The Department of Water, Land and Biodiversity Conservation (DWLBC) strives to ensure that our natural resources are managed so that they are available for all users, including the environment.

In order for us to best manage these natural resources it is imperative that we have a sound knowledge of their condition and how they are likely to respond to management changes. DWLBC scientific and technical staff continues to improve this knowledge through undertaking investigations, technical reviews and resource modelling.

Scott Ashby
CHIEF EXECUTIVE
DEPARTMENT OF WATER, LAND AND BIODIVERSITY CONSERVATION

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SUMMARY

Fractured rock aquifers are becoming increasingly important water supplies as traditional sedimentary aquifers become more fully utilised. Characterisation of groundwater flow in fractured rocks is difficult as hydraulically conductive fractures are inherently complex and often unpredictable. As fractures act as conduits for flow of both groundwater and electrical charge, methods that can efficiently detect the distribution of electrical pathways may be used to infer characteristics of significant hydrological parameters.

Electrical data from direct current borehole-to-surface and self-potential measurements were used for the interpretation of major hydrological structures at 21 sites in the Eastern Mount Lofty Ranges, South Australia. Application of borehole-to-surface methods generated an interpretation of sub-vertical fracture strike and dip. The natural-voltage self-potential signals generated during pumping tests are of a complex nature, but, the magnitude of changes in the electrokinetic measurement can be attributed to fluid flow rates and yield the dominant direction of groundwater flow.

Borehole-to-surface measurements at the majority of sites showed a dominant trend of conductive zones with a fracture strike of north to north-east which are consistent with major regional structural trends.

Electrokinetic measurements are highly variable in the region with large (up to 60 mV) variations with time. Although self-potential is a relatively new technique, a combination of the two electrical methods provides valuable information about in-situ hydraulic pathways and leads to a greater understanding of the subsurface flow in fractured rock aquifers.

1. INTRODUCTION

1.1 PURPOSE

This work is part of a larger Australian Government Water Fund project intended to further the understanding of groundwater flow mechanisms in fractured rock aquifers (FRAs) to improve water resource management decisions.

It is anticipated that the project will be comprised of four key components, each representing areas with significant knowledge gaps and requiring further investigation. These are as follows:

- Surface water–groundwater interaction and the implications for conjunctive use of the resource
- Extent of the zones of influence from pumped wells
- Groundwater movement across regional scale faults and
- Predicting catchment scale processes in a fractured rock environment.

While the project spans these four key areas of study the focus of this report is on the extent of the zones of influence from pumped wells in the Eastern Mount Lofty Ranges (EMLR) (Program 2).

Methods and technologies proposed in this project are considered innovative or non-traditional, as they have not previously been applied to investigations of processes occurring in fractured rock systems. As such, the approach adopted in this project intends to address many of these issues and knowledge gaps which have not previously been approached with such scientific rigor.

1.2 THE STUDY AREA

The Mount Lofty Ranges are the range of mountains to the east of the city of Adelaide in South Australia. They stretch from the southern most point of the Fleurieu Peninsula at Cape Jervis and extend northwards for over 300 kilometres before petering out north of the southern Flinders Ranges. In the vicinity of Adelaide, they separate the Adelaide Plains from the extensive plains that surround the Murray River and stretch eastwards to Victoria.

The Eastern Mount Lofty Ranges (EMLR) Prescribed Water Resource Area (PWRA) occupies an area of 2845 km² on the eastern side of the Mount Lofty Ranges (Fig. 1). It incorporates the eastern slopes of the Mount Lofty Ranges and the Murray Plains, extending from the Currency Creek catchment in the south to the Milendella Creek catchment in the north.

There are thirteen catchments within the EMLR PWRA, which drain into the River Murray and Lake Alexandrina. The water resources of the EMLR PWRA support agricultural and industrial and mining activity but increasing demands on water resources could have a detrimental impact on long-term water use and the environment. Although monitoring to date has generally shown no adverse impacts on the groundwater resource, there are several risks associated with further uncontrolled development in these areas. These include

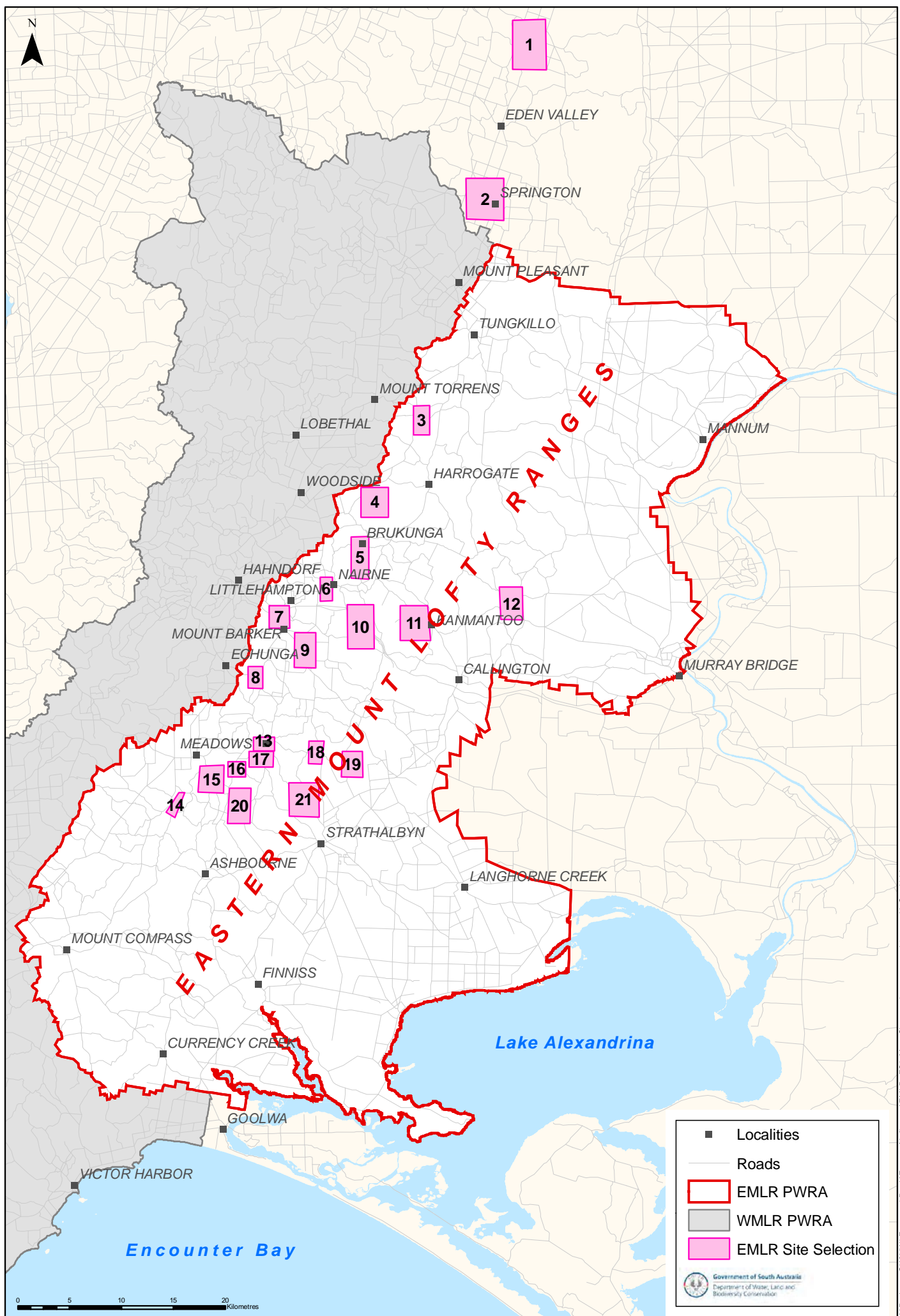


Figure 1. Site selection across the Eastern Mount Lofty Ranges

a decline in watertables and increases in salinity due to the lateral movement of more saline groundwater from surrounding areas. Consequently, there has been a recent focus on investigations into the availability and quality of water supplies, which are highly variable in the area (Zulfic and Barnett 2003).

Data presented in this program were collected at 21 sites across the EMLR (Fig. 1). Site selection was based on lithological variations, position within the regional structure, and accessibility of wells (Table 1). The sites span over 50 kilometres of the EMLR, from Eden Valley in the north to Strathalbyn in the south.

Surveys were also undertaken at sites near Balhannah in the Western Mount Lofty Ranges (WMLR) and the Clare Valley. The information was used to calibrate the hydrogeophysical methods against known hydrogeological parameters.

1.3 BACKGROUND

Fractured rock aquifers (FRAs) underlie approximately 40% of the Australian continent and are becoming increasingly important water supplies as traditional sedimentary aquifers (porous media) are becoming fully utilised (Cook et al. 2001). Despite their importance, it is extremely difficult to quantify the bulk properties controlling fluid transport through fractured rock.

Currently management of well interference in FRAs utilises buffer zones that assume a circular zone of influence around a pumped well. Due to the heterogeneous nature of FRAs the true zones of influence are more likely to be elliptical and controlled by regional fracture systems (Fig. 2).

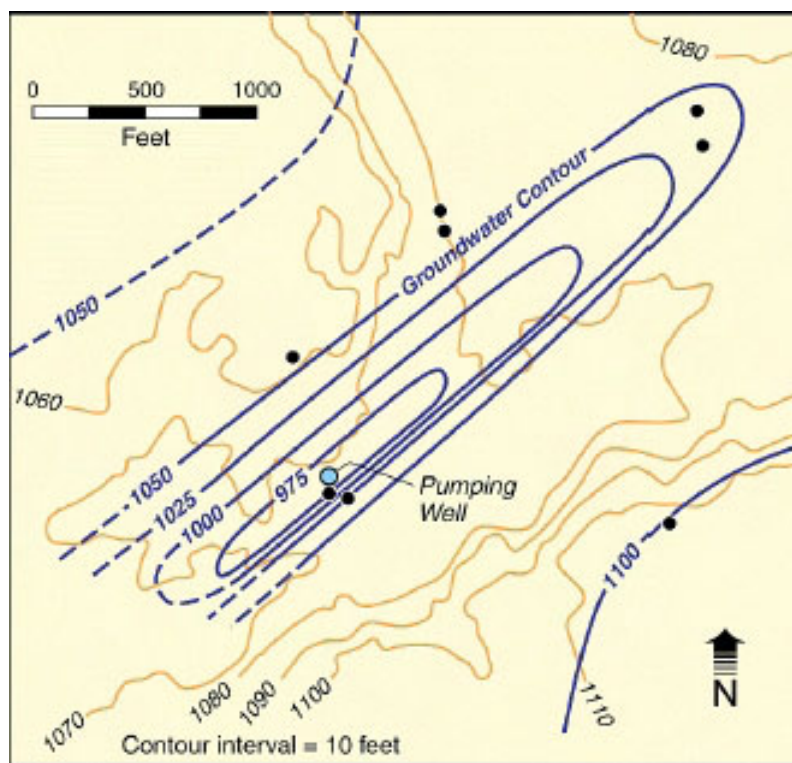


Figure 2. Typical groundwater contours for an aquifer test in fractured rock (Cook 2003).

Geophysical techniques (resistivity and self-potential) have been used previously to delineate groundwater flow paths under pumped conditions. These techniques can also be used to estimate the extent of elliptical zones of influence.

Variations in the zones will be dependent on:

- Location within regional structure (i.e. hinge vs. limb)
- Lithology – control on fracture spacing and aperture
- Extraction rate.

Analysis of data provided from detailed mapping and geophysical surveys would indicate any correlations between these parameters.

The Department of Water, Land and Biodiversity Conservation (DWLBC) has completed several investigations throughout the EMLR in order to provide technical advice for the impending Water Allocation Plans.

This program (Program 2) will be incorporated into a wider project that will result in an increased understanding of groundwater flow mechanisms and surface water–groundwater interactions at local and regional scales. As a result, improved management strategies for fractured rock environments will be implemented. The techniques used and outcomes obtained from this project will also contribute significantly to water resource management strategies at national levels.

2. HYDROGEOLOGY

2.1 GEOLOGY

The EMLR forms part of the larger Adelaide Geosyncline, which is underlain by consolidated basement rocks beneath the hills, and overlain by unconsolidated sediments beneath the Murray Plains (Zulfic and Barnett 2003).

The Adelaide Geosyncline is a failed continental rift valley that is exposed as ranges extending from Kangaroo Island in the south to Freeling Heights in the north of South Australia. Tectonism during the Cambro–Ordovician Delamerian Orogeny caused folding and faulting and subjected the original sediments to low-grade metamorphism (Smit 2007).

The Adelaidean Umberatana, Wilpena and Burra Groups, the Cambrian Kanmantoo Group and the Permian Normanville Group dominate the geology of the area.

The regional geology is characterised by a north-south trending, south plunging anticlinal-synclinal fold pair. The majority of faults in the EMLR trend north-east to south-west (Smit 2007).

2.1.1 HYDROGEOLOGY

Groundwater in the catchments of the EMLR is sourced from two different types of aquifers; fractured rock and sedimentary aquifers (Zulfic and Barnett 2003). Fractured rock aquifers occur where groundwater is stored and moves primarily through joints and fractures in the basement rocks. Sedimentary aquifers occur in the valleys and beneath the Murray Plains where groundwater flows through the pore spaces within the sediments.

Groundwater moves from the higher points in the landscape towards the lowest areas where discharge normally occurs through the sedimentary aquifers in the valleys to the streams. Recharge to both these aquifers occurs from rainfall, which percolates down to the watertable through the soil profile.

The major freshwater streams that flow from the EMLR into the River Murray include the Marne River and Reedy Creek and their tributary streams (Zulfic and Barnett 2003). Other streams include Burra, Truro, Saunders, Preamimma, Salt and Mitchell Creeks, and the Dry Creek–Rocky Gully system. Most of these are typically quite saline and do not persist as surface streams, therefore, contributing little water into the River Murray.

The other streams in the region are those that flow into Lake Alexandrina, including the Bremer River system which includes Dawesley, Nairne and Mt Barker Creeks, the Finniss River which includes Meadows, Tookayerta and Nangkita Creeks, and Currency Creek.

Mean annual rainfall in the area is estimated to be 500–800 mm/year and is highly variable, ranging from 1600 mm/year near the summit of Mount Lofty to less than 300 mm/year in the Monarto area. Typically the majority of the rainfall descends within a four-month period over winter and there are prolonged dry spells during the 2–3 months over summer.

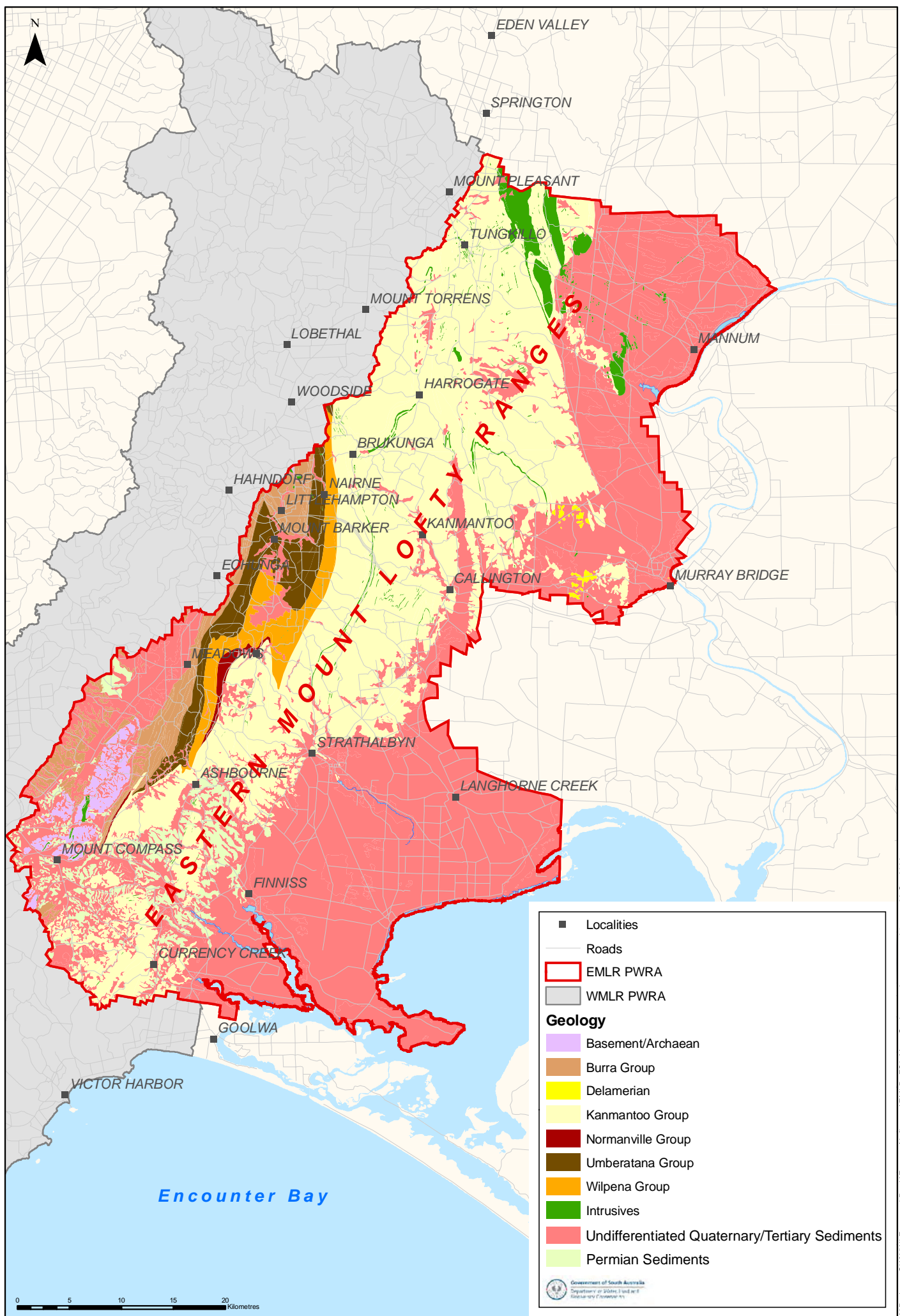


Figure 3. Geology of the Eastern Mount Lofty Ranges

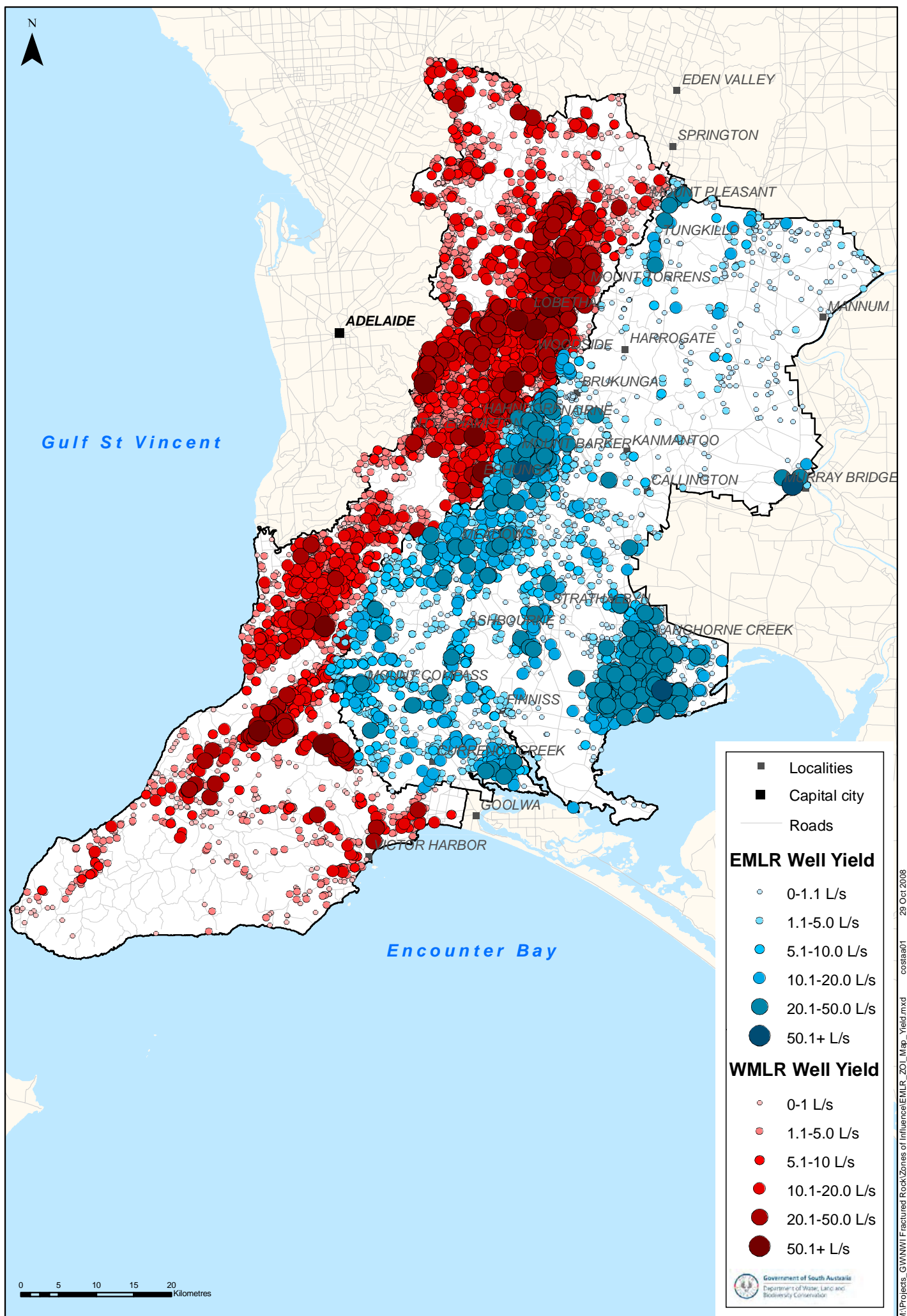


Figure 4. Well yield in the Mount Lofty Ranges, South Australia

Catchments contain groundwater of varying quality and yields. About 75% of the area is underlain by poor aquifers with salinities too high (greater than 3000 mg/L), and yields too low for irrigation (below 5 L/s).

Salinity in the area varies from less than 300 mg/L to greater than 10,000 mg/L, with lower salinities associated with areas of higher rainfall and topography.

Aquifer yields and salinities are more favourable for development in the western and southern parts of the EMLR than in the east due to the presence of the permeable Adelaidean fractured rocks and Permian sands, together with the higher rainfall (Fig. 4).

2.1.2 FRACTURED ROCK AQUIFERS

In fractured rock systems, groundwater fills voids formed by fractures, fissures, faults and joint planes, which are invariably unevenly distributed within the rock formation. Due to their nature they present unique problems in their investigation, evaluation and management, largely because of their heterogeneous nature, and the dependence of aquifer properties on fracture distribution, connectivity and extent.

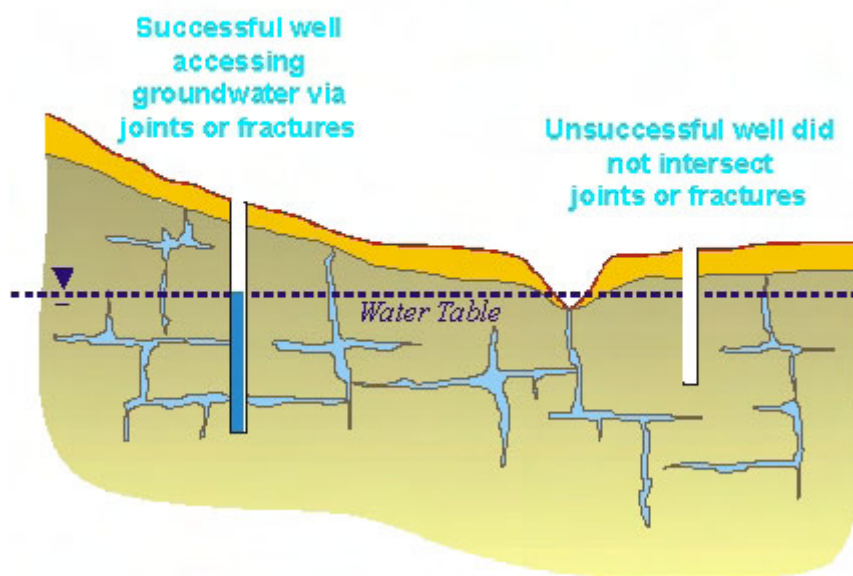


Figure 5. Groundwater wells in a fractured rock environment

Fractured rock aquifers are characterised by high spatial variability in hydraulic conductivity, making traditional hydraulic methods for estimating groundwater flow difficult to apply. Despite the importance of fractured rock aquifers, there is a lack of available knowledge of groundwater processes within these systems, and hence, there is a great need to develop techniques to better characterise hydraulic properties.

3. METHODOLOGY

3.1 BACKGROUND THEORY

Due to the current lack of understanding, management practices for groundwater in fractured rock environments adopt a precautionary approach. The approach currently used is similar to that of traditional sedimentary aquifers.

Water extraction from any well will form an associated cone of depression around the well (Fig. 6). This cone of depression will map out a circle (or zone of influence) on the surface and any neighbouring well that is constructed within this zone will have its water level affected by the extraction. This is called well interference.

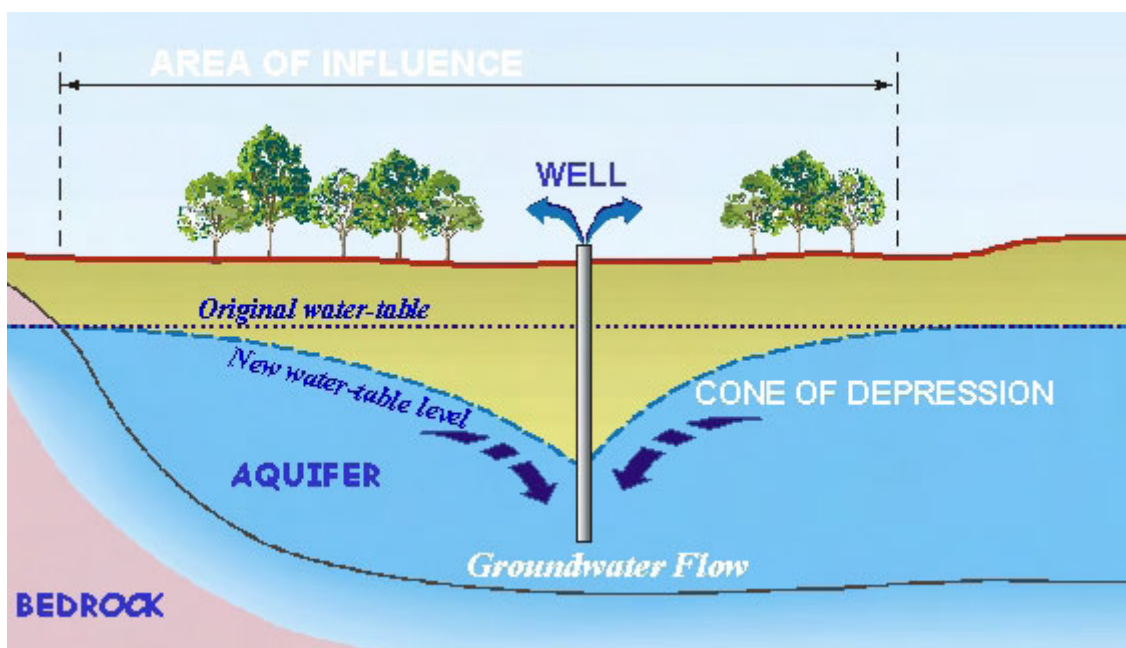


Figure 6. Illustration of a well and its area of influence

At present management of well interference in fractured rock environments has commonly utilised these circular zones of influence typically associated with sedimentary aquifers. However due to the heterogeneous nature of fractured rock aquifers, the zones of influence are more likely to be elliptical and controlled by regional fracture systems. Improving correlations between geology and the spatial extent and distribution of zones of influence would potentially provide a more accurate and predictive management tool than is currently available and could in theory be applied anywhere in a fractured rock environment.

As discussed in the previous section (illustrated by Fig. 2), groundwater flow in a fractured rock environment is influenced by the fracture network. The geometry of the fractures results in a hydraulic anisotropy such that groundwater extraction produces a drawdown cone that is not radially uniform.

The preferential strike orientation of fracture sets cause the rock to be both electrically and hydraulically anisotropic, and the variation in the size and opening of fractures causes additional heterogeneity. Groundwater will tend to flow along these preferential flow paths at rates that may be several orders of magnitude greater than for directions perpendicular to it. Therefore the zone of influence is no longer circular but rather elliptical in shape.

To quantify fractured aquifer properties, a relationship must be found between fluid transport and some other measurable property, such as electrical resistivity (Freeze and Cherry 1979; Brown 1989; Sahimi 1995). The electrical resistivity of rocks depends on several factors including the presence of conductive minerals such as base metal sulphides or oxides and graphite in the rock. Most rocks without these minerals are usually poor conductors and their resistivity is governed primarily by their porosity, degree of fracturing, salinity of pore water and the degree of saturation of the pore spaces (Cook et al. 2001).

As fractures act as conduits for flow of both groundwater and electrical charge, methods that can efficiently detect the distribution of electrical pathways may be used to infer characteristics of significant hydrological parameters (Brown 1989). Geophysical methods used to detect the electrical conductivity are typically fast, repeatable, relatively low-cost and non-intrusive, thus making them a practical alternative to traditional approaches (Skinner and Heinson 2004).

Electrical methods have been used to successfully monitor groundwater occurrence within fractured rock and have provided information on fluid electrical conductivity, fracture orientation and the overall bulk porosity (Dailey et al. 1992; Slater et al. 1996; Skinner and Heinson 2004; Adepelumi et al. 2006; Batayneh 2006; Weiss et al. 2006). Fracture characterisation and understanding fluid flow in fractured environments is not only crucial to monitoring groundwater resources in FRAs but has also been used for:

- Geothermal applications (Robinson and Tester 1984; Fehler 1989; Block et al. 1994)
- Hazardous waste disposal (Davies et al. 1991; Robinson et al. 1993)
- Predicting the movement of contaminants (Nicholas and Healy 1988; Shapiro and Hsieh 1991; Benson et al. 1997), and
- Mapping of conductive plumes (Nimmer et al. 2007).

An alternative geophysical approach that is often more closely coupled to the groundwater flow field is to measure the electrical potential occurring naturally on the ground surface, known as the self-potential (SP). The main sources of SP are diffusive charge separation due to difference in mobility between ions in solution, electrical energy produced from redox reactions around ore bodies and buried metallic objects and charge separation as a result of fluid flow (Sato and Mooney 1960; Sill 1983; Revil et al. 1999; Wishart et al. 2006). This latter electrokinetic process involves the movement of water through porous or fractured rock media which generates an electric potential gradient, sometimes known as streaming potential (Revil et al. 1999; Fagerlund and Heinson 2003; Sheffer and Oldenburg 2007). Self potential has the advantage that it is minimally intrusive and that the hydrological system is not perturbed by the presence of the boreholes, as is the case for borehole-to-surface electrical methods. The method is also very cheap as it requires only simple apparatus that is quick to deploy.

Streaming potentials have been used in many applications including earthquake prediction (Jouniaux and Pozzi 1995), geothermal exploration (Corwin and Hoover 1979; Sill 1983; Ishido and Pritchett 1999) and hydrogeological investigations (Fagerlund and Heinson 2003; Rizzo et al. 2004; Wishart et al. 2006). In addition, Wishart et al. (2006) demonstrated the potential benefits of combining the self potential method with resistivity surveys to improve characterisation of hydraulically-conductive fractures in tight rocks.

This program reports on the capabilities of direct current (DC) borehole-to-surface and self-potential techniques for the interpretation of hydrogeological processes and, in particular, to delineate groundwater flow paths under pumped conditions in fractured rock aquifers.

3.2 GEOPHYSICAL TECHNIQUES

3.2.1 BOREHOLE-TO-SURFACE DC RESISTIVITY METHOD

For most surface characterisation techniques, overburden introduces difficulties because of its attenuation properties and the high contrast in its properties compared to the underlying rock. Methods that place a source and/or receiver in a borehole and in direct contact with groundwater can reduce these limitations. These can however be more costly than comparable surface surveys due to higher drilling and measurement costs (Karasaki et al. 2000).

Geophysical borehole methods are used in several approaches including electrical (Dailey et al. 1992; Slater et al. 1996; Johnson et al., 2002), radar (Stevens et al. 1995) and seismic (Majer et al. 1997).

The borehole-to-surface DC resistivity technique involves placing a current source electrode down a borehole below the watertable and completing the circuit with a current sink electrode at a distance far enough away to be considered infinity (Skinner and Heinson 2004). In practise this current sink should be a minimum of 200 m away.

Current from the down-hole point source electrode will flow radially away from the electrode within a homogenous, isotropic medium. Equipotential surfaces (surfaces of equal voltage) are spherically symmetrical around the current electrode and decrease with distance away from the current source. When the medium is heterogeneous and anisotropic, electrically conductive fractures in the vicinity of the current source will distort the potential field.

Deviations from the spherical equipotential surfaces can be measured between a reference electrode and potential electrodes on the surface. The distortion of the field around electrically conductive features produces a phenomenon known as the *paradox of resistivity anisotropy*. Measured maximum observed apparent resistivity (ρ_a) is parallel to the principal direction of fracture strike and the maximum true resistivity (ρ) is perpendicular to the principal direction of fracture strike (Taylor and Flemming 1988). This counterintuitive occurrence is a result of using current magnitude in the calculation of apparent resistivity, while the actual potential differences are determined by the current density (Keller and Frischknecht 1966).

Thus the measured electrical anisotropy can indicate the preferential direction of hydraulically conductive fractures and the degree of connectivity between the source and receiver electrode (Fig. 7).

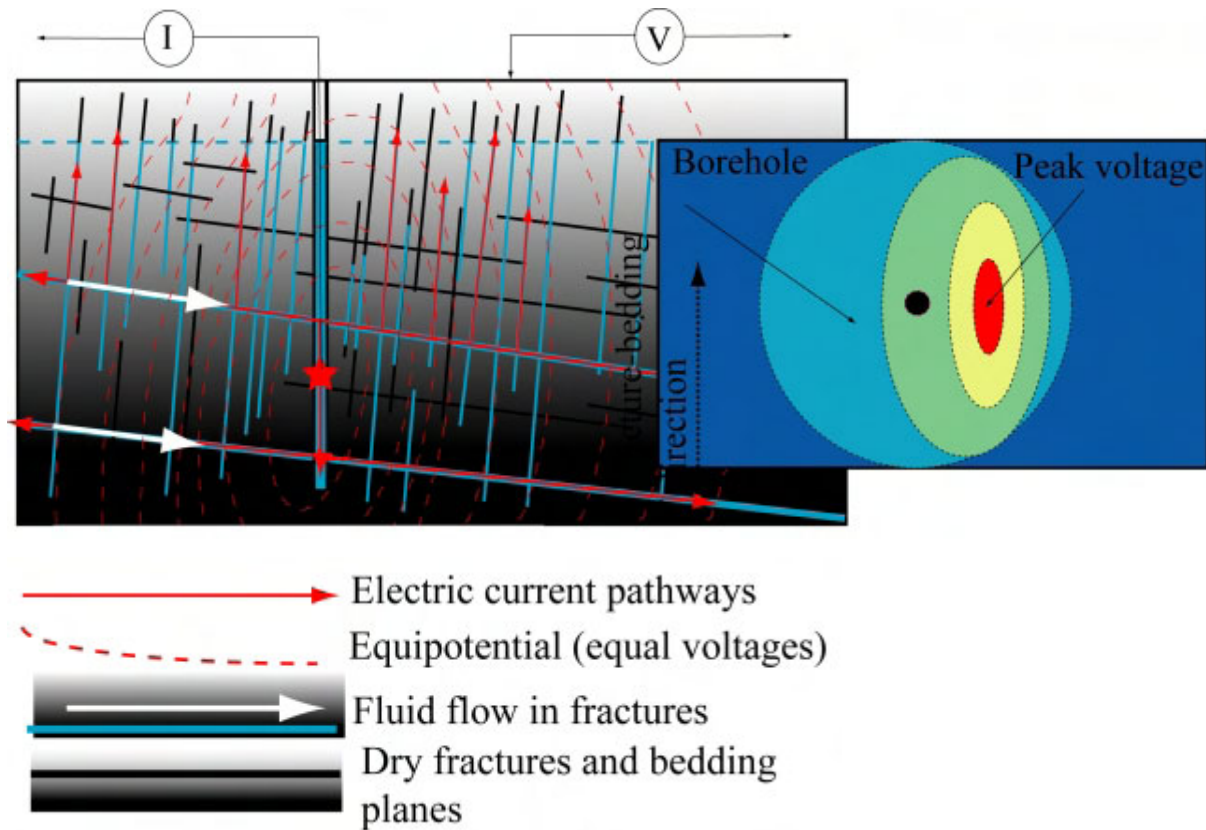


Figure 7. Schematic of DC resistivity survey and output surface potential map

This can then be used to determine porosity as a function of angle away from the hole through an empirical relationship that relates bulk resistivity to pore fluid resistivity and porosity at low frequencies established by Archie (1942):

$$\frac{\rho_r}{\rho_w} = F = \alpha \phi^{-n} \quad \text{Equation (1)}$$

where ρ_r is the bulk resistivity of the rock, ρ_w is the pore fluid resistivity, F is the formation factor, ϕ is the porosity, n is the cementation factor and α is a dimensionless parameter.

This technique is more sensitive to vertical structures and cannot detect the presence of horizontal fractures (Watson and Barker 1999). Therefore, lower-angle fractures are likely to produce more isotropic responses, as electrical connection with the surface is not as pronounced. Although there must be horizontal fractures to feed the borehole, there is vertical control of the near-surface recharge.

3.2.2 SELF-POTENTIAL METHOD

The self-potential (SP) method is a simple electrical technique that requires no source and involves measuring the natural electrokinetic potentials, or streaming potentials, in the earth. Streaming potentials arise due to a naturally-occurring diffusion electrical potential, often known as the zeta potential (ζ -potential), across boundaries between a fluid electrolyte and mineral grains in fractured rock and porous media (Sato and Mooney 1960).

Consider a system consisting of two separate phases such as liquid and a solid medium, in which the phases must be electrically neutral. Thus, the net charge within the liquid medium and the charge on the surface of the solid medium have to be equal in magnitude and of opposite signs (Fagerlund and Heinson 2003). At the interface of the two phases there is an aggregation of excess charge on each side, which establishes an electrical double layer (Fig. 8). When the fluid moves relative to the solid medium, the mobile part of the electrical double layer is dragged along with the flow creating the transport of electric charge with the flow. The amount of charge transported is directly related to the potential on the slipping plane, the ζ -potential, with the magnitude equalling the potential change in the mobile phase. The more negative the ζ -potential the more positive ions are transported with the flow and thus the greater the net transport of negative charge ions (Fagerlund and Heinson 2003).

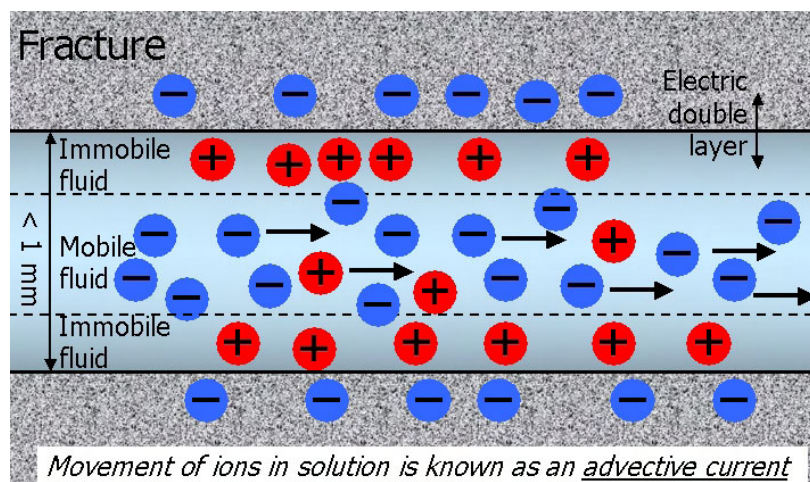


Figure 8. Within the fluid that resides in the fracture there are ions. The movement of these ions sets up what is called advective current

The ζ -potential is shown to increase with increasing temperature and pH and to decrease with increasing salinity (Gustafsson et al. 2000; Saka 2006). Consider particles in suspension with a negative ζ -potential. If more alkali is added to the suspension then particles tend to acquire more negative charge. However, if more acid is added to this suspension then a point will be reached where the charge will be neutralised and eventually build up to a positive charge. Thus, in general, ζ -potentials will be positive at a low pH and slightly positive or negative at a high pH (Gustafsson et al. 2000; Saka 2006).

4. RESULTS

4.1 ELECTRICAL RESISTIVITY

Borehole-to-surface DC resistivity surveys were conducted at 21 sites in the EMLR (Fig. 9). Within these sites, which were determined by lithology, a well was selected based upon its location, construction, depth and ideally was unequipped for access to the open well (Table 1). Note that the geological unit noted in Table 1 features the contributing unit only. Please refer to Appendix B for a more detail on the unit and structural description.

At each site the source current electrode was located either down hole, placed at the surface or connected to the metal borehole casing. The location of the source electrode was variable but, ideally, was set at depths below weathered surface material in an open hole and below the watertable. However, this was not possible at some sites due to the well being equipped and sealed off completely at the surface. In the case that access to the well was not possible, the current electrode was then attached to the metal casing to ensure the borehole was energised to the depth of the casing and below the watertable.

Table 1. Wells selected for survey in the Eastern Mount Lofty Ranges

Site	Unit Number	Easting	Northing	Depth (m)	Date of DTW	DTW (m)	Date of Yield	Yield (L/s)	Date of TDS	TDS (mg/L)	Geological Unit
1	6728-2581	329274	6172305	55.0	Jun-86	17.0	Apr-85	1.3	Apr-86	2199	Eec
2	6728-3159	324535	6158669	113.0	Feb-97	7.0	Feb-97	1.6	Feb-97	2131	Eeb
3	6628-12161	315434	6136571	138.0	Feb-83	25.0	Feb-83	1.3	Aug-07	3063	Eeb
4	6628-12819	312508	6129361	35.0	Dec-83	4.0	Dec-83	4.2	Jul-07	2607	Eeb
5	6627-7520	312133	6122200	81.4	Apr-86	11.8	Mar-86	1.3	Aug-07	2550	Elt
6	6627-10244	308792	6121363	65.0	Mar-00	18.5	Mar-00	0.8	Aug-07	1423	Nnt
7	6627-10727	304257	6118164	88.0	Sep-02	24.0	Sep-02	10.0	Sep-02	1328	Nnt
8	6627-9480	302090	6114402	98.0	Sep-00	9.0	Mar-97	1.9	Mar-97	1311	Nnt
9	6627-3288	305980	6114340	70.2	Feb-04	27.0	Dec-59	3.6-	Aug-07	2579	Nnt
10	6627-10372	311028	6118448	95.0	Oct-98	28.0	Sep-00	1.5	Aug-07	1233	Eeb
11	6627-11022	316225	6117973	128.0	Mar-89	29.2	Feb-04	0.2	Aug-07	3690	Elt
12	6627-2770	325687	6118873	55.0	Dec-76	4.5	Oct-98	4.5	Aug-07	4629	Elt
13	6627-8000	302209	6106299	54.0	Mar-89	29.2	Mar-89	8.8	Aug-07	486	En
14	6627-5650	293332	6099200	137.0	Dec-76	4.5	Dec-76	11.3	Aug-07	774	Ndt
15	6627-7516	297529	6101947	54.9	May-81	36.1	Mar-86	27.5	Jul-07	1029	Nir
16	6627-5598	300282	6103171	45.1	-	-	Jan-82	1.0	Aug-07	641	Eeb
17	6627-5602	301660	6104035	103.0	Mar-02	15.0	Jun-64	2.5	Aug-07	1440	Eeb
18	6627-8951	308017	6104678	77.0	Apr-03	26.0	Mar-06	1.9	Aug-07	3235	Eeb
19	6627-10621	311236	6104671	112.0	Nov-01	6.5	Mar-02	1.1	Aug-07	1990	Elt
20	6627-10856	300035	6097947	152.0	Jun-86	17.0	Apr-03	1.9	Apr-03	1984	Elt
21	6627-10575	306665	6100923	54.0	Feb-97	7.0	Nov-01	10.0	Aug-07	1990	Eeb

Eec – Carrickalinga Head Formation
 Eeb – Backstairs Passage Formation
 Elt – Tapanappa Formation
 Nnt – Tapley Hill Formation

En – Normanville Group
 Ndt – Stonyfell Quartzite
 Nir – Tarcowie Silstone

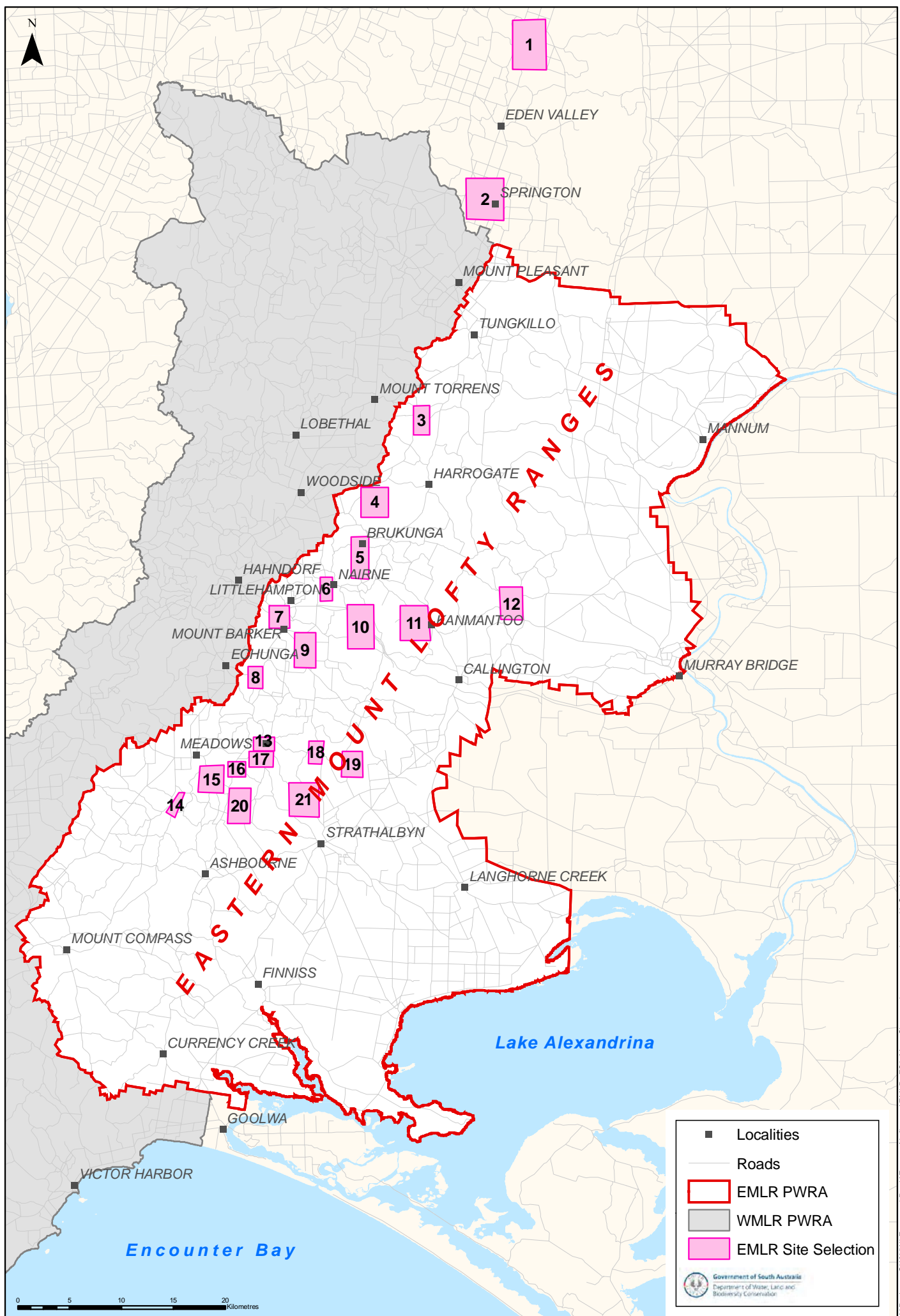


Figure 9. Map of 21 sites located in the Eastern Mount Lofty Ranges

The electric circuit was completed with a return current electrode located at a distance far enough to be considered at infinity (typically >200 m). Surface electrical potential measurements were made in reference to an electrode at a distance at which the potential is defined to be zero from the borehole (typically >100 m, but in the opposite direction to the return current electrode).

An array of 72 surface electrodes were located radially from the borehole at 5 m intervals, with six electrodes on each line between 5 and 30 m, along 12 lines at 30° angular increments (Fig. 10). However, in some survey areas, obstacles either prevented the placement of certain surface electrodes or caused shifts in the angular increments of the lines. Contoured surface maps were then produced showing the electrical potential measured normalised by the input current (sometimes called the transverse resistance; Skinner and Heinson 2004). It is possible to convert the transverse resistance to apparent resistivity from Equation 2, assuming a point current source.

$$\rho_a = 2\pi r \left(\frac{V}{I} \right) \quad \text{Equation (2)}$$

Where ρ_a is the apparent resistivity measured in the field, r is the distance from the borehole and (V/I) is the transverse resistance. This is useful in determining the background resistivity (that is, the overall resistivity of the regolith–bedrock–fluid system), however, interpreting apparent resistivity in terms of fluid pathways is more complex due to the paradox of anisotropy.

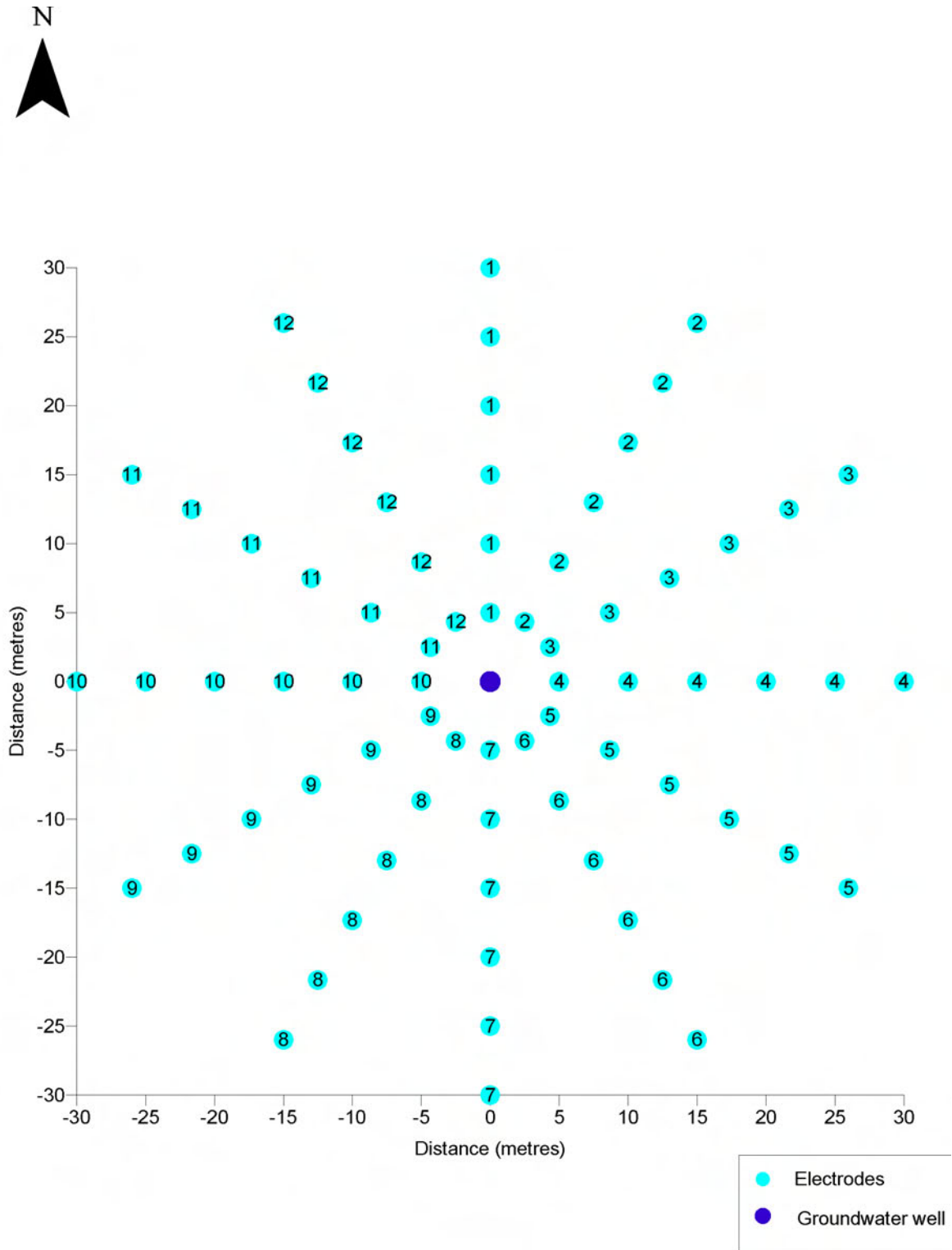


Figure 10. Borehole-to-surface DC resistivity surface setup arrangement

Average apparent resistivity over the 12 lines was calculated for a distance of 25 m away from the borehole. It was then related to bulk porosity using Archie's Law, assuming $n = 2$ and $\alpha = 1$, for surveys where the electrical conductivity of the water was known (Equation 3).

$$\phi = \sqrt{\frac{\rho_w}{\rho_a}} \quad \text{Equation (3)}$$

Where ϕ is the bulk porosity, ρ_w is the pore fluid resistivity and ρ_a is the bulk apparent resistivity.

A 25 m radius was chosen because (a) errors in location of the current and voltage electrodes are less important than for those closer to the borehole, and (b) the approximation of a line source is better.

Simple graphs comparing the apparent resistivity of electrodes at a certain distance away from the borehole as a function of the bearing were then produced to aid in interpretation of strike on conductive fractures. Firstly, by highlighting the bearings where the peaks of apparent resistivity occur, strike can be inferred in much the same way as from surface maps (Skinner and Heinson 2004). Secondly, the nature of the asymmetry may provide more information about conductive fractures. If the graph is symmetrical then it is inferred that there is one major orientation for the conductive fractures (Fig. 11a). However if the graph is asymmetrical, it may indicate a second conductive zone (Fig. 11b). The ratio of maximum to minimum apparent resistivity for a 25 m radius was made to show the relative conductivity of different zones.

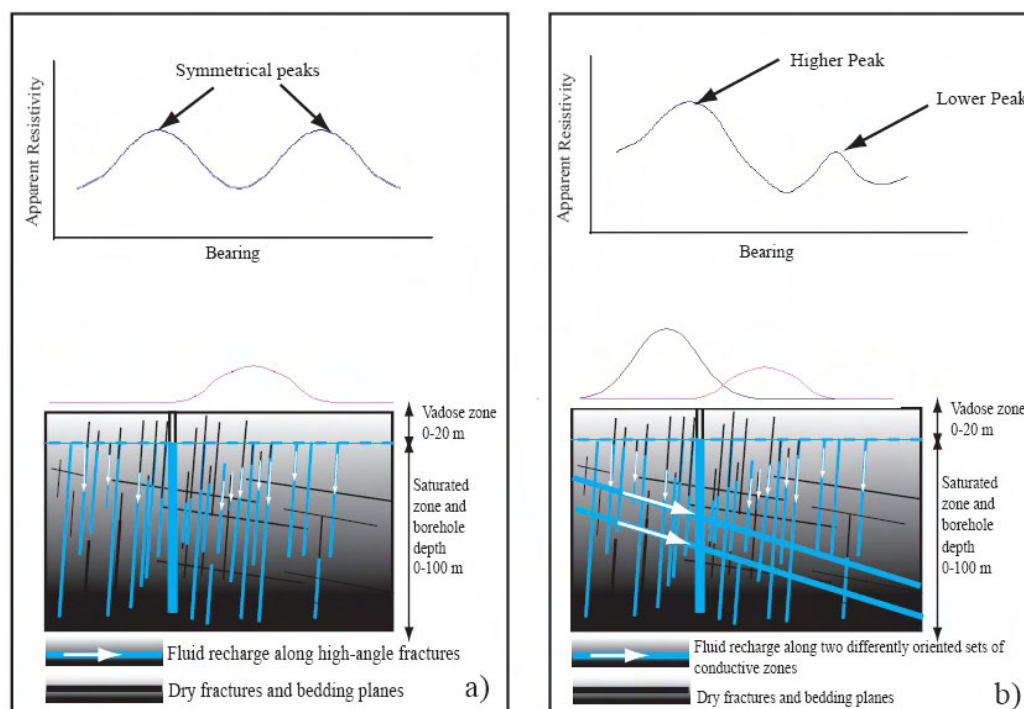


Figure 11. Apparent resistivity of electrodes at 25 m away from the well as a function of bearing. (a) If the graph is symmetrical then it is inferred that there is one major orientation for the conductive fractures. If conductive structures are approximately vertical there is symmetry observed around the borehole. (b) If the graph is asymmetrical, there may be a second differently orientated fracture set. The dip of structures gives rise to anisotropy of the response and will be biased to the upside fracture sets.

The strike of the most conductive feature at each site was primarily inferred from the orientation of the maximum axis of the equipotential ellipse of the surface maps (Skinner and Heinson 2004). Surface maps of normalised potential – measured potential (V) divided by the current (I) – were more complex to interpret and, in conjunction with the graphs of apparent resistivity, were used as supporting information. In particular, apparent resistivity was often unexpectedly lower around boreholes; perhaps an artefact produced by assuming

a point source of current when in reality the source is more complex by virtue of the connection to the casing. Zones of high electric potential (normalised by the input current) were interpreted as having good electrical connection with the borehole, indicating the location of fractures and/or bedding planes in the orientation of the zone.

Figure 12 shows the borehole-to-surface DC resistivity results for Site 19. The results are plotted as a normalised potential distribution contour map. The dip and strike of the most conductive elements at this site were inferred from the data. Dip values were calculated by measuring the distance of lateral offset of the maximum transfer resistance value from its expected location (directly above the current electrode). The strike was determined from the orientation of the maximum axis of the equipotential ellipse. In this case, the centre of the highest potentials were offset indicating a dipping structure to the south-east (SE) while the strike was determined to be in a north-east (NE) direction

Sites were classified in terms of the degree of heterogeneity, electrical resistivity and dominant fracture orientation (Table 2). Due to the large variations in absolute potential, the same colour contour interval was not applied to each surface map otherwise many features would be masked. However, comparisons between sites could be made by classifying each site in terms of high (>1 V/I), medium ($0.1-1$ V/I) and low (<0.1 V/I) normalised potential (Table 2).

Results for each of the parameters were highly variable, ranging from $1-370\ \Omega\text{m}$ for the bulk apparent resistivity, 10-70% for bulk porosity and one to three for the ratio of maximum to minimum apparent resistivity. As expected there is clearly some correlation between apparent resistivity and water salinity, as sites with lower apparent resistivity tend to have lower salinity. Unexpectedly there was no obvious correlation between the parameters and the lithology throughout the region.

Variations in magnitude of electrical potential measurement are indicative of different porosities and saturations. In general, larger potential at all electrodes indicate that the ground has lower electrical resistivity and hence more groundwater.

It is implied that there is an overall dipping conductive structure if the maximum normalised potential was offset from above the borehole (Skinner and Heinson 2004). The direction of dip of the conducting structures could be inferred at some sites as being at right angles to the strike and towards the more resistive structures. As mentioned above, dip values were calculated by measuring the distance of lateral offset of the maximum transverse resistance value from its expected location (directly above the current electrode).

Borehole-to-surface potential maps were completed for all 21 sites and are presented in Appendix A. Surface maps for some surveys showed very little anisotropy, with the normalised potential essentially showing a concentric pattern around the borehole. Slight anisotropy around the borehole may be due to errors in positioning of the electrodes. Any errors in positioning will affect the electrodes closer to the borehole much more than those further out.

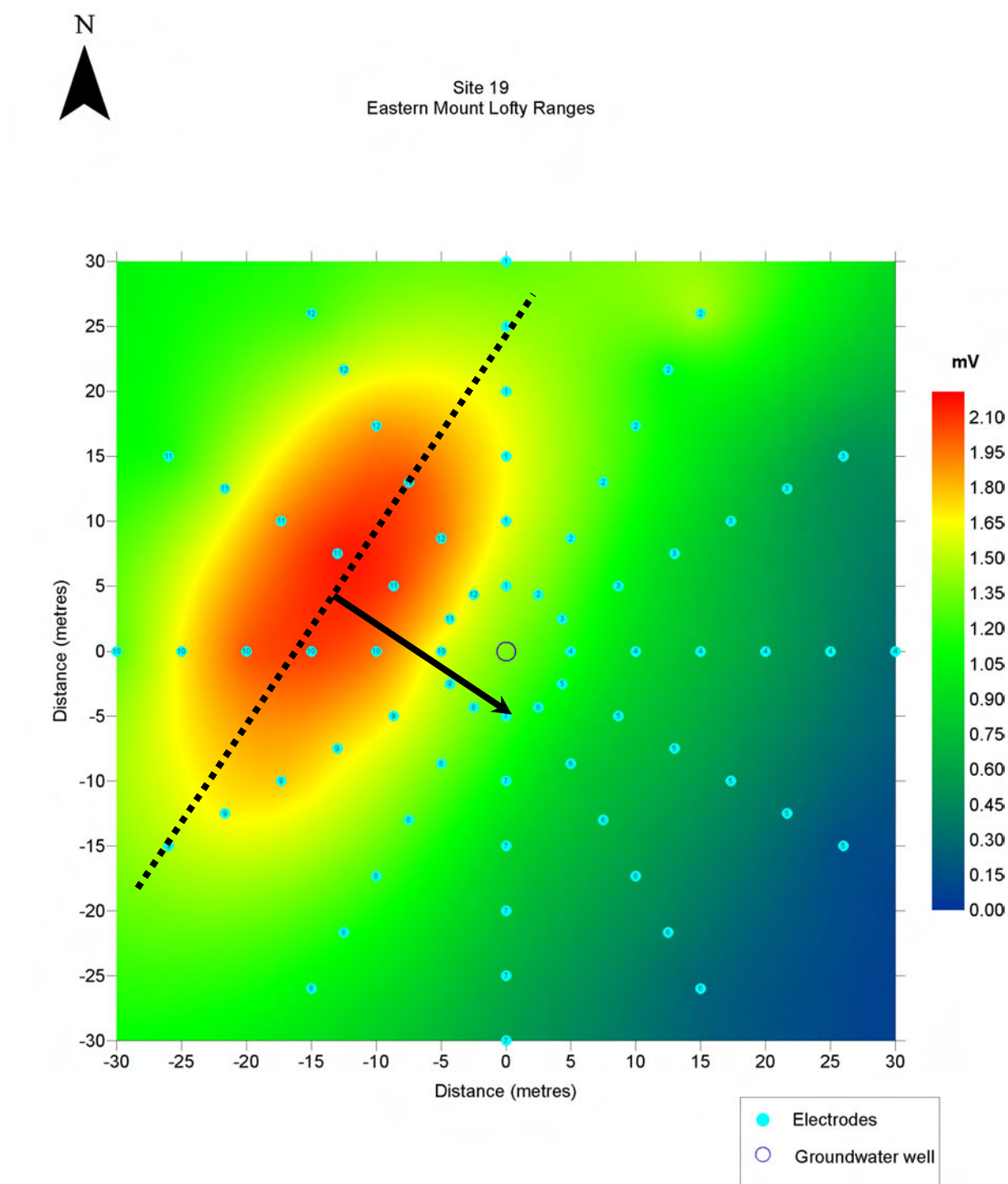


Figure 12. Normalised potential contour map from Site 19, dashed line denotes strike orientation, solid line with arrow denotes a direction of dip

The majority of sites surveyed exhibited some anisotropy and showed dominant conductive zones with NNW, N and NNE strikes. These are consistent with the overall north-east to south-west structural trend in the area.

Table 2. Summary of electrical data interpretations for 21 selected sites in the Eastern Mount Lofty Ranges

Site	Unit Number	Anisotropy (Yes/No)	Strike	Dip	Magnitude (V/I)	Symmetry (Yes/No)	Porosity (%)	Geophysical Anisotropic Ratio
1	6728-2581	Y	NNW	WSW	High	N	15	3.0
2	6728-3159	Y	NNE	-	High	Y	20	2.0
3	6628-12161	Y	N	E	High	N	20	1.5
4	6628-12819	Y	NNE	-	High	Y	10	1.5
5	6627-7520	Y	NNE	SSE	Medium	N	30	2.0
6	6627-10244	Y	NNE	ESE	Medium	N	50	2.0
7	6627-10727	Y	N	-	Medium	Y	50	2.0
8	6627-9480	Y	N	-	High	Y	20	1.5
9	6627-3288	Y	NNW	-	Medium	Y	50	3.0
10	6627-10372	Y	NNW	-	High	Y	10	1.5
11	6627-11022	Y	N	E	Medium	N	20	2.5
12	6627-2770	Y	N	E	High	N	10	2.0
13	6627-8000	Y	NNW	ENE	Low	N	-	2.5
14	6627-5650	Y (low)	ENE	-	Medium	Y	50	1.1
15	6627-7516	Y	NNW	ENE	Low	N	70	2.0
16	6627-5598	Y	(NNE*) (NNE*)	ESE WNW	Low	ukn	ukn	ukn
17	6627-5602	Y	N	-	Medium	Y	35	1.5
18	6627-8951	Y	N	-	High	Y	10	1.5
19	6627-10621	Y	NE	SE	High	N	15	2.0
20	6627-10856	Y	NNW*	WSW	Medium	Y	35	1.5
21	6627-10575	Y (low)	N*	E	Medium	Y	25	1.3

N (strike/dip) – north
E (strike/dip) – east
S (strike/dip) – south
W (strike/dip) – west

Med – medium
ukn – unknown (not enough data)
* Dip direction implies orthogonal strike direction

A collective map with the fracture strike and dip for each of the 21 sites demonstrates a high degree of correlation between fracture orientation and regional structural trends (Fig. 13).

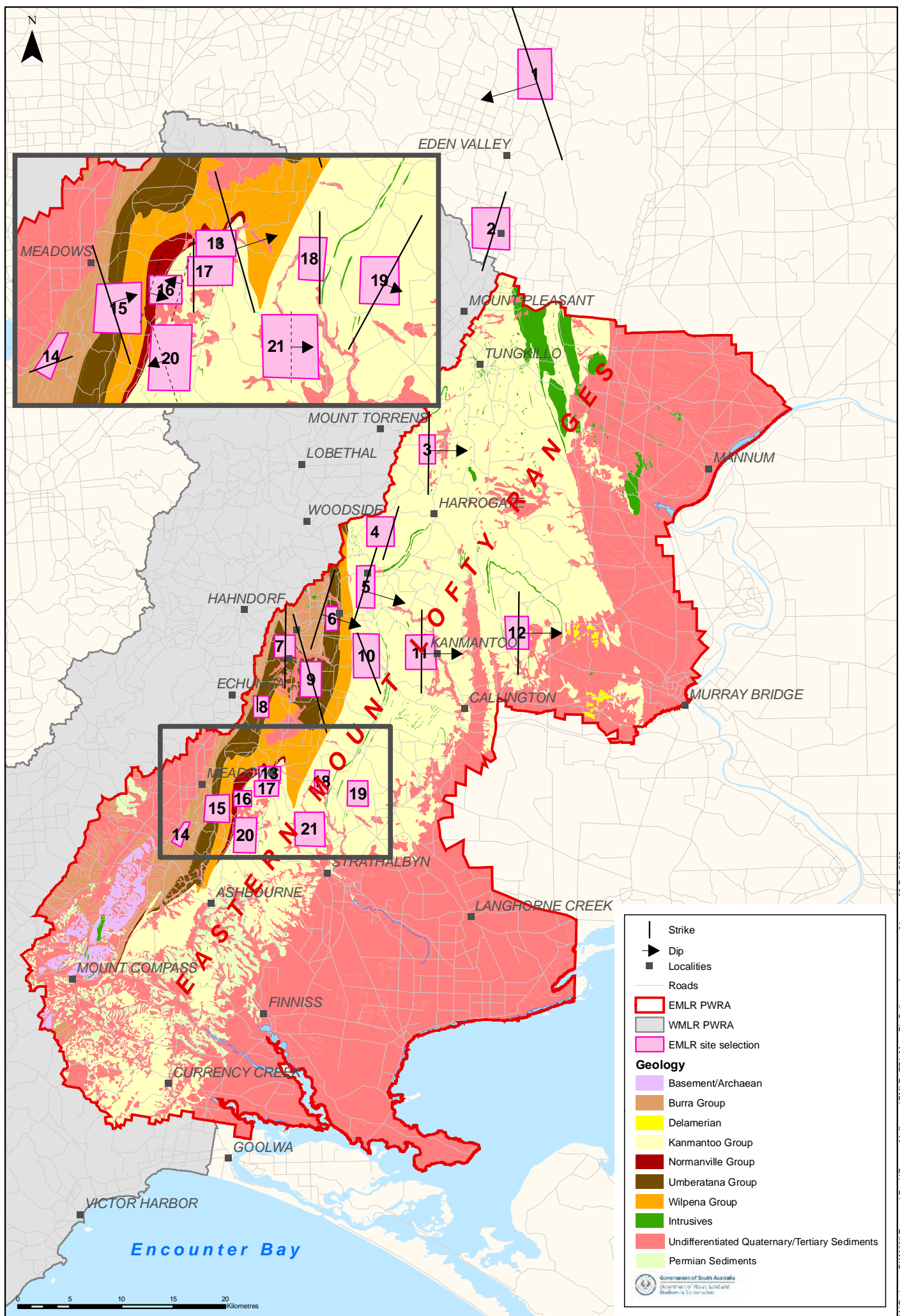


Figure 13. Map of fracture strike and dip for each of the 21 sites in the Eastern Mount Lofty Ranges.

4.2 SELF-POTENTIAL (SP) METHODS

Self-potential (SP) surveys were carried out using an array of 36 surface electrodes at each site. Each array consisted of 6 radial lines (60° separations), with 6 electrodes at 5 m intervals along each line between 5 and 30 m from array centre (Fig. 14). The electrodes were ordered from outermost through to innermost, such that Line 1 has electrodes 1–6, Line 2 has electrodes 7–12, etc. Potentials were measured every 5 seconds at each electrode relative to a distant reference electrode, located far enough away to be considered unaffected by pumping (typically >200 m).

SP measurements were recorded continuously from 5–10 minutes before the start of pumping, through the pumping cycle and also 5–10 minutes after pumping to measure recovery. It has been assumed that the measured SP values are stable before the start of pumping.

The electrodes measure a transient change in surface electrical potential surrounding the pumped well of up to 60 mV. Such changes occur over time-scales varying from a few seconds after turning the pump on, to a few tens of minutes when equilibrium flow is established.

In many cases wells were equipped with pumps, however, for those that were unequipped a pump was brought onto site.

Electrokinetic potential measurements are presented as a function of time away from borehole for all 36 electrodes, with the inset map showing the orientation of the electrodes relative to the borehole (Fig. 15). Four examples showing a range of outcomes are illustrated in Figures 15, 16, 17 and 18 with the red colours indicating high electrokinetic potentials, and the blues indicating low potentials. Most of the changes are seen over the first few minutes of pumping when, presumably, near-surface fractures are quickly drained and the electrokinetic sources are closest to the surface.

At Site 9 (Fig. 15) for each line the largest change in potential is observed for those electrodes closest to the borehole as expected, with the amount of change decreasing the further out the electrodes are from the borehole (e.g. electrode 6 shows large change in potential, electrode 1 shows little change in potential). There is almost no change observed for those electrodes 30 m away from the borehole, suggesting that little change would be seen for distances greater than this. Change in potential also decreases with magnitude after time, with no change after almost 5 minutes, indicating that only the shallow zones are being drained. The largest and longest duration potentials are seen in Line 3, approximately on a bearing of 120°, suggesting that groundwater flow is greatest in this direction and indicating fluid flow being dominant from the south-east. To the north, the fluid flow is presumably deeper, and produces smaller electrokinetic signals. The potential changes are of order of 4 mV over a time span of about 5 minutes. Several electrodes were off-scale, such as electrodes 8 and 9 from line 2, which were made noisy by the pump outflow passing by the metal electrodes.

A similar pattern is exhibited by the electrokinetic measurements at Site 10 (Fig. 16). There is a pronounced change in potential at this site, of opposite polarity, and of magnitude 4 mV. The largest and longest potential change is along Line 3 (bearing of 120°), similarly showing that the dominant flow direction appears to be from the south-east. The negative polarity could be attributed to more alkaline conditions compared to Site 9 (Gustafsson et al. 2000).

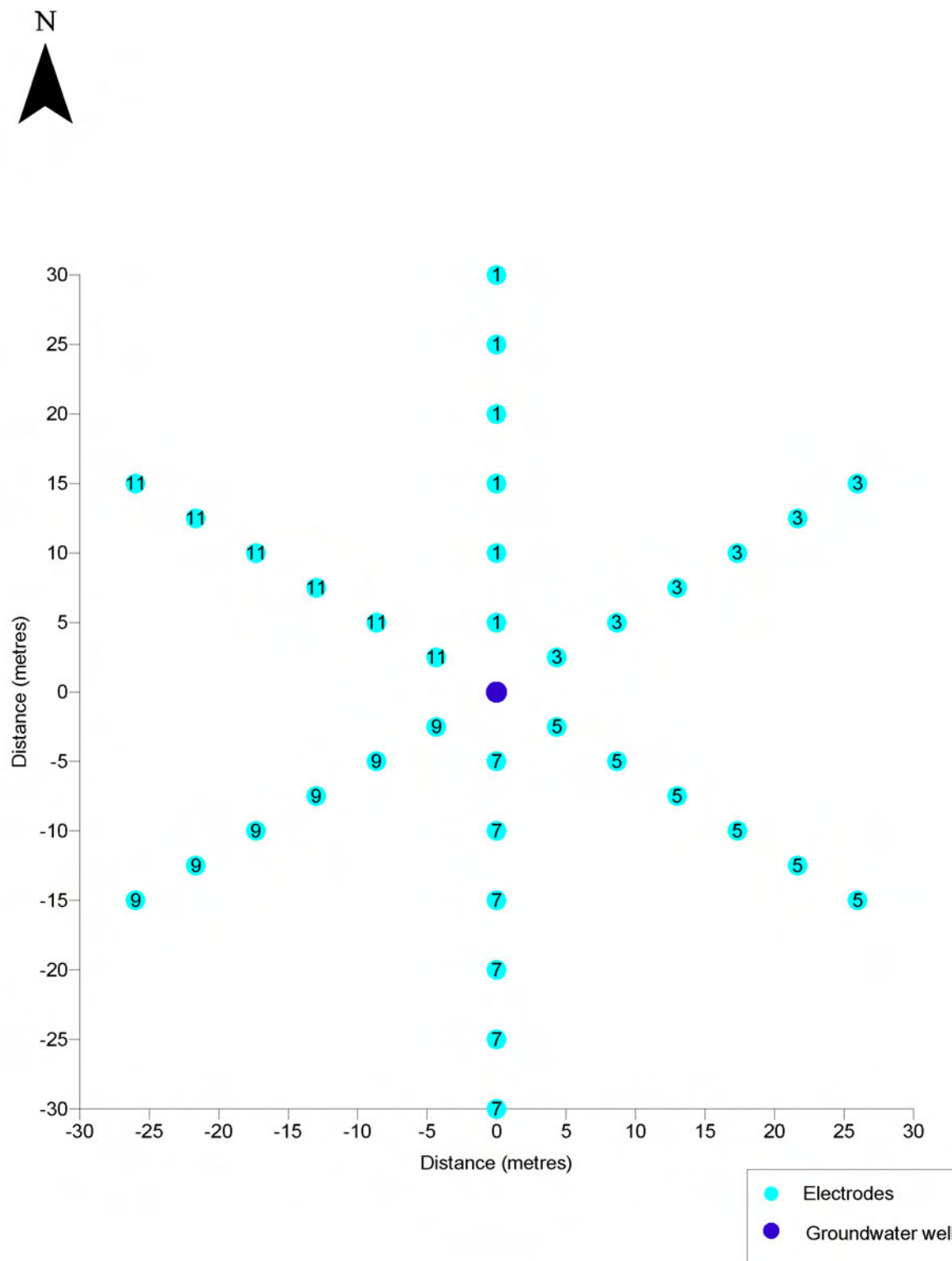


Figure 14. Self-potential surface setup arrangement

Electrokinetic potentials as a function of time for Site 7 are shown in Figure 17, with the inset map showing the orientation of the electrode lines 1–6 from north spaced 60°, 120°, 180°, 240°, and 300°. The electrokinetic voltage change is much smaller than observed at Site 9, of order 0.3 mV, which is close to the ambient noise levels of the data logger. There is a small positive change at the start of the pump tests for less than 1 minute and Line 3 shows

the largest voltage change, but the effect is marginal. These observed smaller voltages are interpreted as being due to much lower fluid flow rates at this site and the main hydraulic fractures are deeper and hence produce a smaller signal.

At Site 6 it is evident that lines south to north-west have largest polarity change, on the order of magnitude 60 mV (Fig. 18). This is substantially larger than many of the sites and is interpreted to be a much higher flow rate at this site, or that the main hydraulic fractures are quite shallow. In particular the largest and longest potential changes are seen for Lines 5 and 6 indicating direction of dominant flow appears to be from the north-west. Again, the opposite polarity may be due to pH variations between sites (Gustafsson et al. 2000).

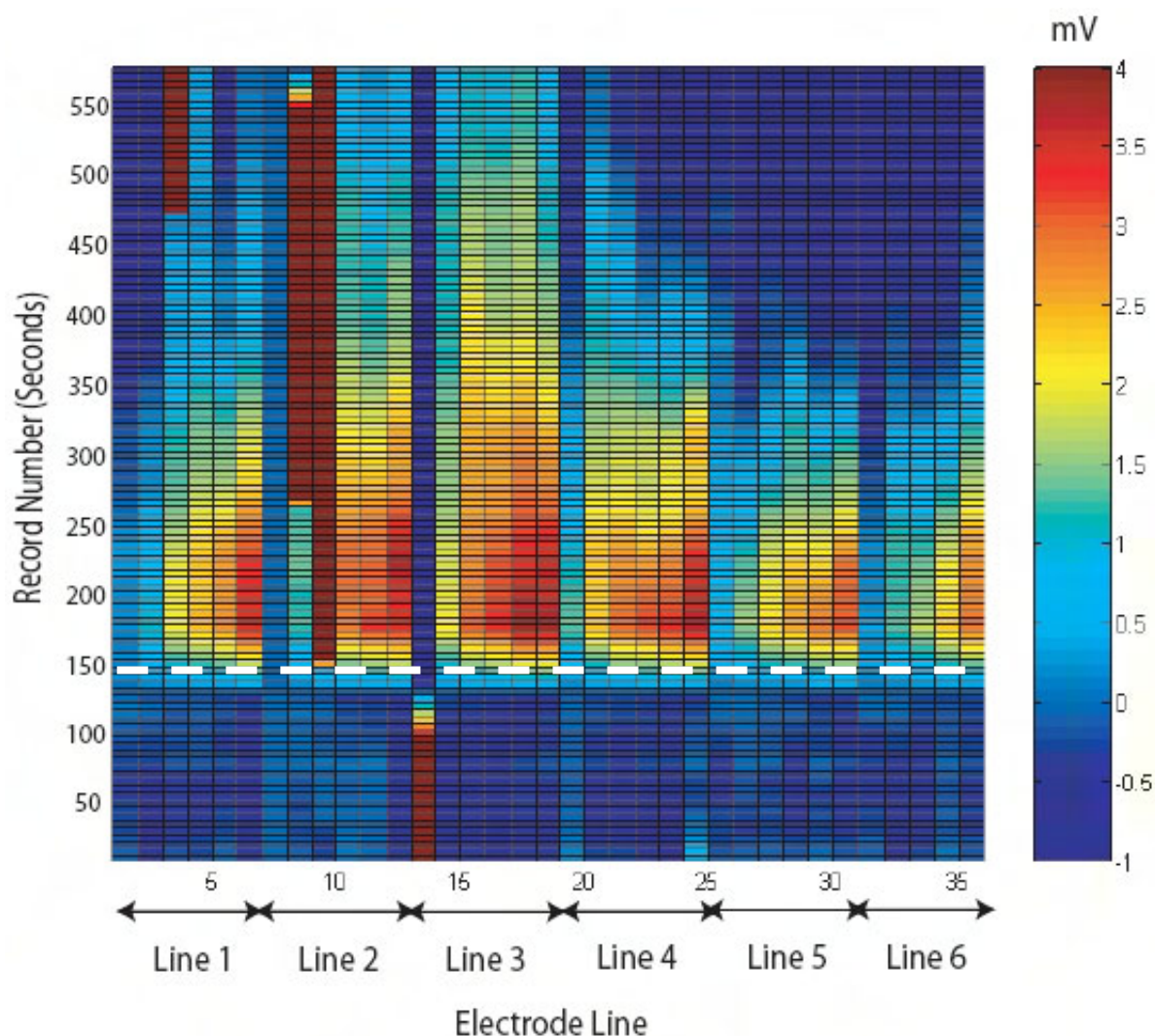


Figure 15. SP results for Site 9. The white dashed line represents the point at which the pump was switched on. Length of record shown here is only the first 5-7 minutes of the pumping duration

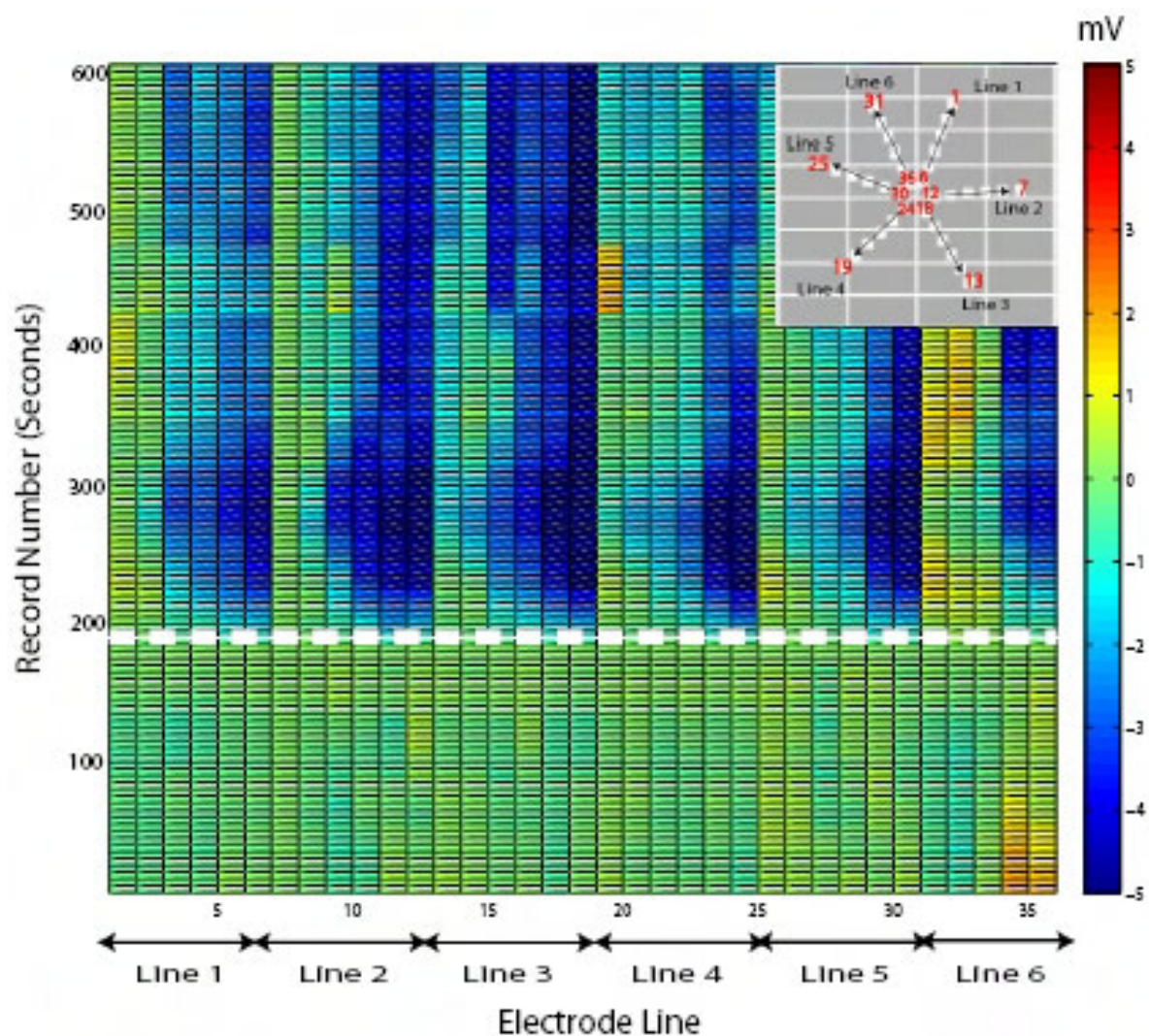


Figure 16. SP results for Site 10. The white dashed line represents the point at which the pump was switched on. Length of record shown here is only the first 5-7 minutes of the pumping duration

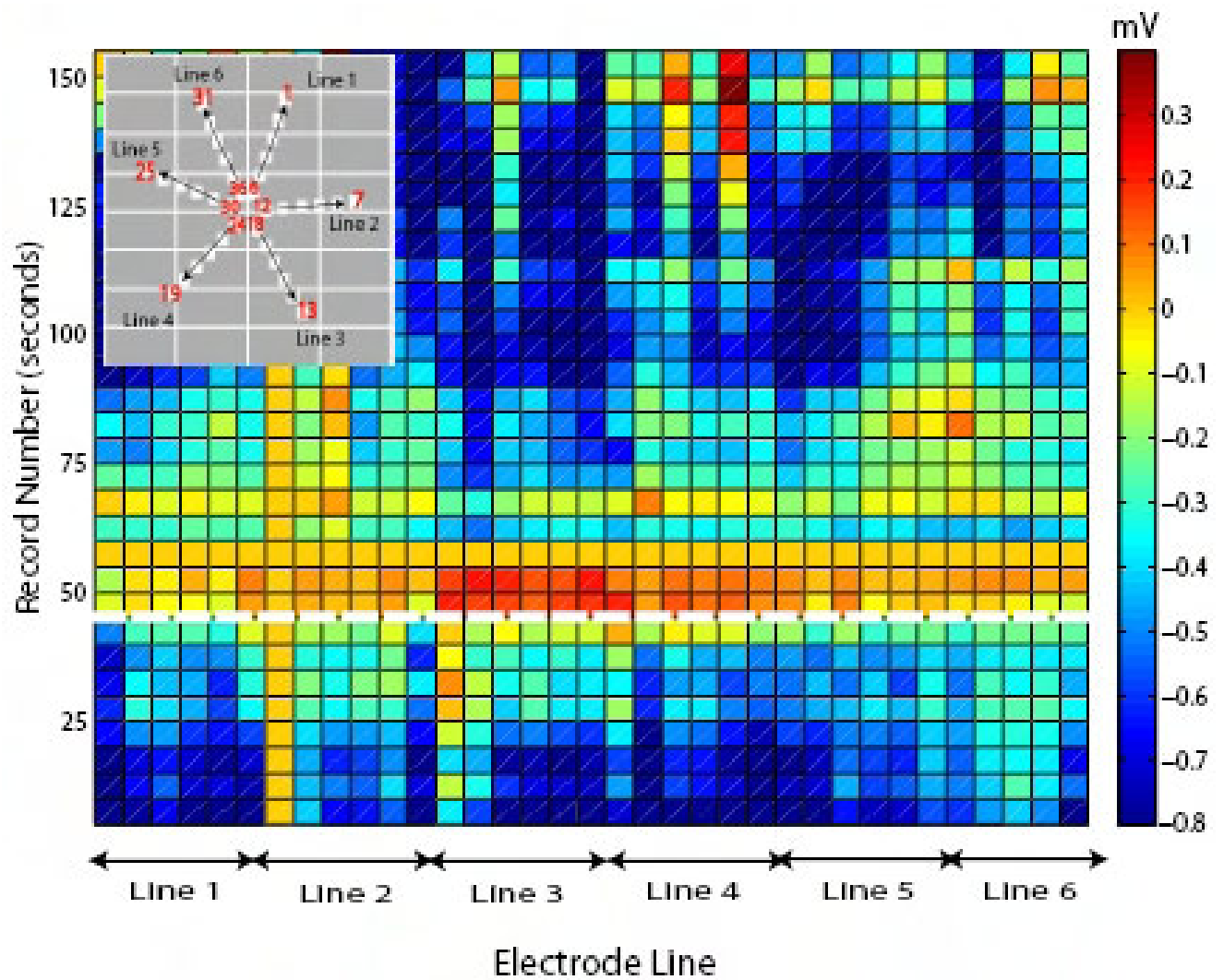


Figure 17. SP results for Site 7. The white dashed line represents the point at which the pump was switched on. Length of record shown here is only the first 5-7 minutes of the pumping duration

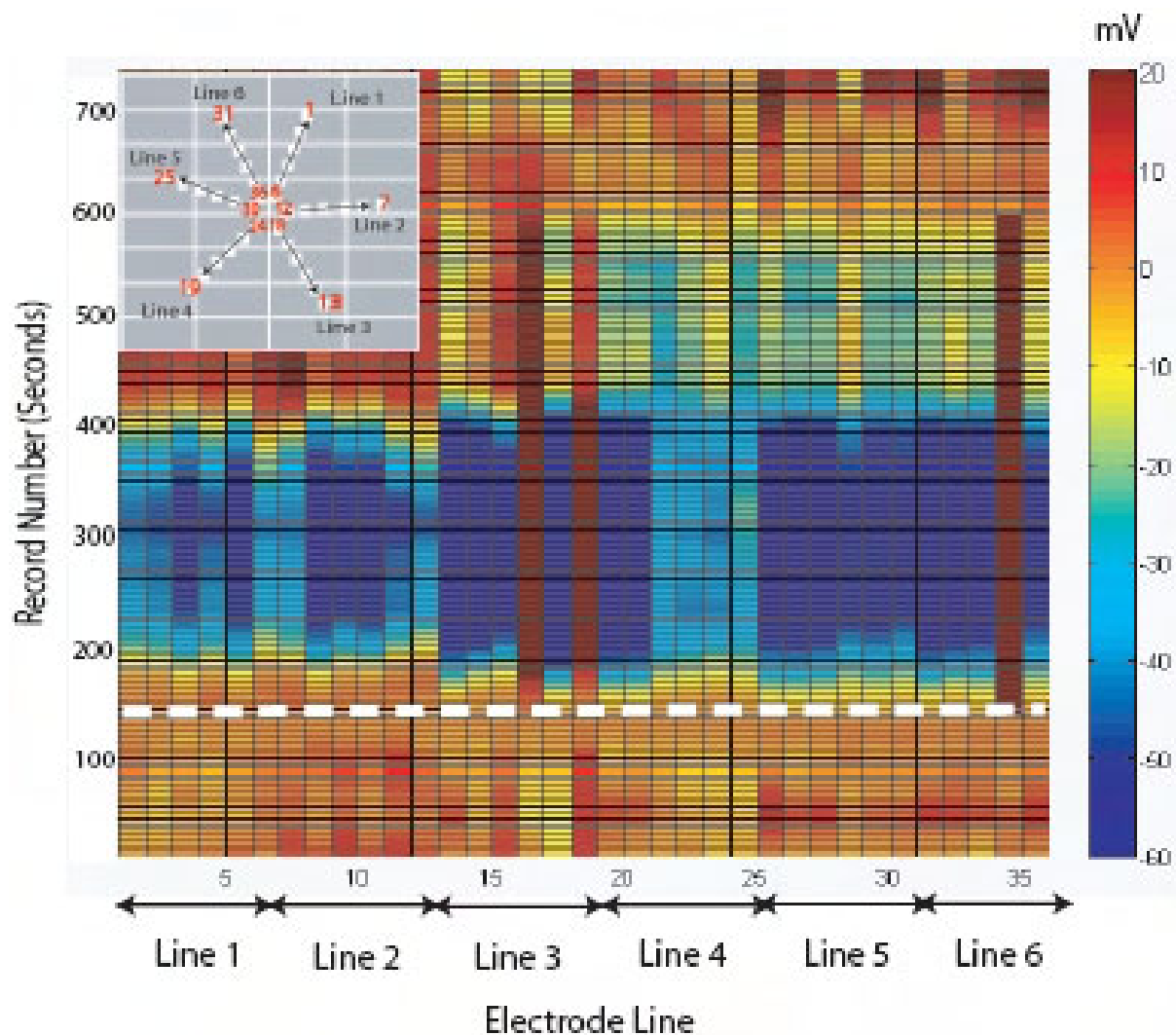


Figure 18. SP results for Site 6. The white dashed line represents the point at which the pump was switched on. Length of record shown here is only the first 5-7 minutes of the pumping duration

Many of the wells in the EMLR are equipped with pumps and are totally sealed at the surface, proving a challenge to gather data. In addition, many of the pumps were suited to stock and domestic use and therefore yielded small flow rates. Studies have been shown that drawdown (drop in water level) of more than 10 metres was advantageous to facilitate adequate movement of water within fractured systems. With such a low yield, and without being able to accurately measure the water level throughout the pumping cycle, it is likely that sufficient drawdowns were not being reached.

5. DISCUSSION

5.1 CALIBRATION STUDIES

As expressed in the previous section, the self-potential (SP) methodology is still being developed. Calibration of this method in regard to comparing the geophysical data measured to pumping test data has been documented and the reader is referred to published work by Fagerlund and Heinson (2003).

In an attempt to calibrate geophysical survey data (namely the surface-to-borehole DC resistivity) to pumping test and hydrogeological data, results from two different sites were used in the calibration process.

The two sites used were:

1. Balhannah site, located in the western Mount Lofty Ranges approximately 50 kilometres east of Adelaide; and
2. Watervale Oval site, located in the Clare Valley approximately 100 kilometres north of Adelaide.

Both of these sites are located in a fractured rock environment, exhibit a network of closely spaced wells (hence these sites have been used extensively for many other hydrogeological and geophysical investigations) and they have pumping test data readily available.

5.1.1 WATERVALE OVAL, CLARE VALLEY

The Watervale Oval site is located south of the township of Clare. This site was chosen initially by Primary Industries and Resources South Australia (PIRSA) as a possible location for an aquifer storage and recovery (ASR) site primarily due to the accessible nature of the site.

Fagerlund and Heinson (2003) used this site for detecting subsurface groundwater flow in fractured rock using SP methods. In order to undertake such work a pumping test was conducted at the Watervale Oval site in April 2001.

The pumping well used was well 6630-3063, referred to as 'Borehole 4' in the text. Well 6630-3063 was continuously pumped at a rate of 2 L/s for the first 100 minutes followed by 1.5 L/s for the remainder of the test which had an entire duration of approximately 500 minutes (Fagerlund and Heinson, 2003). Water levels in four neighbouring observation wells were constantly monitored for the entire test.

While these neighbouring observation wells were not strategically placed, in that they limited the water level data to the western side of the pumping well, an area of influence and a direction of greatest drawdown could be ascertained. It is evident from the water levels in neighbouring wells that well 6630-2796 ('Borehole 3') showed the greatest drawdown (almost 7 m).

Analysing all the observation well data available and the findings of the SP data in Fagerlund and Heinson (2003) it could be inferred that the direction of preferential fracturing is to the north-north-west.

Warren (2001) used this data to establish a calculation of observed hydraulic anisotropic ratio. This was achieved by normalising maximum drawdown values recorded in each of the observation wells. A factor of approximately 5 was calculated for the observed hydraulic anisotropic ratio.

Borehole-to-surface DC resistivity results conducted by Skinner and Heinson (2004) reveal normalised potential distribution contour maps for the same well 6630-3063. At $r = 25$ m the maximum potential = ~ 0.72 ; the minimum for the same distance = ~ 0.45 . Therefore an anisotropic ratio using geophysical methods is approximately 2.

The dip and strike of the most conductive elements at this site were inferred from the data. Dip values were calculated by measuring the distance of lateral offset of the maximum transfer resistance value from its expected location (directly above the current electrode). The strike was determined from the orientation of the maximum axis of the equipotential ellipse.

For well 6630-3063 ('Borehole 4') the calculated dip of the conductive structures was $\sim 80^\circ$ east and the strike was determined to be $\sim 340^\circ$ which is north-north-west (Skinner and Heinson 2004).

This finding of strike direction is consistent with and supports the investigations and pumping test data conducted by Fagerlund and Heinson (2003).

5.1.2 BALHANNAH, WESTERN MOUNT LOFTY RANGES

The Balhannah site is located approximately 2 kilometres west of the township of Balhannah in the Mount Lofty Ranges. The site has been used extensively for various studies and investigations due to the number of wells constructed in close proximity to one another.

In October 2003 a pumping test was conducted by DWLBC (formerly the Department of Water Resources) as part of a separate investigation, however, the information gathered can be used in this work to further calibrate the geophysical data and relate it to the hydrogeology.

The pumping well used was well 6628-21203 which was continuously pumped for approximately 230 minutes at 2 L/s. Ten neighbouring wells were monitored for water level during the pumping test.

The greatest amount of drawdown was measured in well 6628-21211 which was located to the north-east of the pumping well. Over 3 metres of drawdown was observed after 230 minutes of continuous pumping.

The observation well data imply that the direction of preferential fracturing is to the north-east.

Figure 19 shows drawdown contours surrounding the pumping well. The elliptical shape is elongated along a north-east – south-west direction which would indicate the direction of preferential flow. By simple calculation, a hydraulic anisotropic ratio of approximately 2 can be determined from these contours.



Balhannah Site - Aquifer Test Oct 03
Mount Lofty Ranges

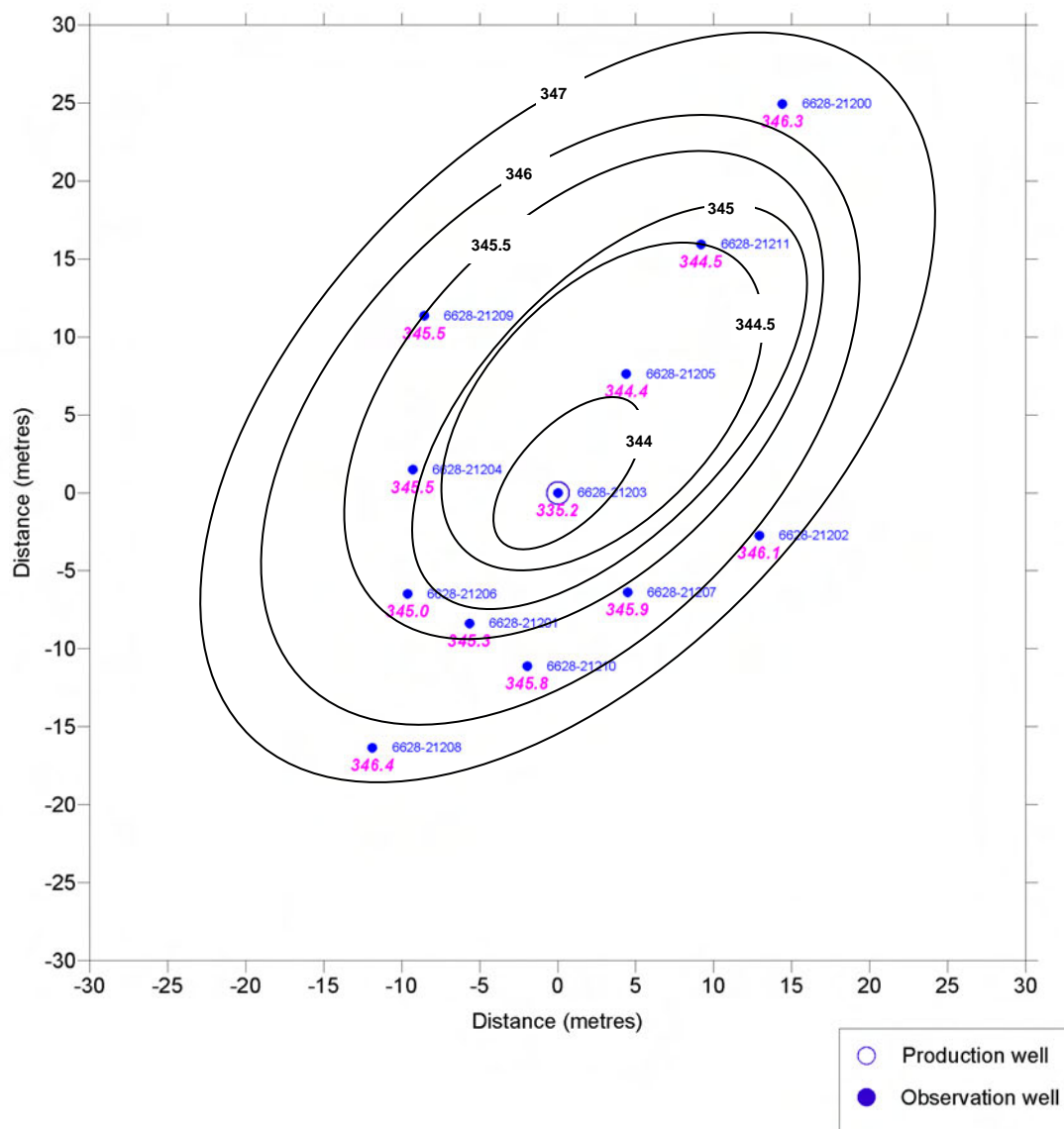


Figure 19. Aquifer test conducted in October 2003. Drawdown contours shown here are after 230 minutes of pumping from well 6628-21203. Well unit numbers are in blue, water levels (mAHD) for each well are in red. Note that water level contours (also mAHD) are approximate and coloured black.

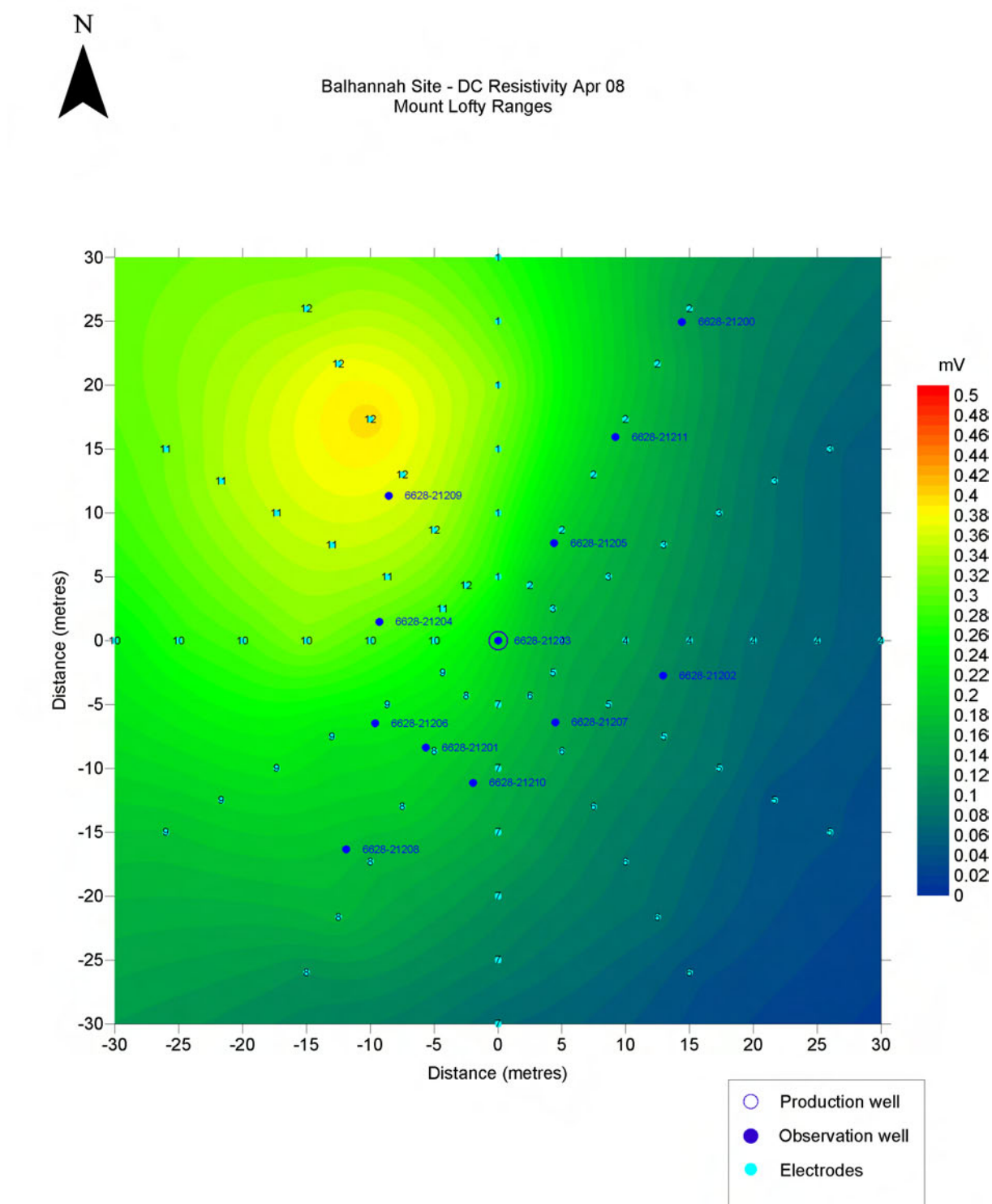


Figure 20. Normalised potential distribution contour map for Balhannah site

In April 2008 a borehole-to-surface DC resistivity survey was conducted at the Balhannah site for purposes of calibration for this investigation. Figure 20 shows the normalised potential distribution contour map for the site.

In order to align with the pumping test, well 6628-21203 was used as the central well where a current potential was lowered to approximately 30 metres. In the same fashion as the other

21 sites in the EMLR, 72 electrodes were placed strategically around the central well and their potentials measured.

The same methodology that was applied in the EMLR and in Skinner and Heinson (2004), was applied to the data at Balhannah where the dip and strike of the most conductive elements at this site were inferred from the data. Direction of dip was calculated by measuring the distance of lateral offset of the maximum transfer resistance value from its expected location (directly above the current electrode). The strike was determined from the orientation of the maximum axis of the equipotential ellipse.

For well 6628-21203 the calculated dip of the conductive structures was to the south – south-east. Since the shape of the potentials was not highly elliptical in shape (infers the site is not highly anisotropic) the strike was determined to be to the north – north-east using simple geological mapping geometry. This is also consistent with Figure 21, which shows a peak in the apparent resistivity (Equation 2) at approximately 210° and a south – south-west to north – north-east strike direction.

Data from a pumping test conducted by DWLBC in 2003 (Fig. 19) supports this strike direction.

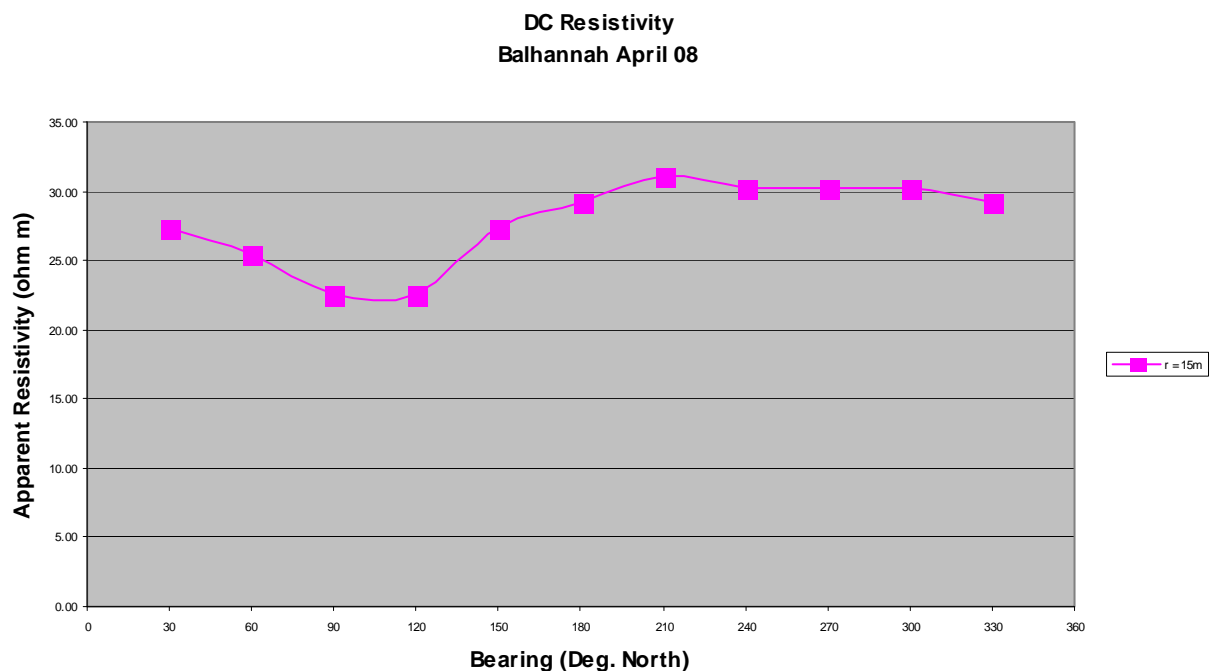


Figure 21. Apparent resistivity of electrodes at 15 m away from the well as a function of bearing

Calculation of maximum to minimum ratio using the normalised potential distribution at $r = 15$ m (lowered due to the offset of the maximum potential), the maximum potential = ~ 0.33 (approximately 31.10 ohm m); the minimum for the same distance = ~ 0.24 (approximately 22.62 ohm m). Therefore an anisotropic ratio using geophysical methods is approximately 1.4.

Due to preferential fracturing, the very nature of a fractured rock environment, there will always be some level of anisotropy (even if low).

It is clear from the calibration that the geophysical method (borehole–to–surface DC resistivity) is not as sensitive to anisotropy as the hydraulic equivalent. However the data (Table 3) does suggest that there is a multiplying factor.

Table 3. Summary of anisotropic ratios for the calibration sites

Site	R (m)	Hydraulic Anisotropy	Geophysical Anisotropy	Ratio
Watervale Oval	25	5	2	2.5
Balhannah	15	2	1.4	1.4
Average				~ 2

Using an average of the ratios found at each calibration site, a measured geophysical anisotropy using borehole–to–surface DC resistivity will need to be multiplied by a factor of 2 in order to calculate a hydraulic anisotropy.

5.2 GENERATING HYDRAULIC ANISOTROPY

Using the calibration methodology (Table 3) and applying this to the electrical data (namely borehole–to–surface DC resistivity, Table 2), one can determine a hydraulic anisotropy for each of the 21 sites investigated in the EMLR (Table 4).

Table 4. Summary of electrical data interpretations for 21 selected sites in the Eastern Mount Lofty Ranges

Site	Anisotropy (Yes/No)	Strike	Dip	Magnitude (V/I)	Geophysical Anisotropic Ratio	Hydraulic Anisotropic Ratio
1	Y	NNW	WSW	High	3.0	6
2	Y	NNE	-	High	2.0	4
3	Y	N	E	High	1.5	3
4	Y	NNE	-	High	1.5	3
5	Y	NNE	SSE	Medium	2.0	4
6	Y	NNE	ESE	Medium	2.0	4
7	Y	N	-	Medium	2.0	4
8	Y	N	-	High	1.5	3
9	Y	NNW	-	Medium	3.0	6
10	Y	NNW	-	High	1.5	3
11	Y	N	E	Medium	2.5	5
12	Y	N	E	High	2.0	4
13	Y	NNW	ENE	Low	2.5	5
14	Y (low)	ENE	-	Medium	1.1	2
15	Y	NNW	ENE	Low	2.0	4
16	Y	(NNE*) (NNE*)	ESE WNW	Low	ukn	-
17	Y	N	-	Medium	1.5	3
18	Y	N	-	High	1.5	3
19	Y	NE	SE	High	2.0	4
20	Y	NNW*	WSW	Medium	1.5	3
21	Y (low)	N*	E	Medium	1.3	2

N (strike/dip) – north

E (strike/dip) – east

S (strike/dip) – south

W (strike/dip) – west

Med – medium

ukn – unknown (not enough data)

* Dip direction implies orthogonal strike direction

6. CONCLUSION

Borehole-to-surface DC resistivity data obtained by placing an electrode down a borehole and measuring the distribution of transverse resistance on the surface has been used to delineate the orientation of dominant sub-vertical fractures intersecting the borehole.

Surveys conducted at numerous sites within the EMLR have confirmed that dominant fracture sets in the Adelaidean metasediments and Kanmantoo Group are controlled by the major north-north-west to north-north-east structural trends in the area. Deviations from this dominant strike pattern are seen around a few sites in the Mt Barker area, most likely because they are located within the hinge of major regional synclines and anticlines.

Although the borehole-to-surface technique shows localised results, it is evident from the consistent interpretations throughout the field area that orientations of the dominant hydraulically conductive sub-vertical fractures are consistent with regional trends. Borehole-to-surface electrical measurements exhibited significant variations in magnitude, which is indicative of different porosities and saturations within the area. Bulk electrical resistivity could be estimated from apparent resistivity and, at sites for which electrical conductivity was measured, porosity could also be estimated. The ratio of maximum to minimum apparent resistivity could be attributed to the hydrogeology and used to characterise areas exhibiting substantial differences in fluid flow. Due to the linear vs. cubic nature of electric hydraulic conductivity, a doubling of electrical conductivity could potentially correspond to an eight-fold increase in fluid flow in the dominant fracture orientation. The bulk resistivity is also linked to the salinity of the groundwater and variations are partially attributed to this.

Deviations of surface potential from those expected within a homogeneous medium can be attributed almost exclusively to fracture or bedding-plane orientations, although other conductive materials may contribute. However, aligned conductive minerals may still be a proxy for fracture orientation due to the nature of the structural control in the area and, as such, could have similar orientation to dominant conductive zones resulting from open fractures. It is unlikely that this is a major concern for the EMLR region as a discernable trend of greater anisotropy was not seen in lithological units with more conductive material.

While borehole-to-surface surveys are limited to sites where at least one borehole exists, the method is neither time-consuming nor labour-intensive. Surveys undertaken (including SP methods) in the EMLR took about four hours per site, meaning that two sites could usually be surveyed per day.

The electrokinetic measurements at some sites show large (up to 60 mV) variations with time due to drawdown associated with pumping, particularly over the first five to ten minutes. These changes showed groundwater movement in the proximity of the electrodes and allowed quantification of the direction of groundwater flow at some sites.

However, at some sites, the potential changes are less than 1 mV, and hence are difficult to detect above the noise levels. The magnitude of changes in the electrokinetic measurement can be attributed to fluid flow rates and the depth of conductive zones. A comparison of surface profiles for analytical and observed solutions of SP can be used to determine an average hydraulic conductivity for the site. This potentially can be related to the drawdown although it is more complicated with depth when attributes of the media act extremely different to porous media. Electrokinetic potentials allow a greater understanding of the subsurface fluid flow and could be used to infer distances for zones of influence around the well.

The interpretation that borehole-to-surface electrical methods are mapping the bedding planes, and not the deeper fractures feeding the system, is consistent with previous work (Skinner and Heinson, 2004). The deeper fractures may be sub-horizontal, such that borehole-to-borehole electrical methods may enhance interpretation of cross connection (a third method not explored in this study).

These two electrical methods are sampling the top 20 metres at most, however this is a depth range from which the majority of pumping occurs in the EMLR. Much of what is being imaged is the water in fractures parallel to bedding planes and these are likely to be open due to uplift and stress relief (Fig. 22).

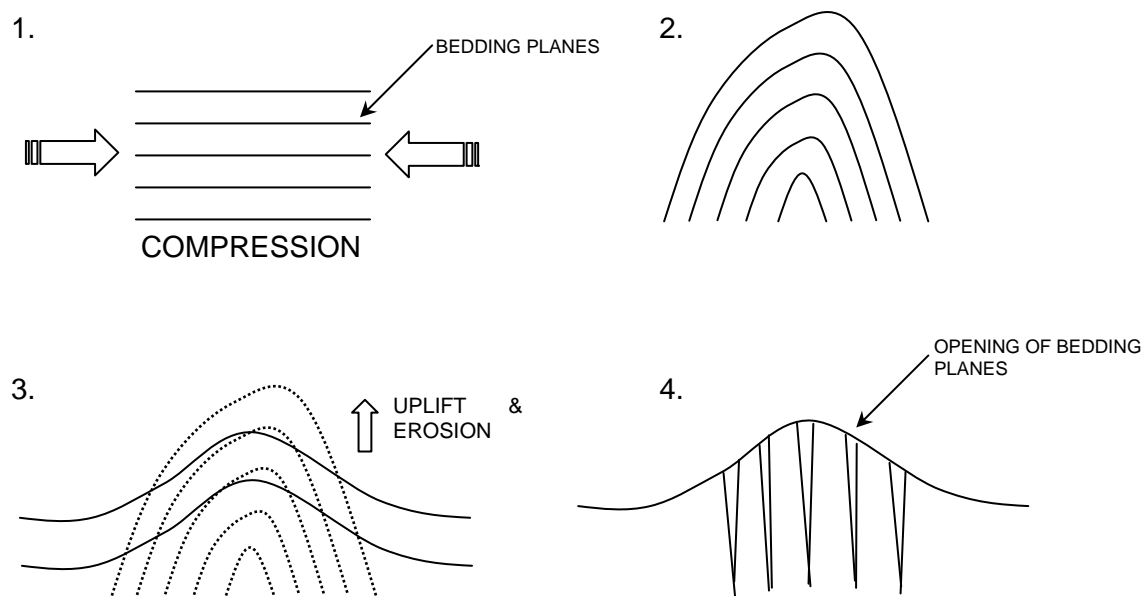


Figure 22. Sequence of events which facilitate fracture development in a fractured rock environment

Recharge in this top 20 metres is a mixture of local rainfall (which moves down the bedding planes) with some contribution from deeper fractures.

Due to the complex distribution of fractures in almost every type of rock, no single method can unambiguously map fractures and their capacity for fluid movement. Although self-potential is a relatively new technique, using interpretations from the two methods will lead to a greater understanding of characterisation subsurface flow in recharge zones and can be used to define orientation of fractures in terms of strike and dip, as well as broadly defining bulk electric resistivity, bulk porosity and hydraulic conductivity. By using a combination of the methods described it could be possible to determine zones of influence around pumping wells in the future, primarily inferring dominant orientation of strike from resistivity methods and an estimate of the elliptical radius from magnitude of electrokinetic measurements.

7. RECOMMENDATIONS

The investigation showed that the borehole-to-surface DC resistivity proved to be effective in determining preferential fracture orientation as defined by both strike and dip. It compares well with the known structure in the EMLR.

Based upon these geophysical findings, the extents of the zones of influence around a number of extraction wells in the EMLR have been identified. These buffer distances can be recommended for these specific sites and provide a guide to the method by which buffer distances can be determined in water management plans. The direction and range of magnitudes of the hydraulic anisotropy identified at the locations assessed provides a guide to the specification of buffers for wells in similar geological settings.

Hydraulic anisotropy may be applied to (or refine) existing extraction well buffer guidelines in line with the following example. A nominal buffer for a particular area depending on geology, geological structure and rate of and volume of extraction, may typically have a radius of 200 metres. Current guidelines assume equal drawdown in each direction from the extraction well and hence a circular buffer (with this radius) is applied. However in a fractured rock environment there will be preferential fracturing in a particular direction. Using Site 19 (Table 4) as an example, this site exhibits preferential fracturing in the north-east to south-west direction (direction of strike and anisotropy). The hydraulic anisotropic ratio was calculated to be 4 (Table 4). Therefore the radius of the maximum axis (in the north-east to south-west direction) would be four times that of the minimum axis (in the south-east to north-west direction).

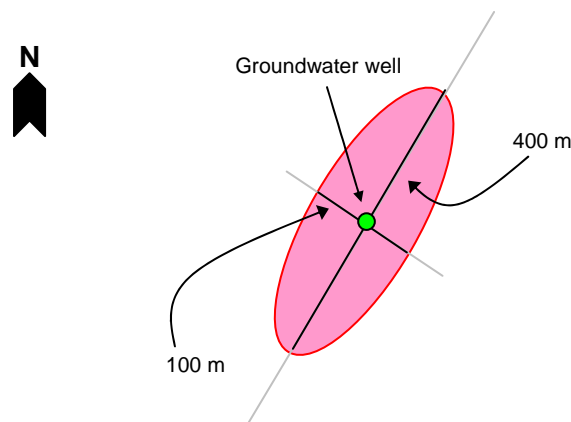


Figure 23. Hypothetical example of anisotropic direction and ratio as applied to circular buffering system. Assuming circular buffer radius of 200 m with a anisotropic strike direction of NE/SW and a hydraulic anisotropic ratio of 4.

In order to maintain an area size similar to the current (circular) buffer guidelines, the radius would be reduced by 50%, this becomes the radius of the minimum axis. The anisotropic ratio is then applied to this minimum axis to generate a radius for the maximum axis. Using the example of Site 19 and an original (circular) buffer of 200 metres, an ellipse with the following specifications would apply (Fig. 23):

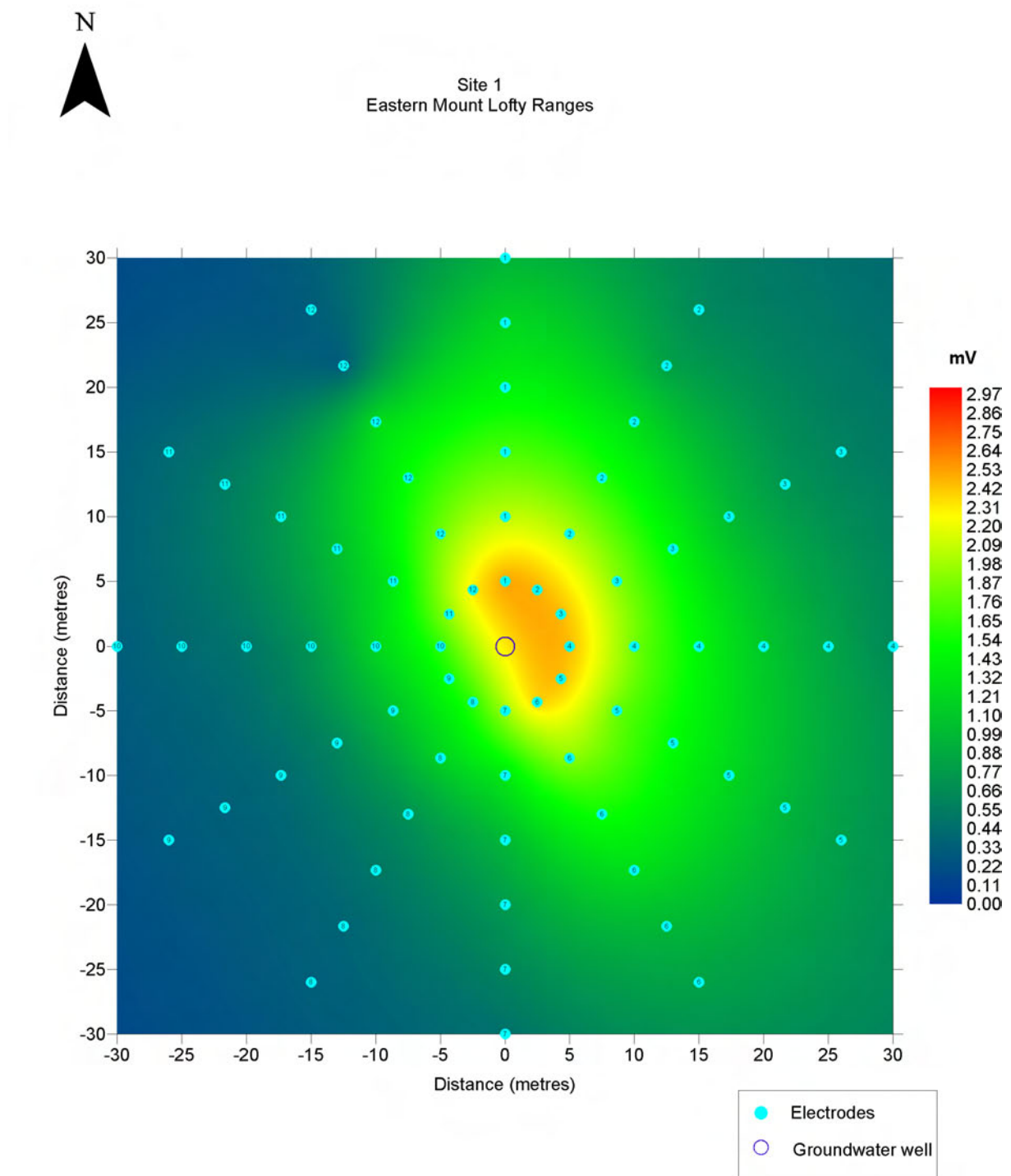
- Minimum radius in the SE/NW direction = 100 metres
- Maximum radius in the NE/SW direction = 400 metres

It is recommended that these guidelines are used when reviewing buffer zones in current and future groundwater resource management plans.

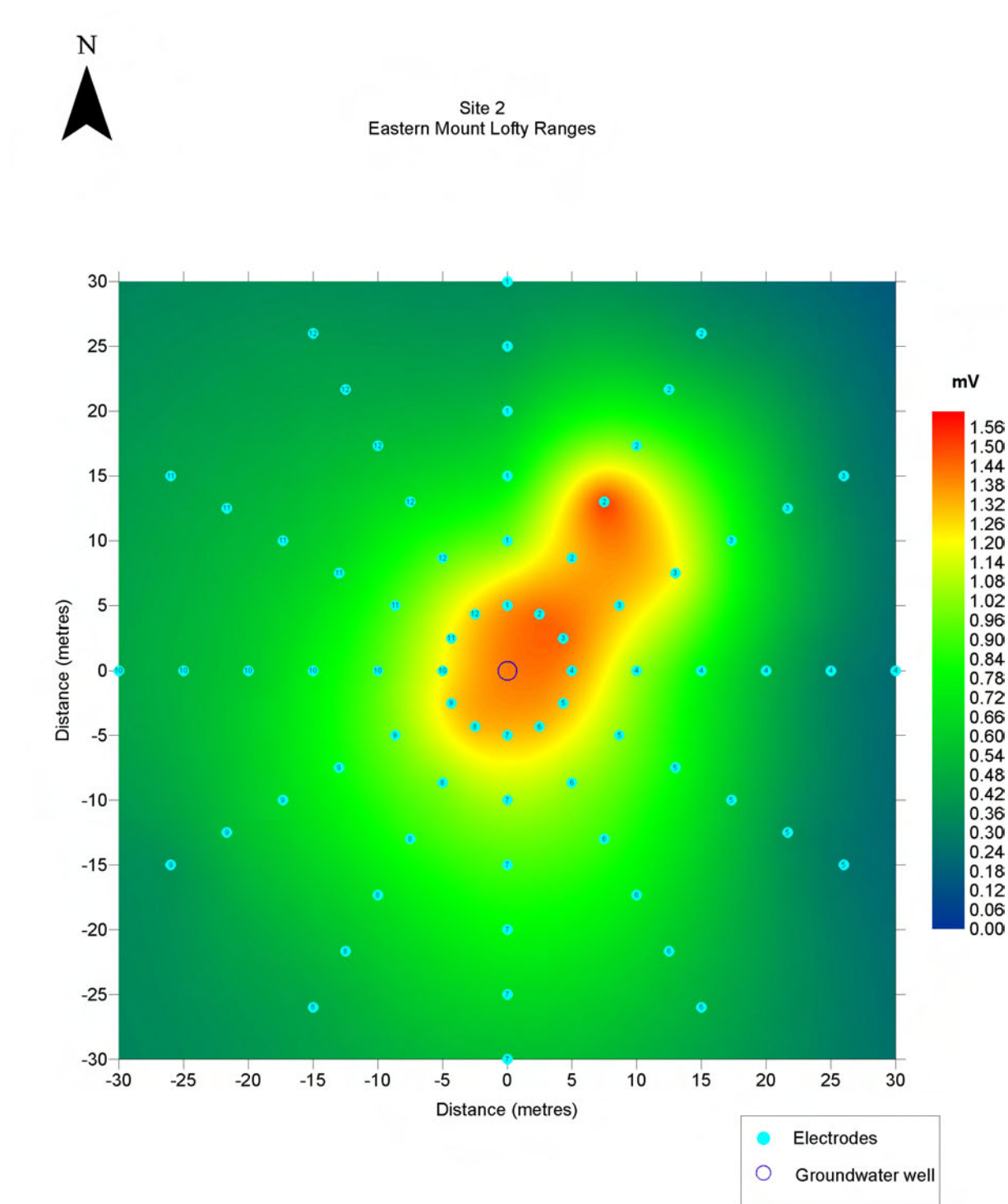
APPENDICES

A. SURFACE MAPS OF ELECTRICAL POTENTIAL FOR ALL 21 SITES IN THE EASTERN MOUNT LOFTY RANGES

SITE 1



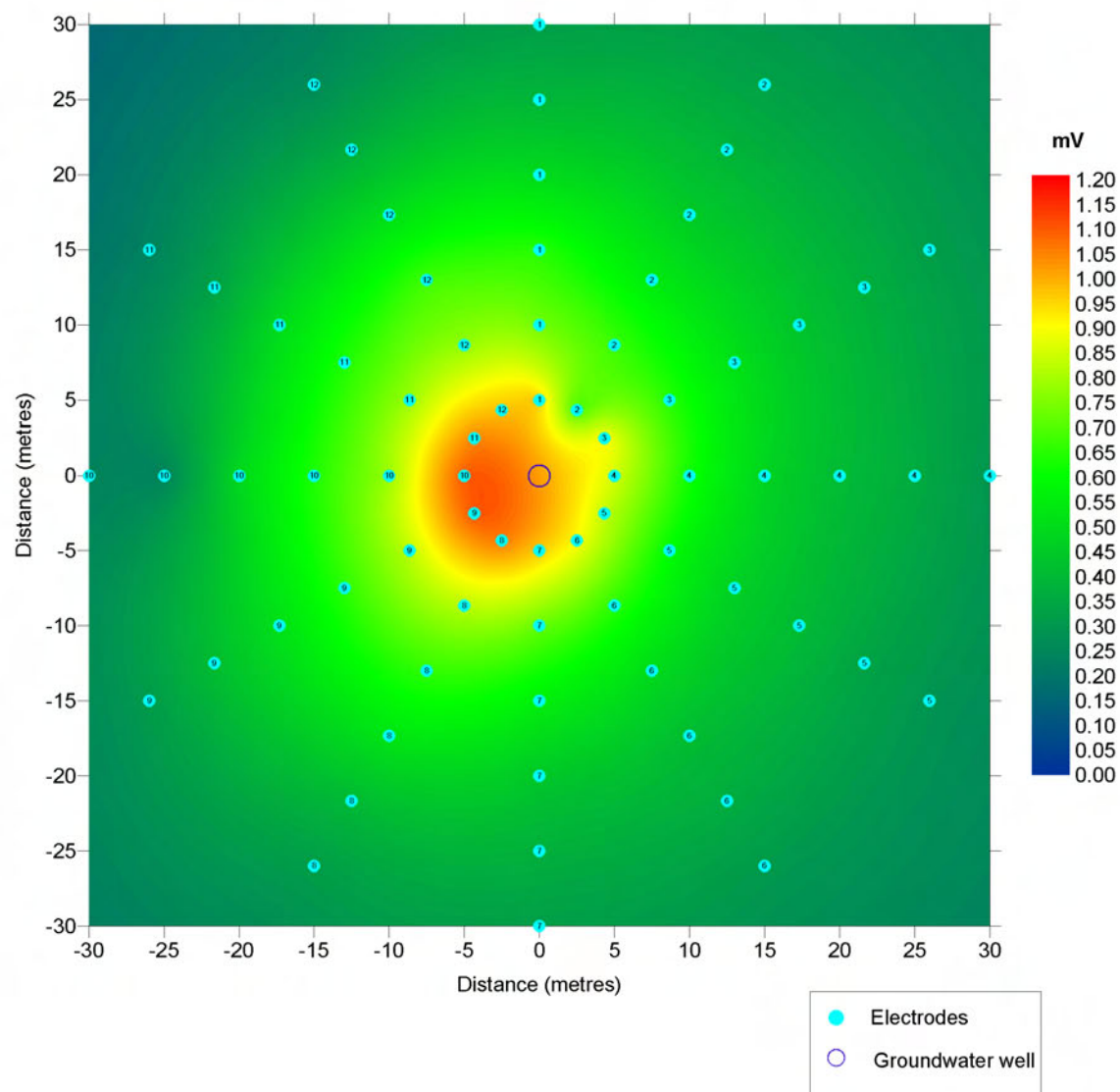
SITE 2



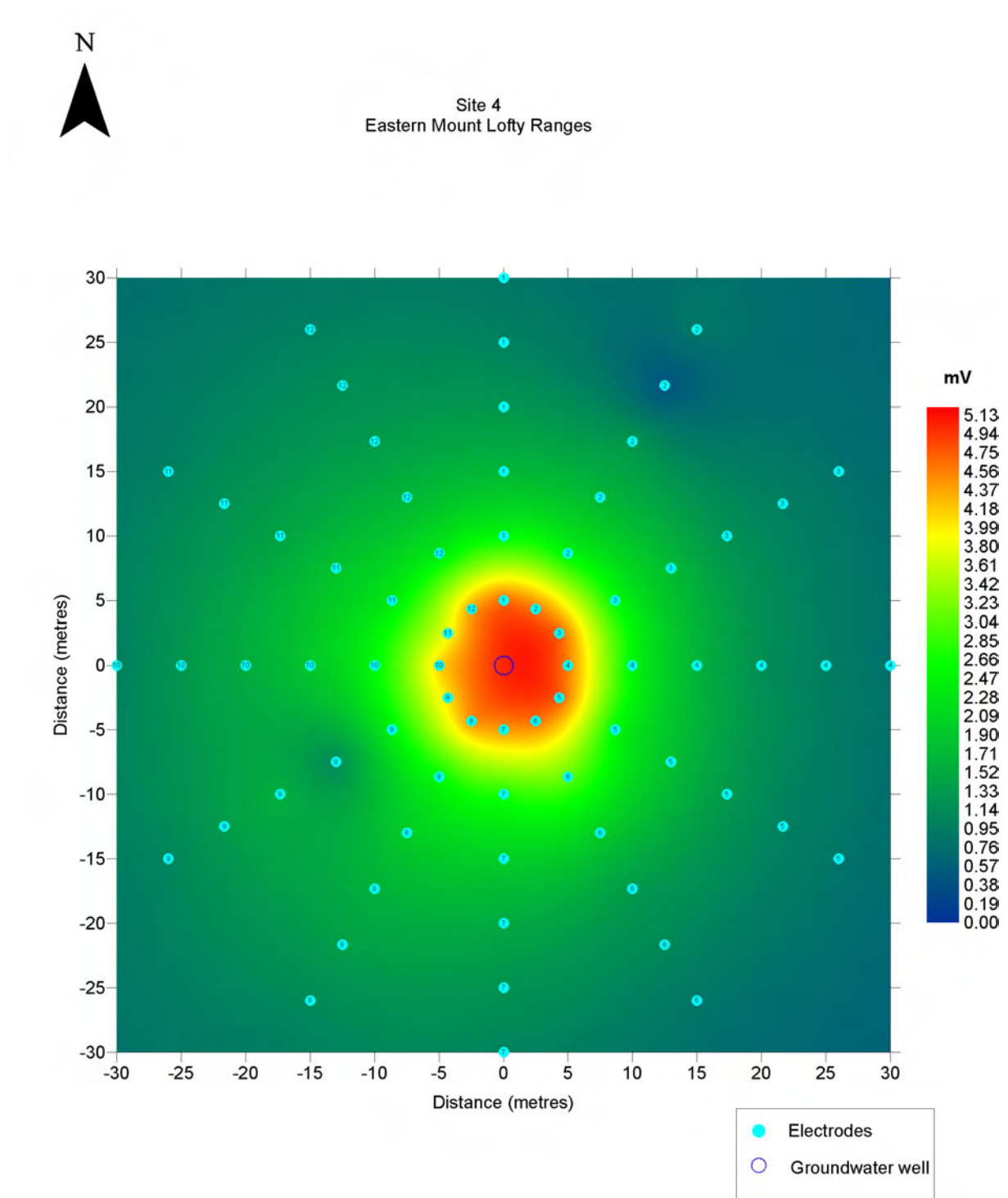
SITE 3



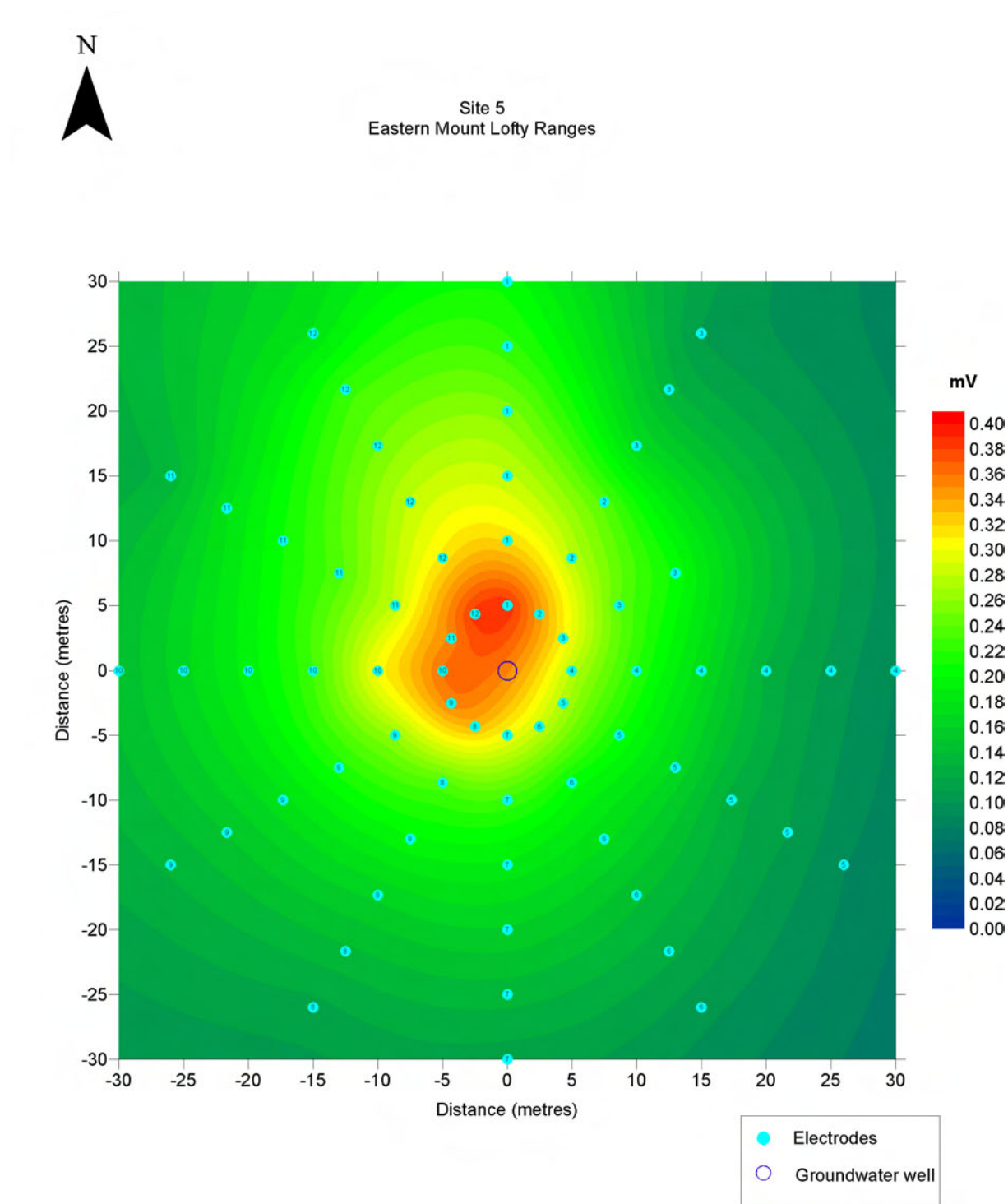
Site 3
Eastern Mount Lofty Ranges



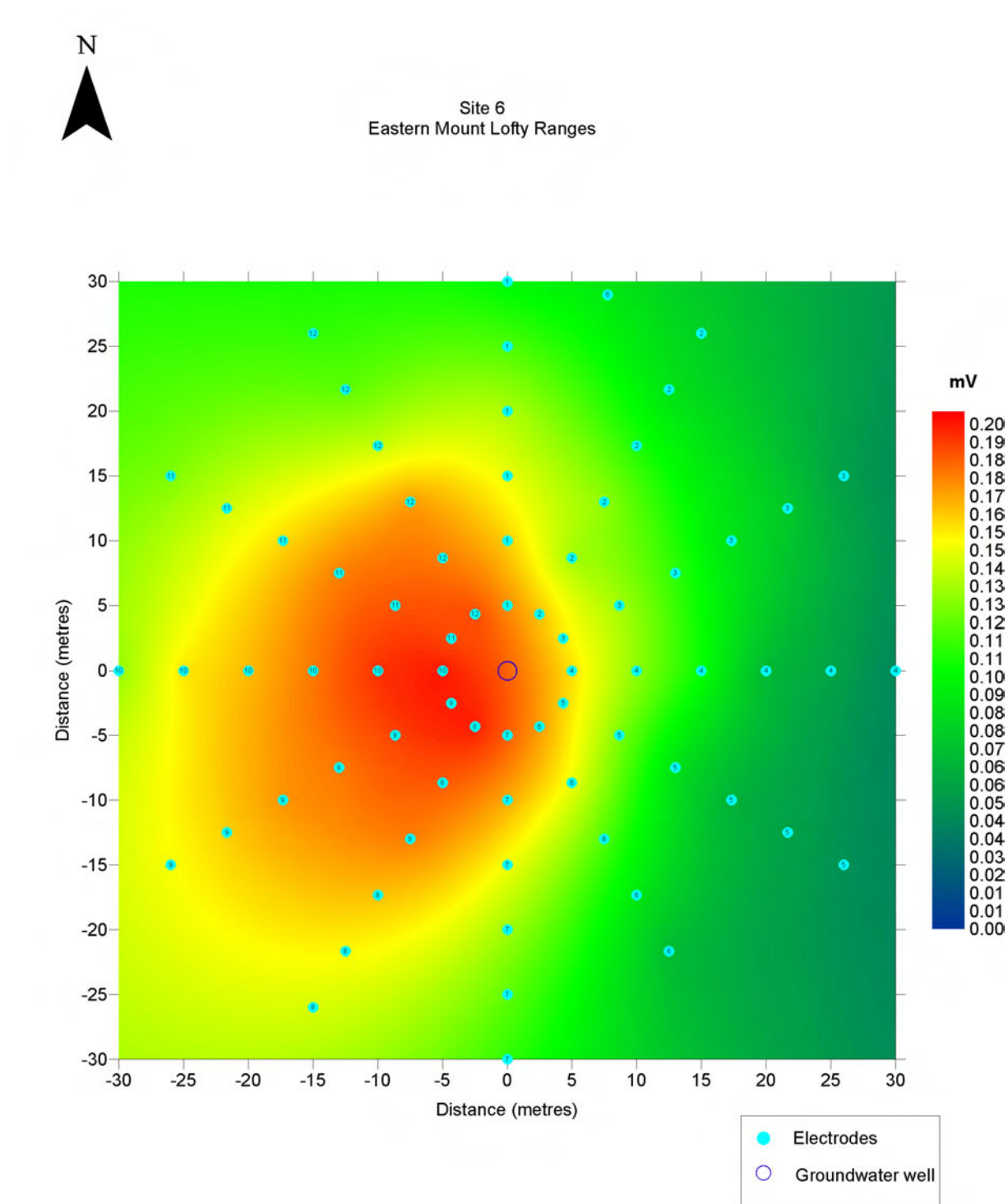
SITE 4



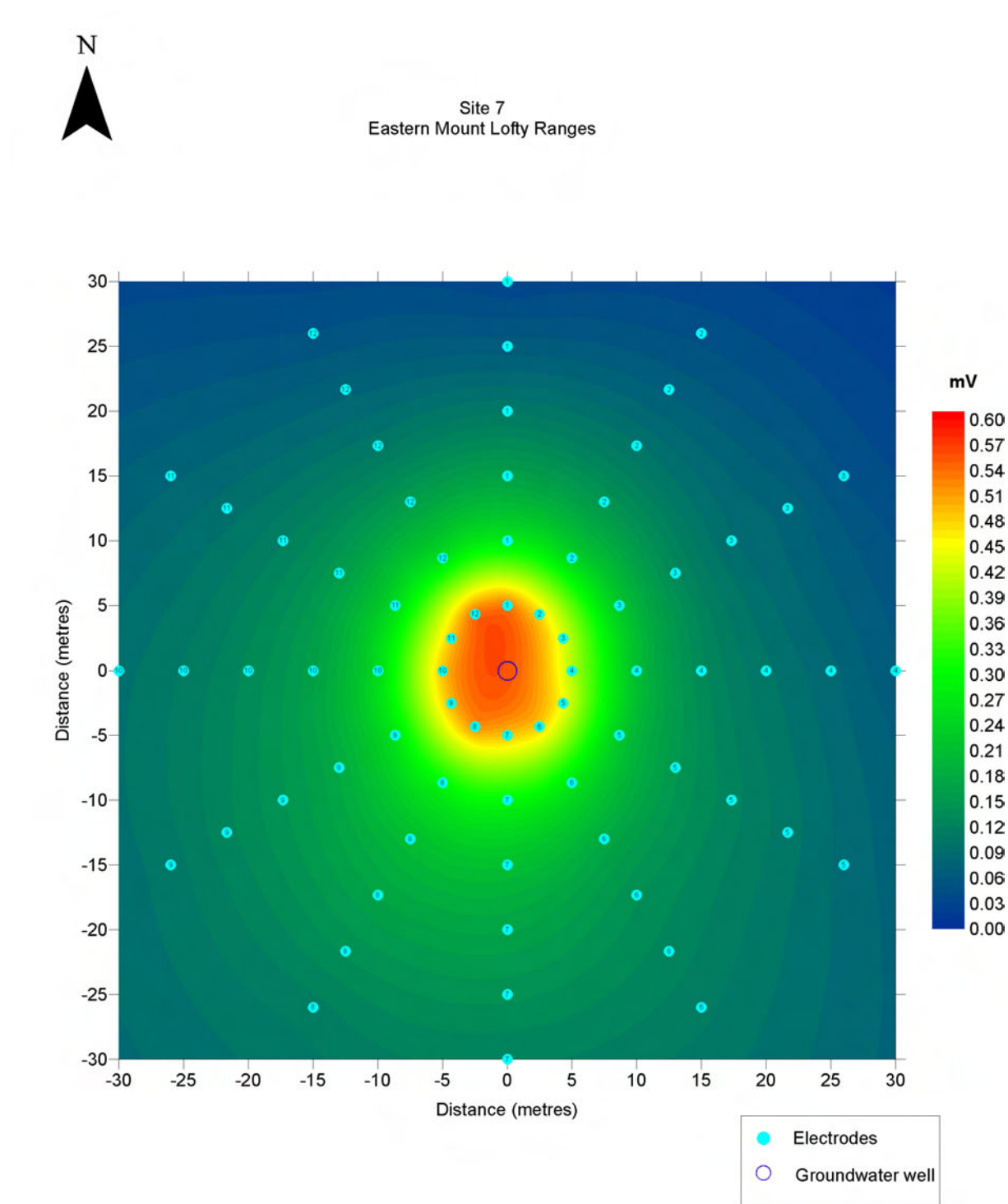
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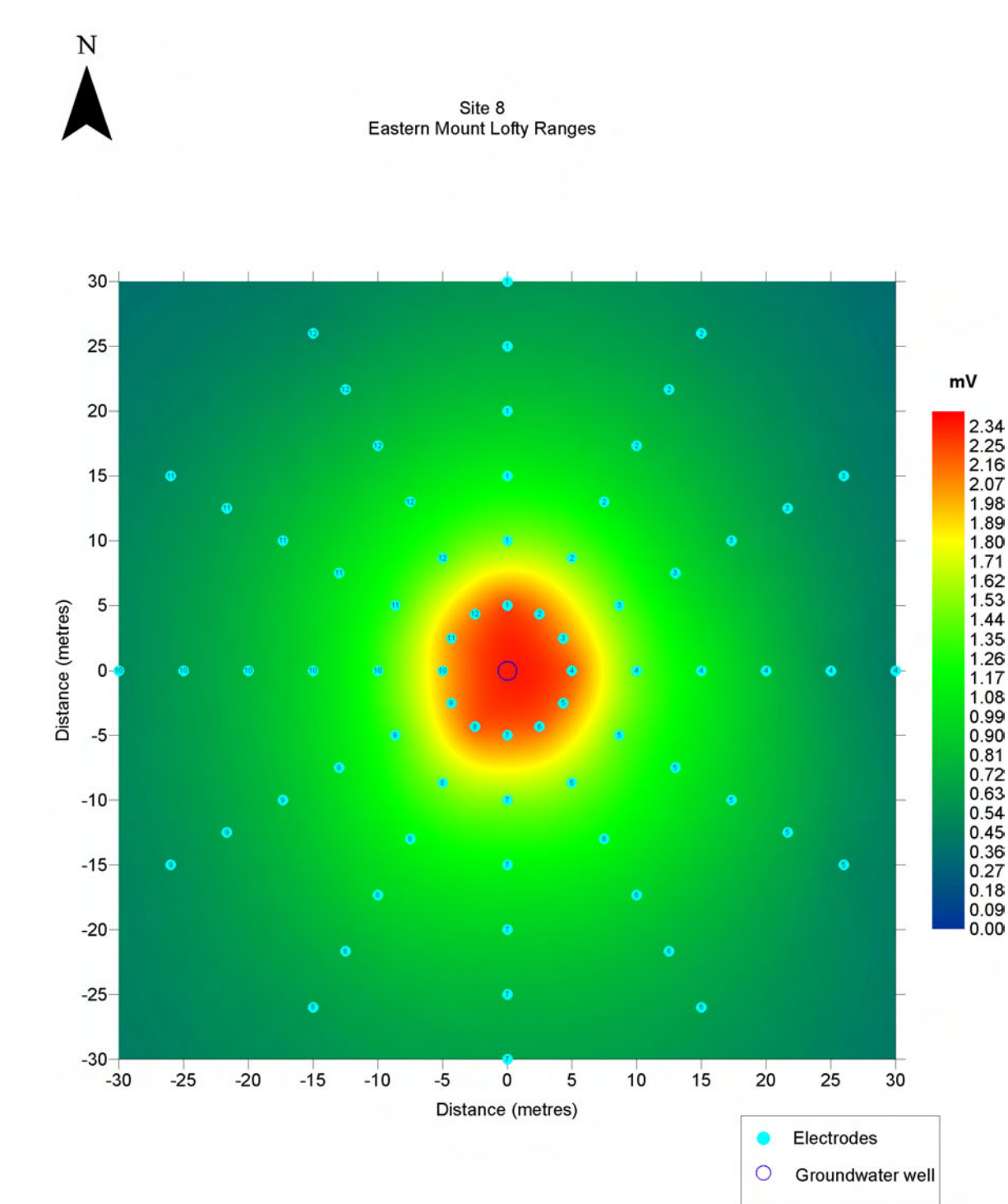
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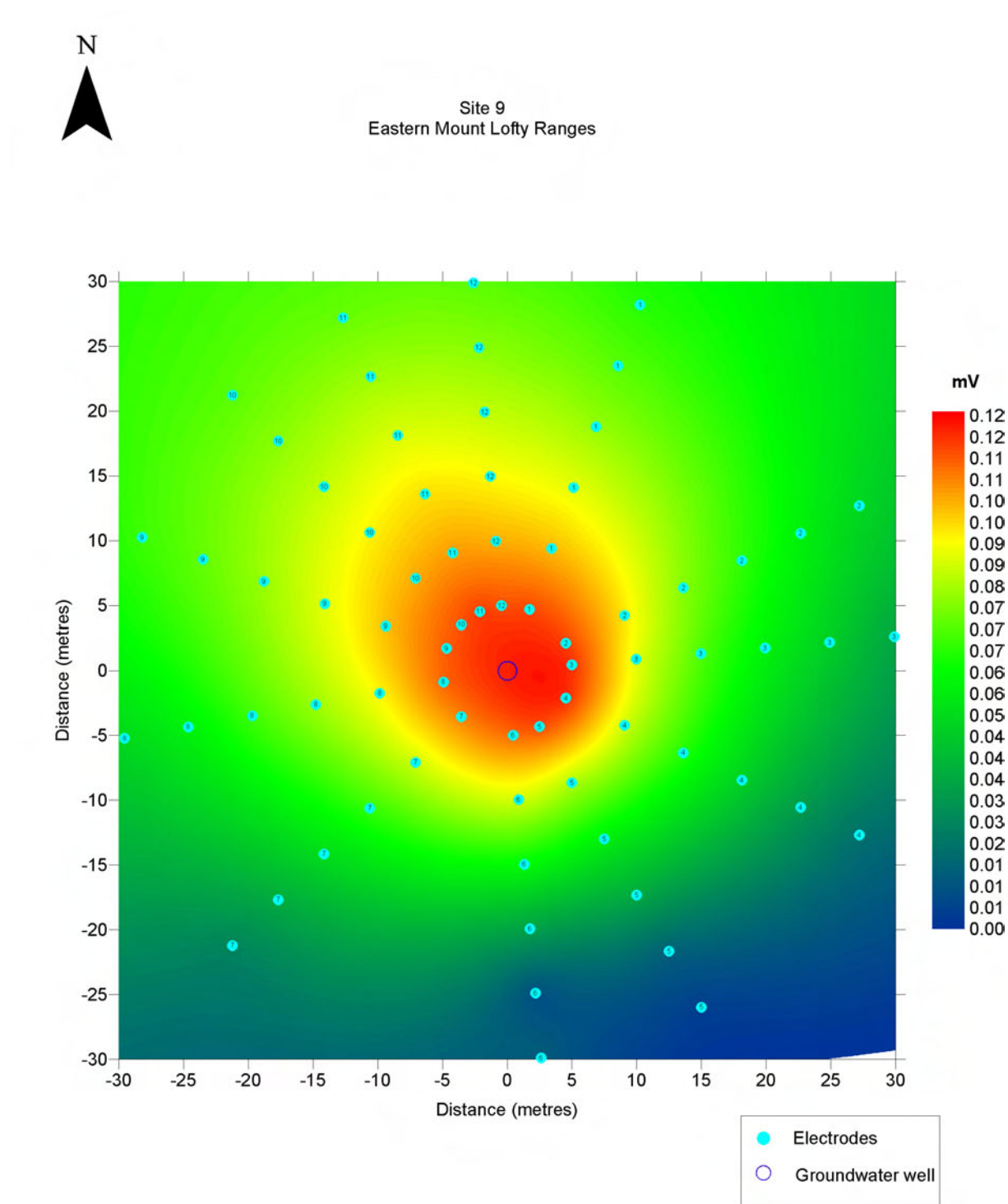
SITE 7



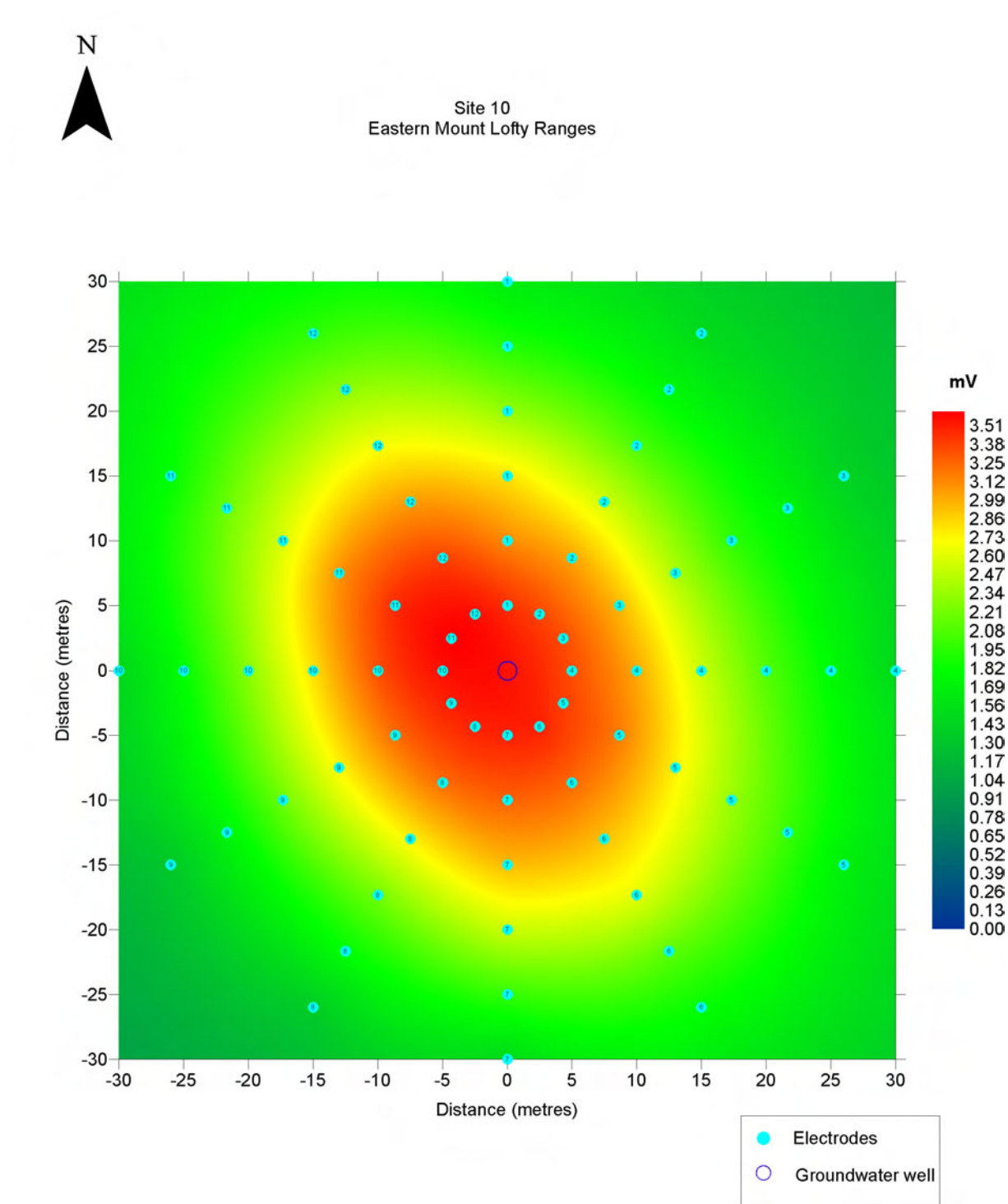
SITE 8



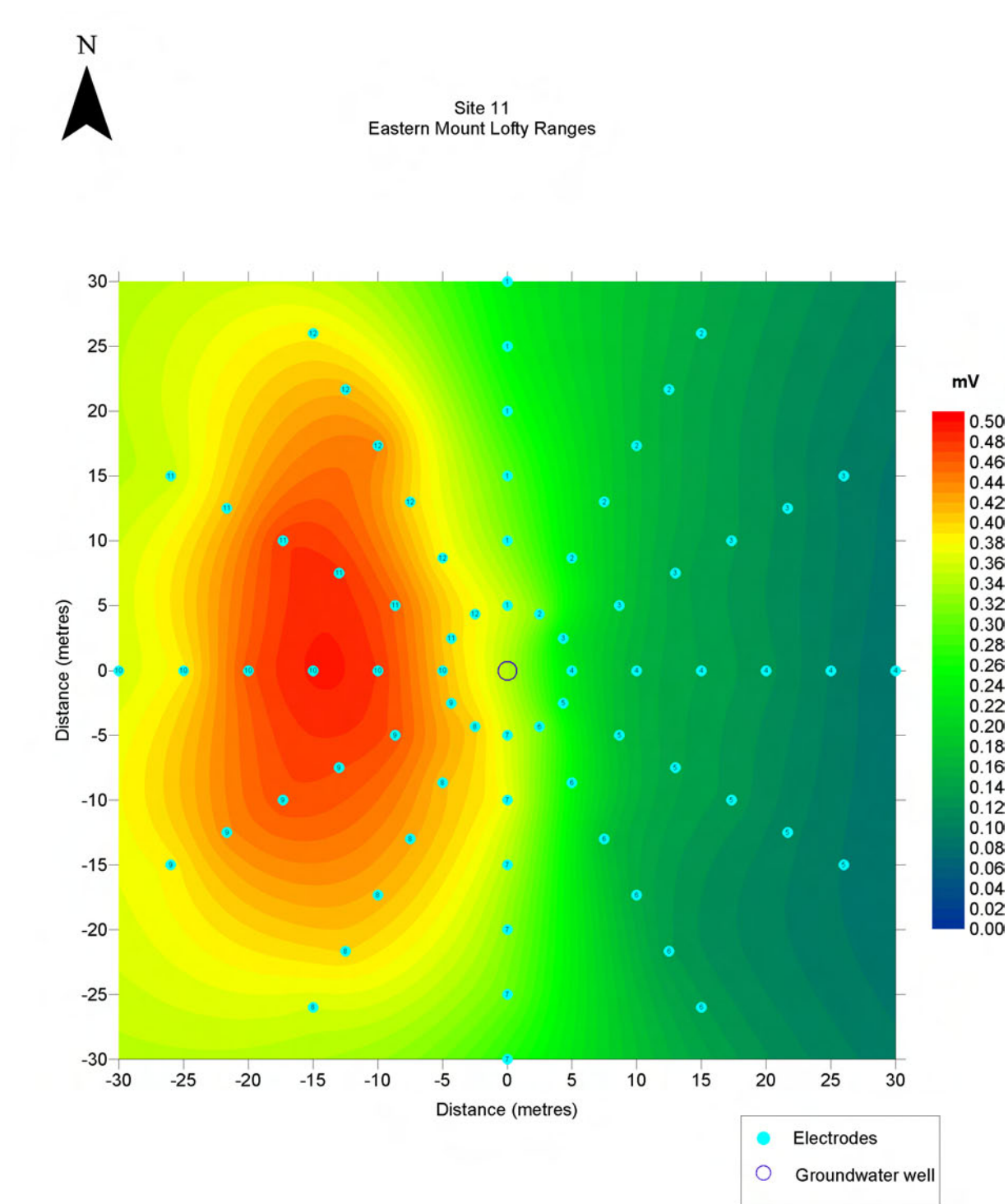
SITE 9



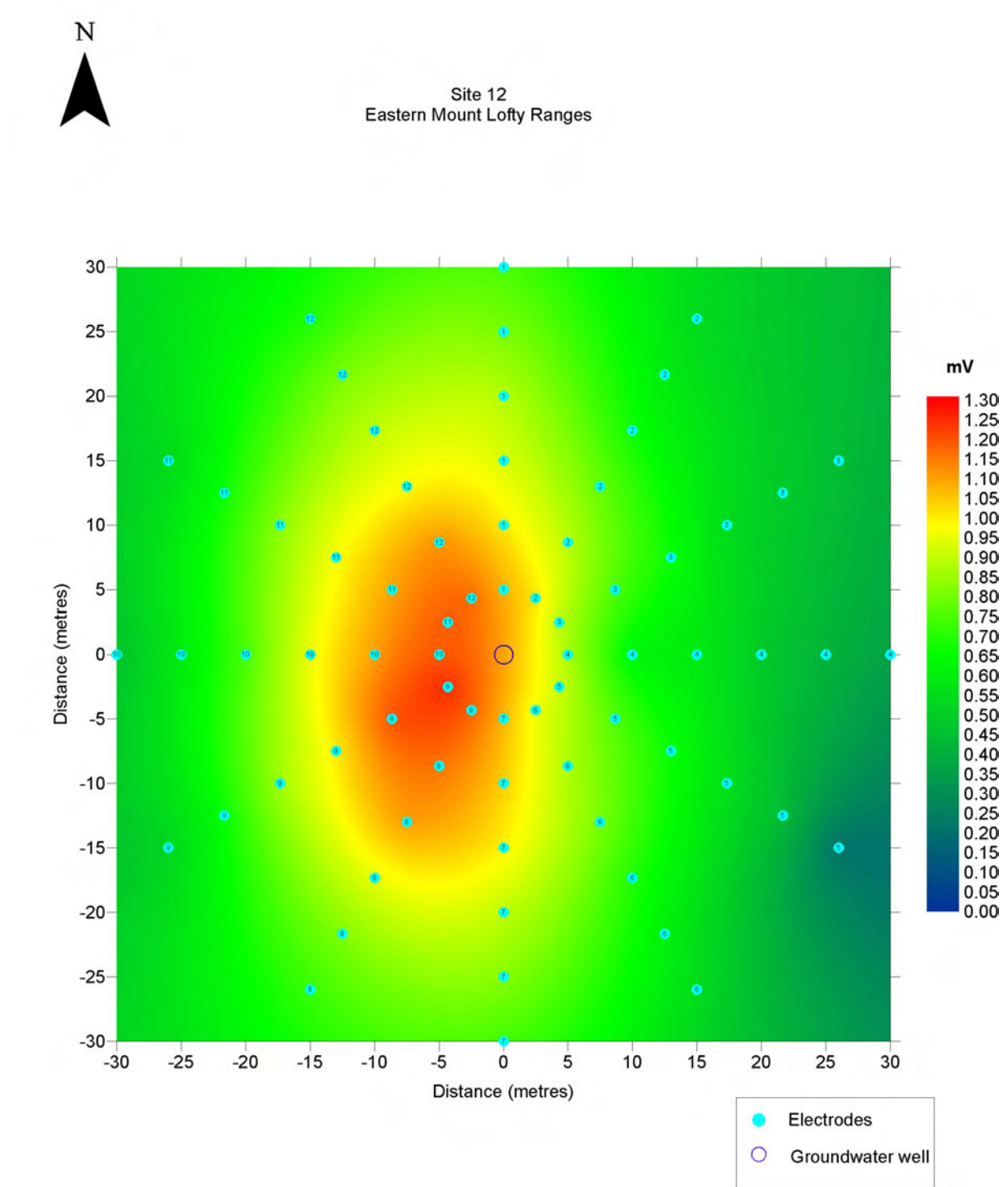
SITE 10



SITE 11



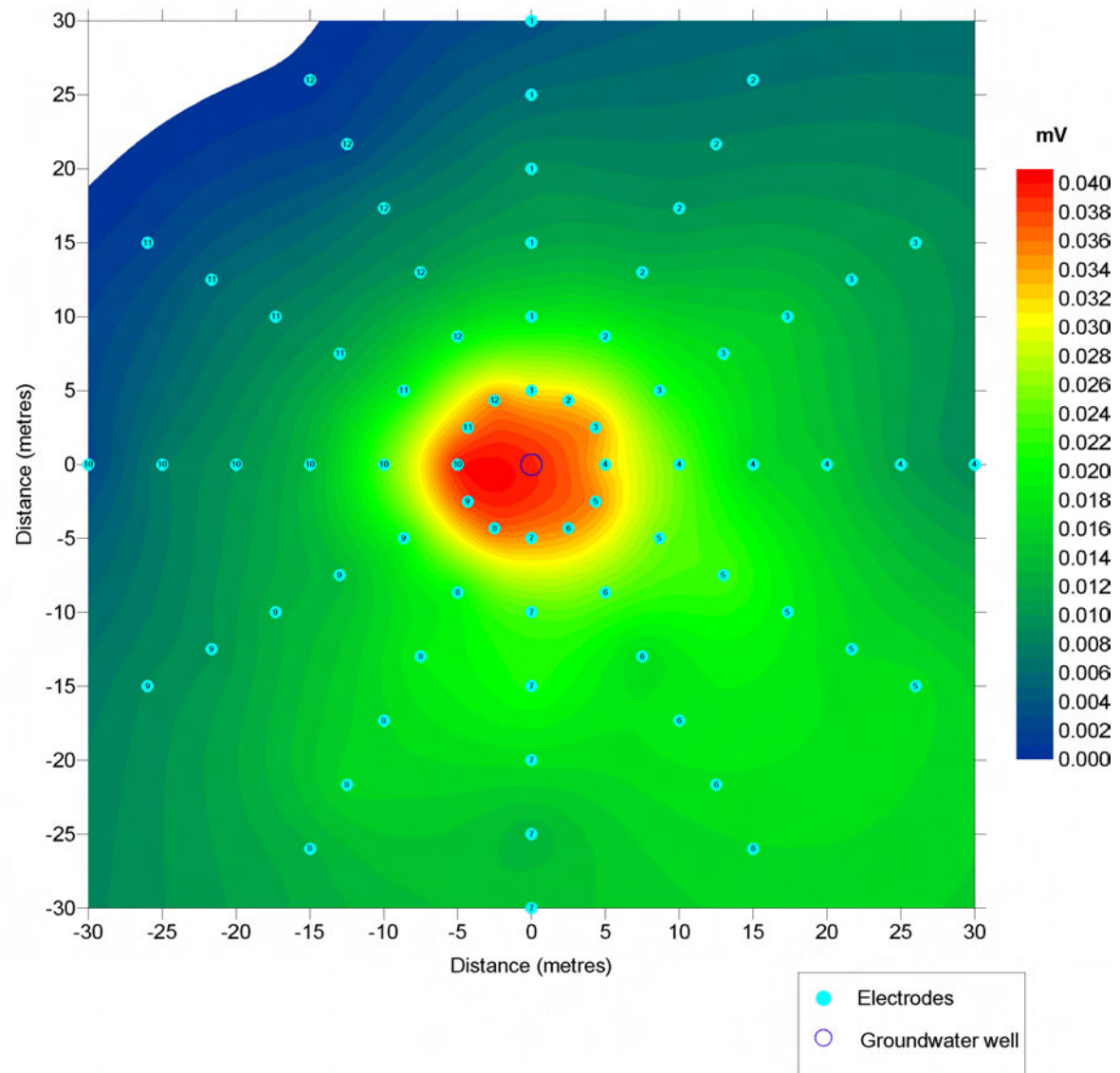
SITE 12



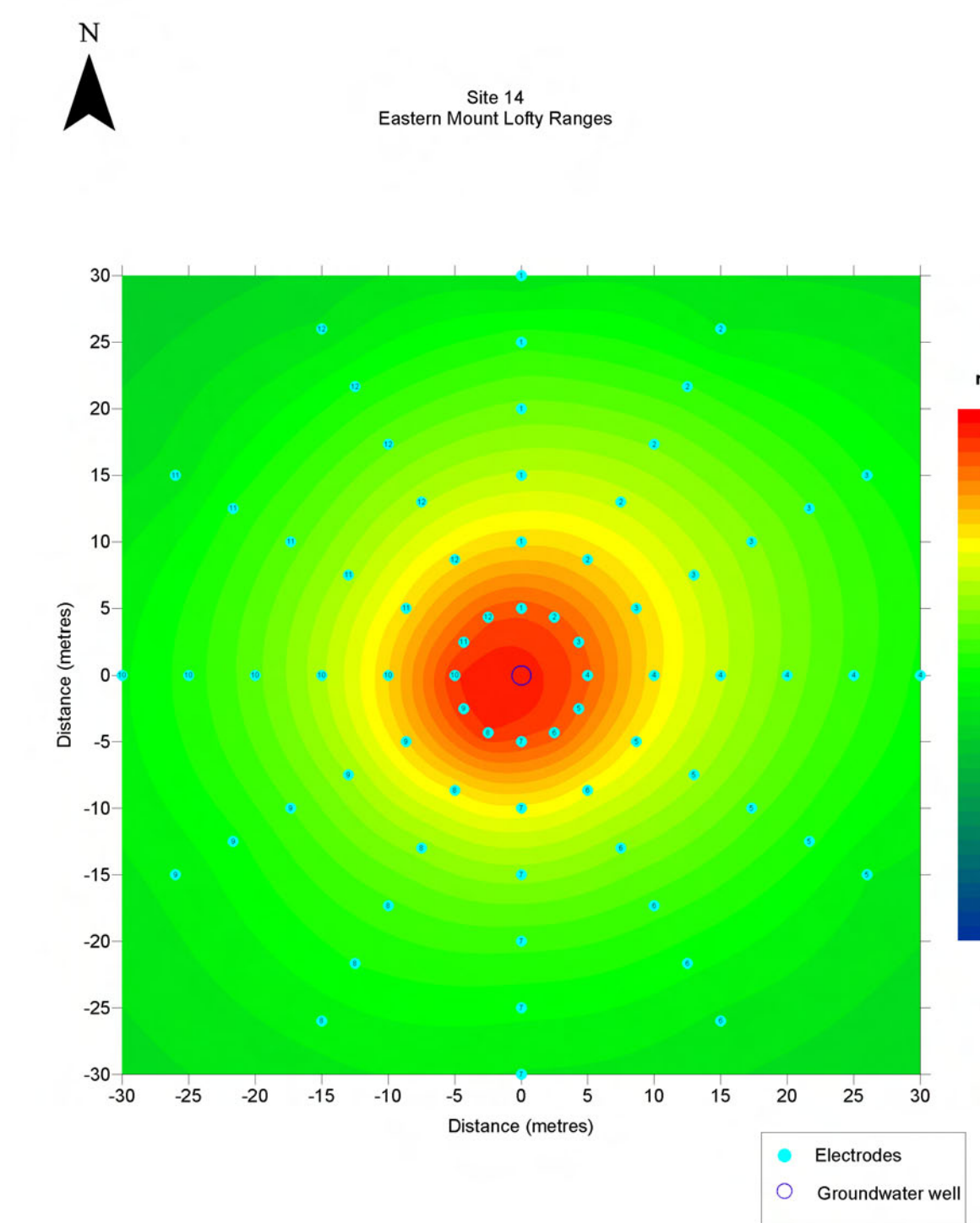
SITE 13



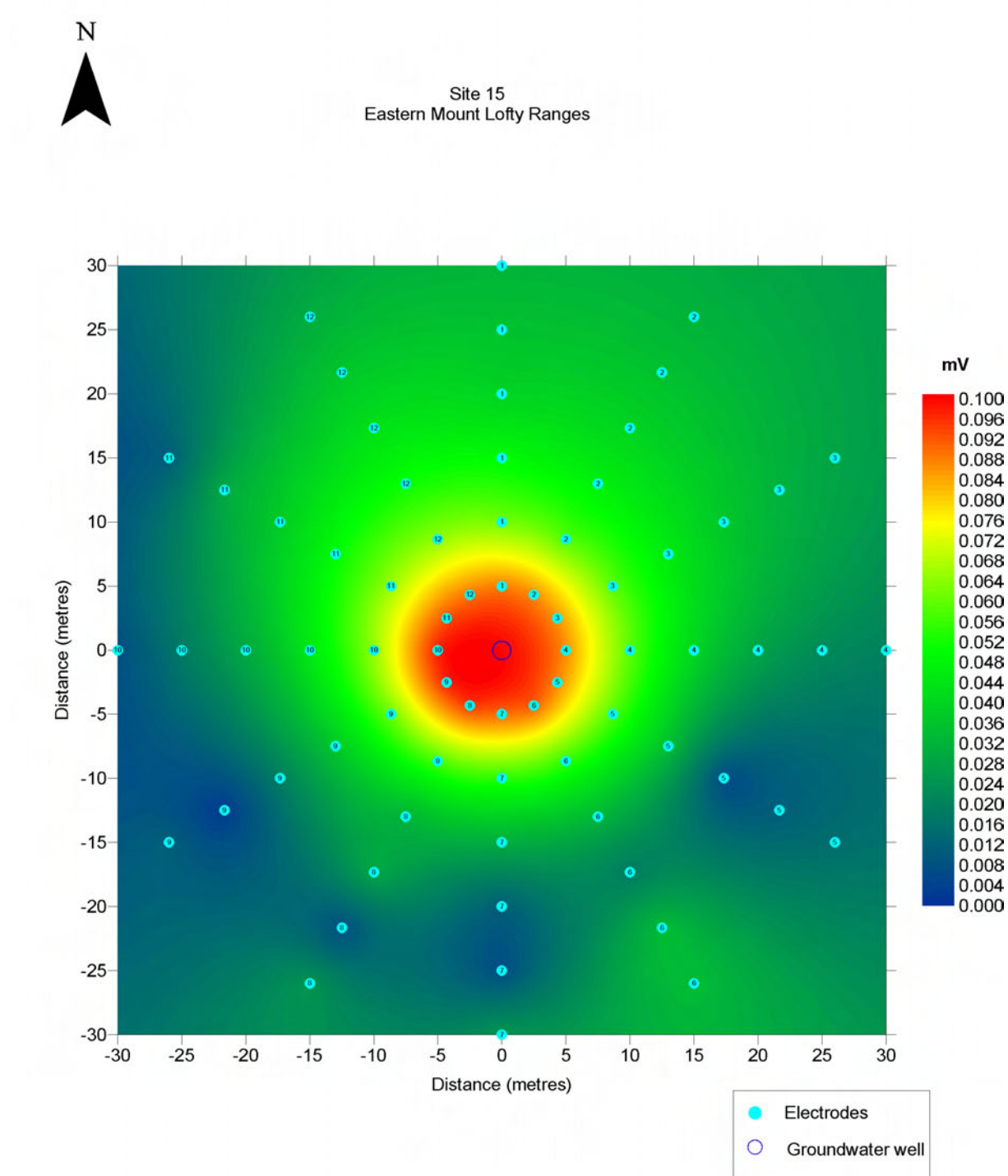
Site 13
Eastern Mount Lofty Ranges



SITE 14



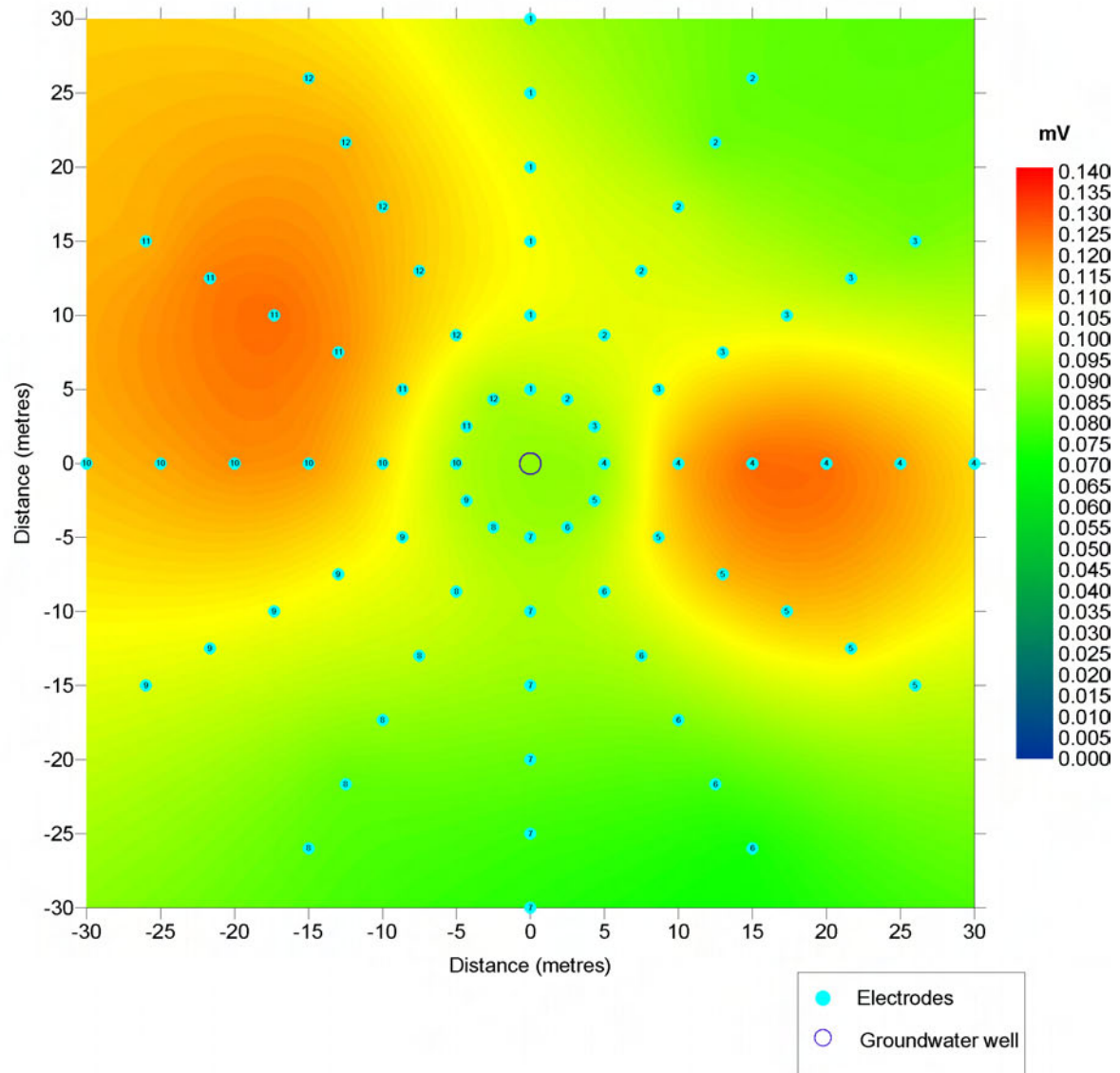
SITE 15



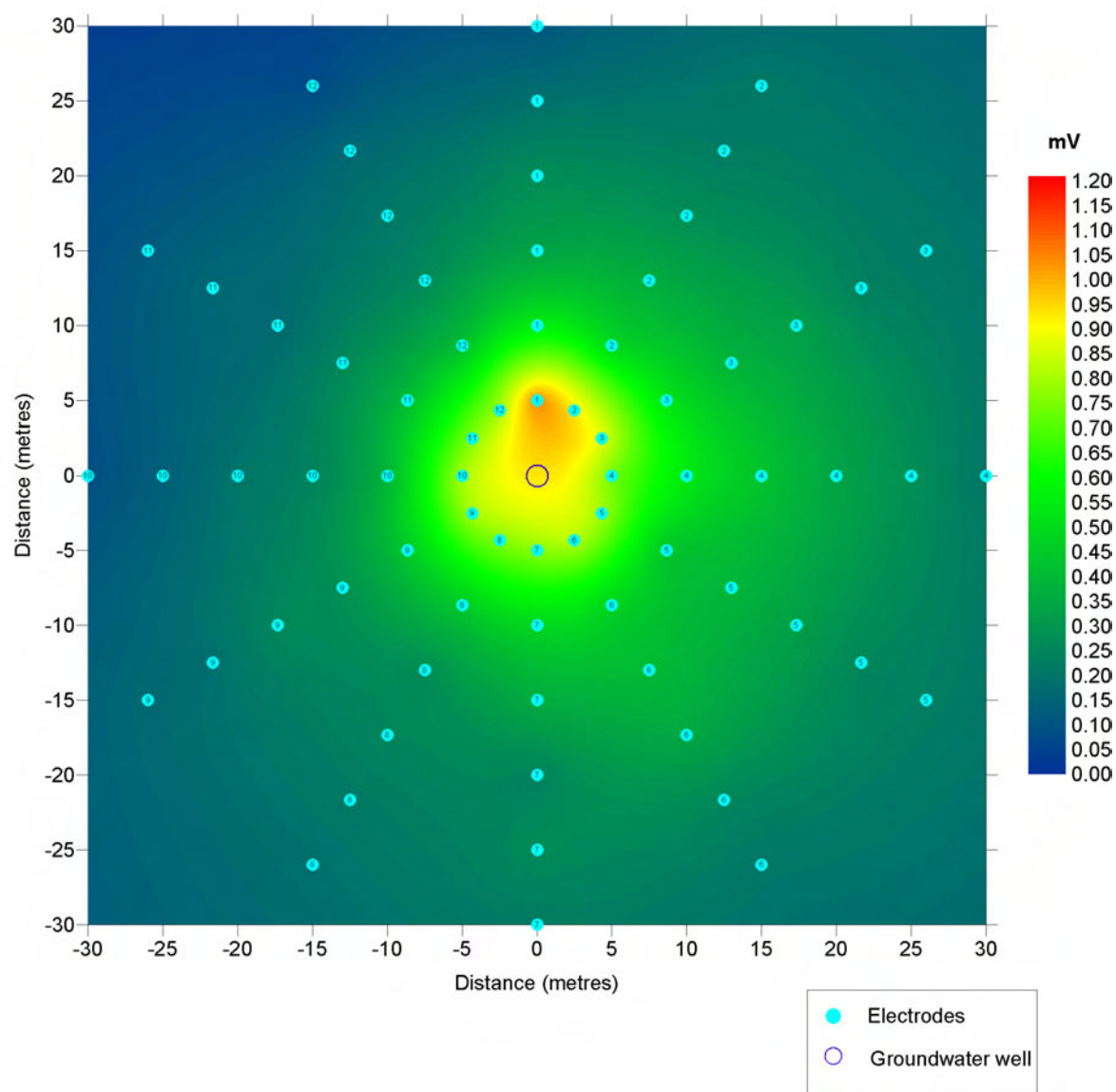
SITE 16



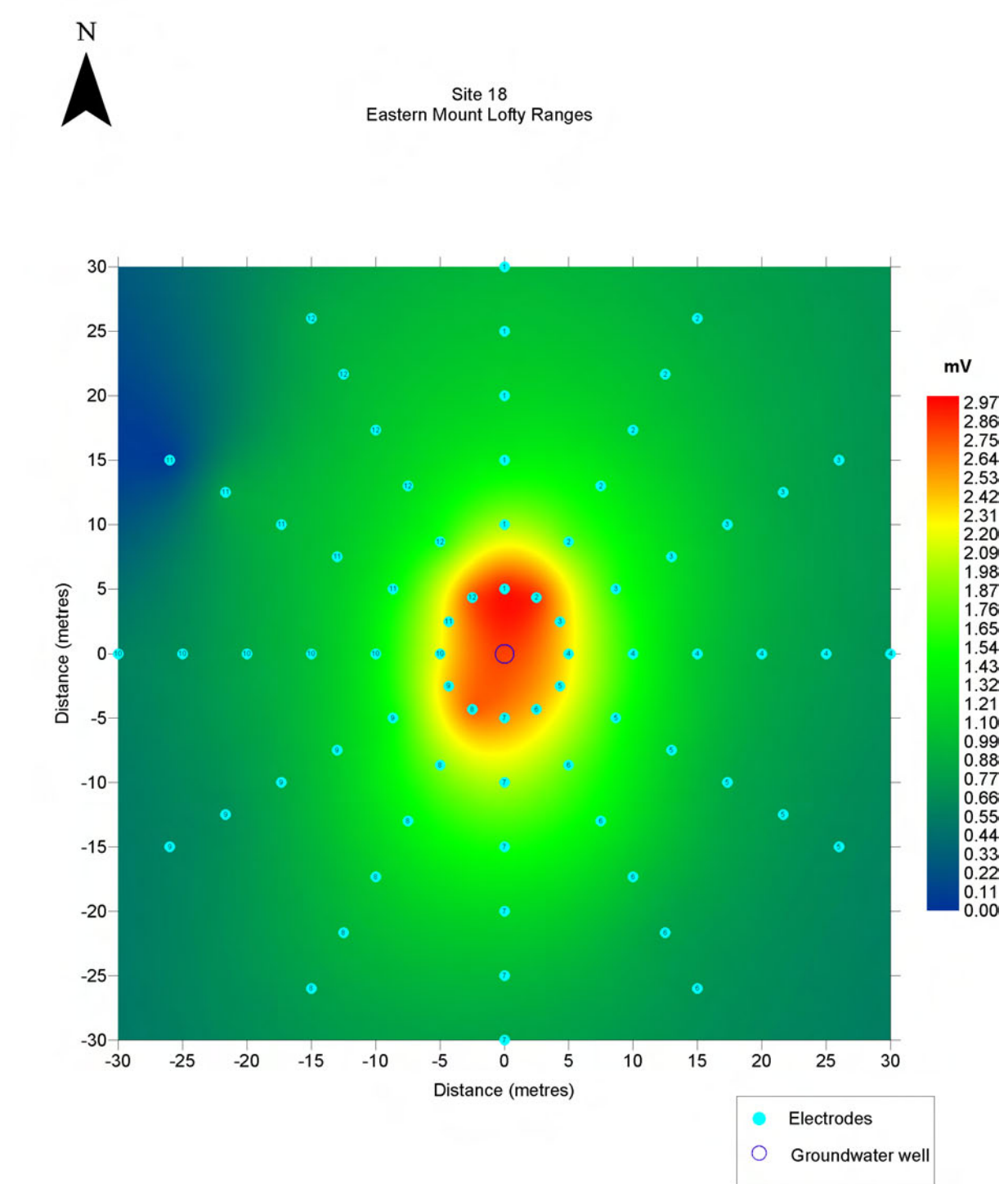
Site 16
Eastern Mount Lofty Ranges



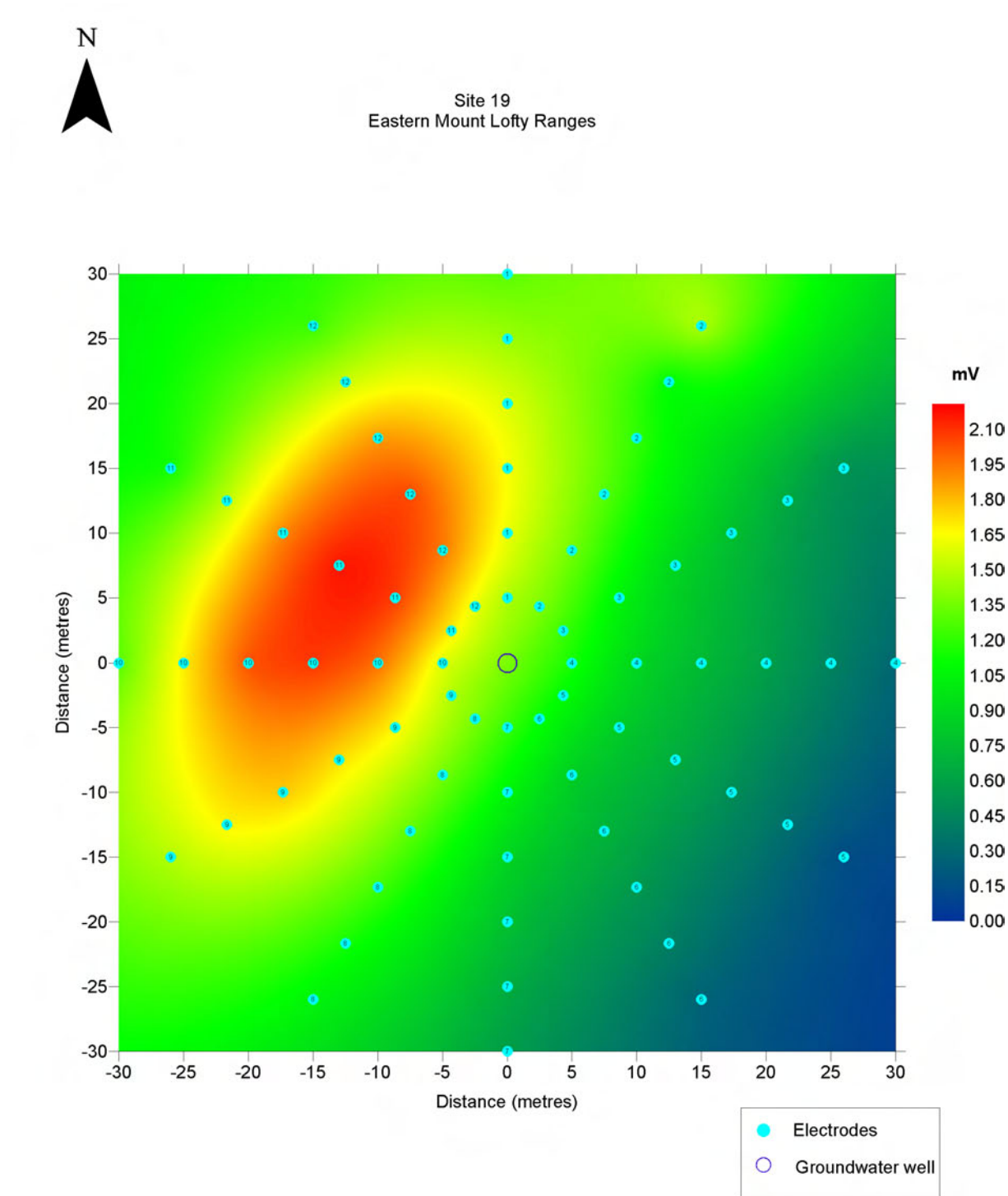
SITE 17



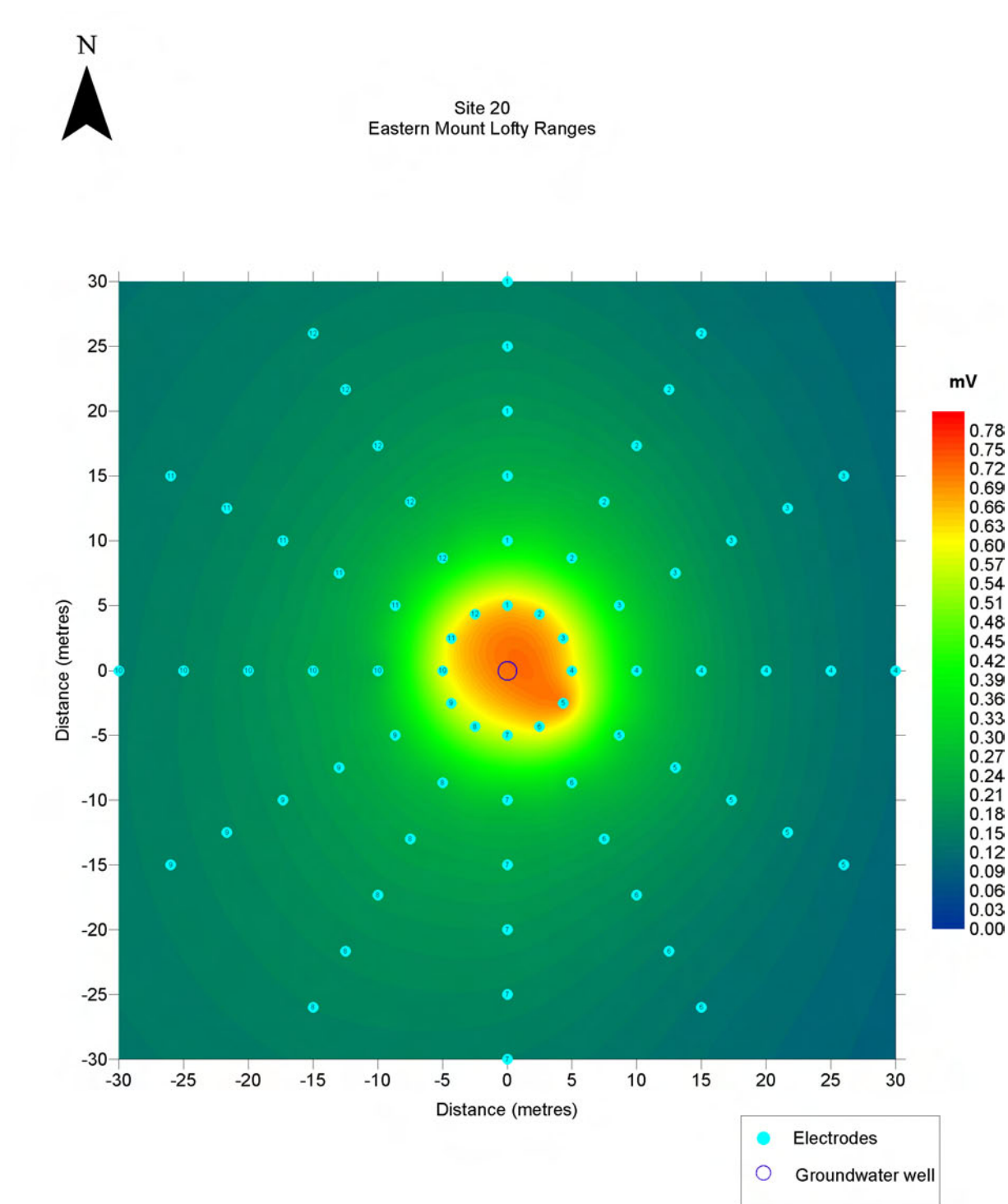
SITE 18



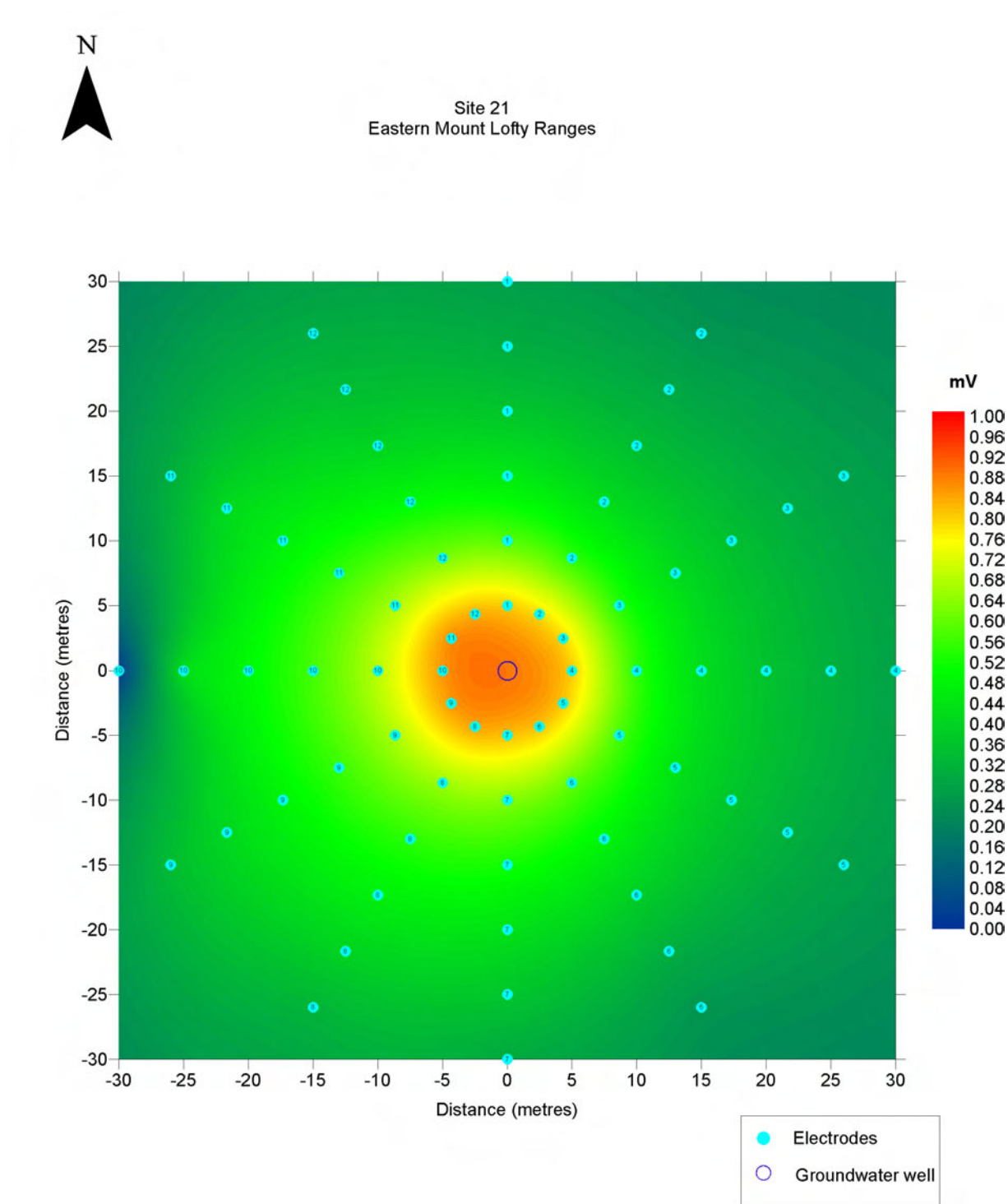
SITE 19



SITE 20



SITE 21



B. WELLS SELECTED FOR SURVEY IN THE EASTERN MOUNT LOFTY RANGES WITH GEOLOGICAL DESCRIPTION

Site	Unit Number	Depth (m)	Geological Unit	Geological Formation	Structural Description	Formal Map Description
1	6728-2581	55.0	Eec	Carrickalinga Head Formation	n/a	Sandstone, grey, thick bedded, with thinly bedded, muddy, siltstone interbeds. Minor cross-bedding, ripples, rare trace fossils.
2	6728-3159	113.0	Eeb	Backstairs Passage Formation	n/a	Sandstone, laminated, thick bedded, slumped, crossbedded, with minor siltstone interbeds. Widespread siltstone unit at base.
3	6628-12161	138.0	Eeb	Tapanappa Formation Talisker Calc-Siltstone Backstairs Passage Formation	E limb of regional, F ₁ , N-S trending, S plunging syncline. Kanmantoo Syncline.	Sandstone, laminated, thick bedded, slumped, crossbedded, with minor siltstone interbeds. Widespread siltstone unit at base.
4	6628-12819	35.0	Eeb	Backstairs Passage Formation	Hinge of regional, F ₂ , anticline, NNW-SSE trending, S plunging. Parasitic fold 40->160.	Sandstone, laminated, thick bedded, slumped, crossbedded, with minor siltstone interbeds. Widespread siltstone unit at base.
5	6627-7520	81.4	Elt	Tapanappa Formation Talisker Calc-Siltstone Backstairs Passage Formation	W limb of regional, F ₂ , NNW-SSE trending, S plunging anticline. Crenulation cleavage developed in N section of area.	Sandstone to greywacke, fine to coarse-grained, dark grey, thick-bedded to laminated; interbedded with laminated siltstone and thin, sulphidic siltstone and lenticular grit to conglomerate beds. Scour and fill channels, rare cross-bedding.
6	6627-10244	65.0	Nnt	Tapley Hill Formation	E limb of regional, F ₁ , N-S trending, S plunging anticline. Strathalbyn Anticline.	Siltstone, grey to black, dolomitic and pyritic grading upwards to calcareous, thinly laminated, locally cross-bedded; dolomite, grey, flaggy to massive; limestone conglomerate, intraformational; greywacke.
7	6627-10727	88.0	Nnt	Tapley Hill Formation	Hinge of regional, F ₁ , syncline, N-S trending (170°), S plunging. Tight, angular fold, W vergence, inclined to E. Macclesfield Syncline.	Siltstone, grey to black, dolomitic and pyritic grading upwards to calcareous, thinly laminated, locally cross-bedded; dolomite, grey, flaggy to massive; limestone conglomerate, intraformational; greywacke.
8	6627-9480	98.0	Nnt	Tapley Hill Formation Tarcowie Siltstone	W limb of regional, F ₁ , syncline, N-S trending (170°), S plunging. Macclesfield Syncline.	Siltstone, grey to black, dolomitic and pyritic grading upwards to calcareous, thinly laminated, locally cross-bedded; dolomite, grey, flaggy to massive; limestone conglomerate, intraformational; greywacke.

9	6627-3288	70.2	Nnt	Tapley Hill Formation	Hinge of regional, F ₁ , anticline, N-S trending, S plunging. Strathalbyn Anticline.	Siltstone, grey to black, dolomitic and pyritic grading upwards to calcareous, thinly laminated, locally cross-bedded; dolomite, grey, flaggy to massive; limestone conglomerate, intraformational; greywacke.
10	6627-10372	95.0	Eeb	Backstairs Passage Formation	W limb of regional, F ₂ , NNW-SSE trending, S plunging syncline.	Sandstone, laminated, thick bedded, slumped, crossbedded, with minor siltstone interbeds. Widespread siltstone unit at base.
11	6627-11022	128.0	Elt	Tapanappa Formation	W limb of regional, F ₁ , N-S trending, S plunging syncline. Plunge possibly 20°S	Sandstone to greywacke, fine to coarse-grained, dark grey, thick-bedded to laminated; interbedded with laminated siltstone and thin, sulphidic siltstone and lenticular grit to conglomerate beds. scour and fill channels, rare cross-bedding.
12	6627-2770	55.0	Elt	Tapanappa Formation	W limb of regional, NNW trending, S plunging syncline. Plunge 20°S	Sandstone to greywacke, fine to coarse-grained, dark grey, thick-bedded to laminated; interbedded with laminated siltstone and thin, sulphidic siltstone and lenticular grit to conglomerate beds. Scour and fill channels, rare cross-bedding.
13	6627-8000	54.0	En	Carrickalinga Head Formation Normanville Group	Hinge of regional, F ₁ , N-S trending, S plunging syncline. Macclesfield Syncline.	Limestone; sandstone; shale; volcanics
14	6627-5650	137.0	Ndt	Stonyfell Quartzite	W limb of regional, F ₁ , N-S trending, S plunging syncline. Macclesfield Syncline. Immediately adjacent to fault.	Quartzite, feldspathic, with shale interbeds; silty sandstone in part schistose and calcareous.
15	6627-7516	54.9	Nir	Tarcowie Siltstone	W limb of regional, F ₁ , N-S trending, S plunging syncline. Macclesfield Syncline. Immediately adjacent to fault.	Siltstone, sandy, flaser bedded.
16	6627-5598	45.1	Eeb	Normanville Group Carrickalinga Head Formation Backstairs Passage Formation	W limb of regional, F ₁ , N-S trending, S plunging syncline. Macclesfield Syncline. Immediately adjacent to fault.	Sandstone, laminated, thick bedded, slumped, crossbedded, with minor siltstone interbeds. Widespread siltstone unit at base.
17	6627-5602	103.0	Eeb	Backstairs Passage Formation Talisker Calc-Siltstone Tapanappa Formation	Hinge of regional, F ₁ , N-S trending, S plunging syncline. Macclesfield Syncline.	Sandstone, laminated, thick bedded, slumped, crossbedded, with minor siltstone interbeds. Widespread siltstone unit at base.

18	6627-8951	77.0	Eeb	Backstairs Passage Formation	E limb of regional, F ₁ , anticline, N-S trending, S plunging. Strathalbyn Anticline.	Sandstone, laminated, thick bedded, slumped, crossbedded, with minor siltstone interbeds. Widespread siltstone unit at base.
19	6627-10621	112.0	Elt	Tapanappa Formation	E limb of regional, F ₁ , anticline, N-S trending, S plunging. Strathalbyn Anticline.	Sandstone to greywacke, fine to coarse-grained, dark grey, thick-bedded to laminated; interbedded with laminated siltstone and thin, sulphidic siltstone and lenticular grit to conglomerate beds. Scour- and fill channels, rare cross-bedding.
20	6627-10856	152.0	Elt	Carrickalinga Head Formation Backstairs Passage Formation Tapanappa Formation	W limb of regional, F ₁ , syncline, N-S trending, S plunging. Macclesfield Syncline.	Sandstone to greywacke, fine to coarse-grained, dark grey, thick-bedded to laminated; interbedded with laminated siltstone and thin, sulphidic siltstone and lenticular grit to conglomerate beds. Scour- and fill channels, rare cross-bedding.
21	6627-10575	54.0	Eeb	Backstairs Passage Formation	Hinge of regional, F ₁ , anticline, N-S trending, S plunging. Strathalbyn Anticline.	Sandstone, laminated, thick bedded, slumped, crossbedded, with minor siltstone interbeds. Widespread siltstone unit at base.

UNITS OF MEASUREMENT

Units of measurement commonly used (SI and non-SI Australian legal)

Name of unit	Symbol	Definition in terms of other metric units	Quantity
day	d	24 h	time interval
gigalitre	GL	10^6 m^3	volume
gram	g	10^{-3} kg	mass
hectare	ha	10^4 m^2	area
hour	h	60 min	time interval
kilogram	kg	base unit	mass
kilolitre	kL	1 m^3	volume
kilometre	km	10^3 m	length
litre	L	10^{-3} m^3	volume
megalitre	ML	10^3 m^3	volume
metre	m	base unit	length
microgram	μg	10^{-6} g	mass
microlitre	μL	10^{-9} m^3	volume
milligram	mg	10^{-3} g	mass
millilitre	mL	10^{-6} m^3	volume
millimetre	mm	10^{-3} m	length
minute	min	60 s	time interval
second	s	base unit	time interval
tonne	t	1000 kg	mass
year	y	365 or 366 days	time interval

Shortened forms

~	approximately equal to	ppb	parts per billion
bgs	below ground surface	ppm	parts per million
EC	electrical conductivity ($\mu\text{S}/\text{cm}$)	ppt	parts per trillion
K	hydraulic conductivity (m/d)	ρ_a	apparent resistivity (Ωm)
mV	millivolts	TOC	top of casing
NS	natural surface	w/v	weight in volume
pH	acidity	w/w	weight in weight

GLOSSARY

Anisotropic — Applied to substances whose optical or other physical properties vary according to the direction from which they are observed

Apparent resistivity — A measurement of resistivity which is calculated as the product of the measured resistance and a geomagnetic factor; units are ohms/m. It is important to note that the apparent resistivity is not an explicit measurement of the electrical resistivity of a material and should not be interpreted as being diagnostic of a given material

Aquifer — An underground layer of rock or sediment that holds water and allows water to percolate through

Aquifer test — A hydrological test performed on a well, aimed to increase the understanding of the aquifer properties, including any interference between wells, and to more accurately estimate the sustainable use of the water resources available for development from the well

Cone of depression — An inverted cone-shaped space within an aquifer caused by a rate of groundwater extraction that exceeds the rate of recharge; continuing extraction of water can extend the area and may affect the viability of adjacent wells, due to declining water levels or water quality

Continental margin — Zone that extends from the shoreline to the deep-ocean floor at a depth of 2000 metres. The zone is underlain by continental crust

DC — Direct current

EMLR — Eastern Mount Lofty Ranges

Equipotential line — The two-dimensional focus of all points with equal value for a potential field

Equipotential surface — The three-dimensional distribution of all points of equal value for a potential field. Equipotential lines and surfaces are perpendicular to the lines of force associated with the potential field

DWLBC — Department of Water, Land and Biodiversity Conservation (Government of South Australia)

EC — Electrical conductivity; 1 EC unit = 1 micro-Siemen per centimetre ($\mu\text{S}/\text{cm}$) measured at 25°C; commonly used as a measure of water salinity as it is quicker and easier than measurement by TDS

FRA — Fractured rock aquifer

Fracture — General term applied to any break in a material, but commonly applied to more or less clean breaks in rocks or minerals

Geophysics — The science concerned with all aspects of the physical properties and processes of the Earth and planetary bodies and their interpretation

Geosyncline — Large, downwarp structure generally of considerable extent, which may develop along a continental margin

Groundwater — Water occurring naturally below ground level or water pumped, diverted and released into a well for storage underground; see also 'underground water'

Hydraulic conductivity (K) — A measure of the ease of flow through aquifer material: high K indicates low resistance, or high flow conditions; measured in metres per day

Hydrogeology — The study of groundwater, which includes its occurrence, recharge and discharge processes, and the properties of aquifers; see also 'hydrology'

Lithology — The description of the microscopic features of a rock

m AHD — Defines elevation in metres (m) according to the Australian Height Datum (AHD)

MLR — Mount Lofty Ranges

Observation well — A narrow well or piezometer whose sole function is to permit water level measurements

Porosity — Absolute porosity is the total of all void spaces present within a rock, but not all these spaces will be interconnected and thus be able to contain and transmit fluids. The effective porosity is thus defined as the proportion of the rock which consists of interconnected pores. Porosity is expressed as a percentage of the bulk volume of the rock

Potential electrode — An electrode used as a ground contact in a voltage-measuring circuit

Production well — The pumped well in an aquifer test, as opposed to observation wells; a wide-hole well, fully developed and screened for water supply, drilled on the basis of previous exploration wells

SP — Self potential. A method which measures the naturally occurring potential differences between two non-polarizable electrodes

TDS — Total dissolved solids, measured in milligrams per litre (mg/L); a measure of water salinity

Underground water (groundwater) — Water occurring naturally below ground level or water pumped, diverted or released into a well for storage underground

Unit number — A unique identifier given to all registered wells within South Australia

Well — (1) An opening in the ground excavated for the purpose of obtaining access to underground water. (2) An opening in the ground excavated for some other purpose but that gives access to underground water. (3) A natural opening in the ground that gives access to underground water

WMLR — Western Mount Lofty Ranges

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