COPPER to the WORLD 2018 CONFERENCE

CONFERENCE TOPICS WILL INCLUDE

- International trends
- Copper exploration updates
- Ongoing developments in innovation and research

Tuesday 26 June 2018
Adelaide Convention Centre

#CTTW

minerals.dpc.sa.gov.au/copper_to_the_world
an initiative of South Australia's Copper Strategy
Contents

Using electromagnetic geophysics for hydraulic stimulation monitoring – Stephan Thiel

High-density magnetotelluric mapping across uranium deposits highlights lithospheric controls on deposit location – Stephan Thiel, Paul Soeffky, Lars Krieger, Klaus Regenauer-Lieb, Jared Peacock, Graham Heinson and Kate Robertson

Geological outcomes of the Mineral Systems Drilling Program along the southern Gawler Ranges – Adrian Fabris

Mineral Systems Drilling Program – testing and delivering tomorrow’s mineral discovery technologies – Adrian Fabris

Characterisation of the Samphire granite, Hiltaba Suite, northeastern Eyre Peninsula – Russel Bluck and Callan Brown

Remediating the Leigh Creek coal mine – Mineral and Energy Resources
Using electromagnetic geophysics for hydraulic stimulation monitoring

Stephan Thiel¹, ²
¹ Geological Survey of South Australia, Department of the Premier and Cabinet ² School of Physical Sciences, The University of Adelaide

Introduction

Hydraulic stimulation, also referred to as hydraulic fracturing or fracking, is a geoengineering application in which fluids or supercritical fluids are pumped to depths of several hundred metres to several kilometres to enhance the connectivity of the pores within the rock matrix (Gérard et al. 2006). The enhanced connectivity, or permeability, of the medium has the effect of enabling a more efficient fluid or gas flow through the matrix. This enhancement of subsurface permeability forms the basis for enhanced geothermal systems (EGS), as well as tight shale gas and coal-seam gas plays. While the Australian geothermal industry is largely dormant at this point, the investments made over the last decade still provide important insights into the geoengineering challenges surrounding EGS and holds learnings for other applications of hydraulic stimulation technology.

In EGS, a cool fluid is pumped under high pressure to depths of several kilometres where temperatures can rise up to 200 °C (Peacock et al. 2012a). A second borehole closes the loop and pumps the hot fluids back up to the surface, at which point the thermal energy of the fluids can be used for heating, direct use applications or electricity generation if the temperature is sufficiently high (Fig. 1). In gas plays, the high-pressure fluids establish an enhanced fracture network. After the enhancement, the fluids are then extracted leaving behind pathways for the formation-bound gas to escape via the enhanced permeability pathways into the well.

Monitoring the distribution of the connected fluid-filled fracture network remains at the forefront of scientific study. Commonly, microseismic deployments are used to map fracture opening due to the injected high-pressure fluids. The seismicity in a reservoir is therefore a proxy for establishing enhanced permeability (Phillips et al. 2002).

Over the last seven years, the University of Adelaide established one of the world’s biggest research hubs for field-based electromagnetic geophysics, with particular focus on magnetotellurics (MT) experiments for fluid injection monitoring, which was supported by Renewables SA and the South Australian Government. This article summarises the recent advances in monitoring fluid injections at depth using electromagnetic geophysics, with particular focus on South Australia. A more comprehensive in-depth review has just been published by Thiel (2017) focusing on global efforts in using electromagnetic geophysics for monitoring of hydraulic stimulation. This review paper was presented as a keynote address at the 23rd Electromagnetic Induction Workshop in Chiang Mai, Thailand, 2016.

---

Figure 1  Schematic diagram depicting an EGS setup. Fluids are pumped at depth of typically around 4 km under high pressure to cause an enhanced fracture network susceptible to fluid flow. Once a permeable fractured network is established the heated fluids are pumped back to the surface through a second borehole to generate electricity from a power plant. Used fluids are then recycled to hot rocks at depth. (Courtesy of the United States Department of Energy 2008)
Motivation for novel monitoring methods

While microseismic methods are the industry standard and achieve a high resolution of mapping microseisms (typically recorded in the range from magnitude -2 to 3 on a Richter scale for EGS injections), they are not directly sensitive to the injected fluids themselves, but to the movement of fractures opening under the high injection-induced pressure in the formation. For this reason, the University of Adelaide began a research program in 2010 to test surface MT measurements for monitoring temporal changes in the surface electromagnetic field due to fluid movement at depth. This approach not only maps the distribution of stimulated fractures, but demonstrates that they are connected and open to the transmission of fluid.

South Australian enhanced geothermal systems

South Australia does not have the tectonic setting for conventional geothermal energy resources where hot near-surface fluids due to volcanic activity can be tapped for electricity generation. However, anomalously high temperatures occur at depths of several kilometres within the South Australian Heat Flow Anomaly (SAHFA), a roughly north–south corridor along the Flinders Ranges and adjacent basins extending north to the Cooper Basin (Fig. 2; Neumann, Sandiford and Foden 2000). Over the last decade, several South Australian companies explored the possibility of utilising these high temperatures for EGS electricity generation. These systems require prior permeability enhancement using a hydraulic stimulation approach. Hydraulic stimulation in EGS typically occurs deep beneath the surface at depths of around 4 km. Within the SAHFA, temperatures at 4 km depth can reach to around 200 °C. This temperature is required to achieve economic viability for electricity generation. Two companies have drilled into hot basement rocks of the SAHFA to test the viability of geothermal electricity generation – Geodynamics Limited at the Habanero EGS site and Petratherm Limited at the Paralana EGS site (Fig. 2). It is around these two geothermal sites, the University of Adelaide initially trialled surface MT deployments to study the effectiveness of MT to monitor fluid movement at depth during injection of the hydraulic stimulation.

The Paralana EGS site was the first monitoring experiment using MT worldwide and generated a number of field and theoretical studies (Albaric et al. 2014; Alexander, Thiel and Peacock 2012; MacFarlane et al. 2014; Peacock et al. 2012, 2013; Rosas-Carbajal et al. 2015). The high heat flow (~126 mW/m²) near the Paralana EGS site is attributed to elevated uranium and thorium concentrations in the Proterozoic Mount Painter Inlier basement rocks (Cull 1982; Brugger et al. 2003). The Paralana EGS is ~10 km east of the Flinders Ranges in the Frome Embayment near the Beverley uranium mine.

The prerequisites for a successful EGS, which are enhanced heat flow and thick insulating sedimentary rocks to trap the heat of the granites below the cover, are present at Paralana. The pre-existing higher density of fractures at the sediment to basement contact, observed in seismic reflection profiles, is also beneficial to establish further enhancement of the fracture network post fluid injection. In July 2011 Petratherm injected 3,100 m³ of saline water into Mesoproterozoic metasedimentary rocks over a period of five days at a depth of 3,680 m within the 4,012 m deep Paralana 2 drillhole. The drillhole was cased to 3,725 m depth and perforation occurred over a height interval of 6 m (Bendall et al. 2014).
Another time-lapse MT installation occurred at the Habanero EGS in 2012 (Didana et al. 2017). It was the most developed EGS project in Australia at the time with four geothermal wells intersecting hot Carboniferous granitoids of the Big Lake Suite beneath the Cooper Basin. The Habanero EGS fractured reservoir sits about 400 m deeper than the Paralana EGS reservoir. In November 2012 Geodynamics injected 36,500 m$^3$ over 14 days into the hot granitic reservoir at 4,077 m depth using a near-surface aquifer fluid. The target fracture zone at depth, intersected by all four geothermal wells, was a shallow WSW-dipping fracture zone of 5–6 m thickness (Bendall et al. 2014).

**Magnetotelluric experiments**

In both scenarios two types of MT deployments were undertaken to monitor the fluid injection – continuous and time lapse. Continuous deployment is limited by the number of instruments available, whereas time-lapse monitoring involves a larger array of sites that are deployed before and after the fluid injection by using the instrument pool at multiple sites, similar to a typical MT deployment. An example of the MT layout for the Paralana EGS is given in Figure 3. During the continuous deployment at Paralana, broadband MT sites were placed within a couple of kilometres radius around the borehole, measuring throughout the entire hydraulic stimulation program (Peacock et al. 2012). For the time-lapse monitoring at Paralana, 56 MT sites were deployed around the injection hole before and after the hydraulic fracturing (Peacock et al. 2013). Similarly, at the Habanero EGS site, two main profiles of 40 km length centred on the injection well were deployed for the time-lapse deployment (Didana et al. 2017).

The continuous and time-lapse deployments were designed to establish the suitability of surface MT studies for monitoring the hydraulic fracturing given that future monitoring exercises may have limited land access or instruments available. The site spacing in both types of deployment was chosen based on the variation in surface MT response changes derived from hypothetical 3D forward modelling. For all of these deployments, baseline data (defined as the MT responses prior to the injection) is compared to the MT responses during and after the fluid injection. Typically, we studied the MT responses derived from a day of time series data of the electric and magnetic field. When plotted for several consecutive days during the fluid injection, the results showed a temporal change in the responses due to the fluid injection. While the temporal changes in the response are small, they are nevertheless visible. Furthermore, the tensorial character of the MT responses allows a direction-dependent assessment of the change due to the fluid injection at depth. We found that the primary control of the connectivity enhancement at depth is controlled by the applied stress field in the study area. It preferably connects fractures perpendicular to the maximum horizontal stress direction (Didana et al. 2017).

Further monitoring studies were performed for fluid injections in hydrocarbon plays in Australia, including coal-seam gas and shale gas fluid injections (Rees et al. 2016a, 2016b; Rees, Heinson and Krieger 2016).

**Conclusion**

Electromagnetic monitoring of fluid injections has shown promising results across the South Australian EGS sites. Further studies were undertaken across other fluid injection scenarios in coal-seam gas and shale gas plays. Results from case studies suggest that electromagnetic monitoring is a viable tool to detect changes in electrical resistivity of the fluid reservoir at depth with surface measurements. However, the changes in the electromagnetic response functions are very small for the injections occurring at several hundred metres to a few kilometres depth and there still exist shortcomings in adequately mapping the horizontal fluid extent of the injection plume. Repeatability studies are an important part of the studies to ensure relatively noise free environments and stable baseline data.

![Figure 3](image-url)
Further petrophysical studies are needed to explain fracture development and its influence on fluid flow and relation to electrical resistivity over time within the fracture network. The percolation threshold of a fracture network plays an important role for permeability enhancement of the reservoir. At the percolation threshold, the connectedness increases in a highly non-linear fashion, and permeability and electrical conductivity are enhanced by several orders of magnitude (Kirkby and Heinson 2017; Kirkby, Heinson and Krieger 2016).

Downhole measurements would significantly improve the resolution to in situ processes during fluid injection. Modelling studies indicate a significant increase in sensitivity to target for borehole to borehole, or borehole to surface configurations (Tietze, Ritter and Veeken 2015). This would alleviate resolution of the fluid plume extent at depth.

Acknowledgments
This summary is an overview of work undertaken in recent years. Thanks go to the students at the University of Adelaide who worked on this over the years, in particular Jared Peacock who performed the pioneering analyses on the Paralana EGS.

References


FURTHER INFORMATION
Stephan Thiel
Stephan.Thiel@sa.gov.au
High-density magnetotelluric mapping across uranium deposits highlights lithospheric controls on deposit location

Stephan Thiel¹, ², Paul Soeffky², Lars Krieger², Klaus Regenauer-Lieb³, Jared Peacock⁴, Graham Heinson² and Kate Robertson¹, ²  
¹ Geological Survey of South Australia, Department of the Premier and Cabinet  
² School of Physical Sciences, The University of Adelaide  
³ Faculty of Engineering, University of New South Wales  
⁴ US Geological Survey

Introduction

With the Australian Lithospheric Architecture Magnetotelluric Project (AusLAMP) deployment across South Australia nearing completion (Thiel and Robertson 2017), the subsequent 3D inversion modelling of the magnetotelluric (MT) data and integration with other geophysical, geochemical and geological data will provide a new fundamental precompetitive dataset for the state. It will highlight areas of enhanced conductivity in the crust, which were shown by Thiel et al. (2017) to be a potential proxy for fertile crust, one characteristic for establishing mineral deposits.

However, with the site spacing of ~55 km for the AusLAMP grid, the resolution in the upper crust is not sufficient to confidently map the high conductivity zones extending into the surface cover sequence. Closely spaced broadband MT surveys are required to obtain greater resolution across the areas of interest identified by AusLAMP. There are already some examples across the state where this approach has been used to great benefit across known deposits such as Olympic Dam (e.g. Heinson, Direen and Gill 2006). This article summarises the results of a recently published closely spaced (1 km site spacing) broadband MT survey across the Beverley uranium deposit, located east of the northern Flinders Ranges (Fig. 1; Thiel et al. 2016). The results provide another example of how the crustal structure appears to exert a control on the location of mineral deposits.

Method

MT is a passive electromagnetic technique which involves the recording of naturally occurring magnetic and electric fields at the surface of the earth to obtain information on the electrical resistivity structure of the subsurface. During two field campaigns, MT measurements were recorded along two 35 km, ESE–WNW-oriented parallel profiles spaced 7 km apart (Fig. 1). The northern transect comprised 36 broadband (0.004–1,000 s) stations with 13 of these also recording long-period (10–10,000 s); the southern transect comprised 59 broadband stations. An additional 22 broadband MT sites along a NNE–SSW profile were used from an array of stations centred at the Paralana enhanced geothermal systems test site (Fig. 1; Peacock et al. 2012, 2013; Thiel 2017). Site spacing was 1 km across most of the profiles, extending up to 3 km at the far east of the northern profile. The data, which is overall of good quality, is predominantly 2D based on phase tensor analysis (Caldwell, Bibby and Brown 2004) with subsequent rotation to a geoelectric strike of 5° to align with surficial faults. Data from the northern and southern lines was inverted separately using the OCCAM 2D inversion code (deGroot-Hedlin and Constable 1990, Fig. 2).

Results

The resistivity structure revealed a 1–2 km thick layer of low resistivity (<10 Ωm) sediments above a highly resistive (>1,000 Ωm) ~15–25 km thick layer with a predominantly 2D structure (R1), which extends along the azimuth of the geoelectric strike to a depth of ~30 km. A subvertical mid-crustal conductor extends to about 10 km beneath the surface (C1),
Figure 1  MT stations (black triangles, this study; white triangles, Peacock et al. 2013) over topography. Coloured circles denote earthquake epicentres and magnitudes across the survey area although depths are poorly constrained. Reprinted from Thiel et al. (2016; fig. 1) with permission from the American Geophysical Union.

Figure 2  Two-dimensional resistivity models of the MT profiles obtained using the 2D OCCAM inversion of deGroot-Hedlin and Constable (1990). The models show increased conductivity in the lower crust at around 30 km (C2). Localised near-vertical zones of higher conductivity extend to the brittle–ductile transition (BDT) at around 10 km depth (C1). Lower conductivities extend to the surface along faults at 45° angle. Earthquake locations in the vicinity of the profile were projected along strike onto the nearest MT profile (black dots). Hypocentres are poorly constrained, and we assign a generic 15 km error. There is generally higher uncertainty in the E–W direction of epicentres due to the seismometer network geometry. Reprinted from Thiel et al. (2016; fig. 2) with permission from the American Geophysical Union.
interpreted as a signature of fluid ponding beneath the brittle–ductile transition, which tends to resist the passage of fluids (Connolly and Podladchikov 2004). Narrow, 45°-angle conductive faults extend to the surface. The eastern mid-crust conductor beneath the Paralana enhanced geothermal system (C1) has a maximum width of about 10 km. The western region of the profiles contains very resistive (10,000 Ωm) unfractured basement rock. Along the western edge of both profiles in the mid-crust is a conductor (C4) that aligns with the range-bounding Paralana Fault (Fig. 1). The NNE–SSW profile ties in with the results of the main profiles with a lower crustal conductor and a subvertical low-conductivity extension into the mid-crust below the brittle–ductile transition (Fig. 2).

Conductivity anomalies within a few hundred kilometres of the survey area are associated with Mesoproterozoic magmatic events along the margin of the Archean–Proterozoic Gawler Craton to the west (Heinson, Direen and Gill 2006; Thiel and Heinson 2013). To the south, Delamerian–subduction associated serpentinitisation and resultant enhanced magnetite within mafic and ultramafic rocks is interpreted to cause higher crustal conductivity (Robertson et al. 2015; Robertson et al. 2017). Low resistivity in the lower crust and upper mantle beneath the Newer Volcanic Province to the south is a result of recent decompressional melting within a lithospheric step (Aivazpourporgou et al. 2015). Recently, long-period MT AusLAMP data revealed a pervasive lower crustal conductor of the Curnamona Province and isolated conductors within the Nackara Arc province of the Ikara-Flinders Ranges (Robertson, Heinson and Thiel 2016; Robertson, Heinson and Thiel 2017). Both present and fossil crustal fluids may result in enhanced conductivity through precipitation of sulfides, graphite or magnetite on interconnected grain boundaries under the right conditions (Nover 2005; Thiel, Heinson and White 2005).

The coincident position of enhanced conductivity in the lower crust (C2; Fig. 2) and enhanced strain derived from geodynamic modelling (Célérier et al. 2005) beneath the area of maximum topographic flexure is suggestive of a connection between neotectonic uplift of the Flinders Ranges and reactivation of the lower crust beneath the survey area. The horizontal geometry of the lower crust conductor (C2; Fig. 2) does not appear to have mantle connections; however, mantle resolution is limited due to the small profile aperture (~40 km).

It is unlikely that the fluids are entirely meteoric due to the fluid flow resistant brittle–ductile transition (Connolly and Podladchikov 2004; Raimondo et al. 2013); a potential additional fluid source is geologically recent fluid release from metamorphism of lower crustal rocks.

The westernmost upper crustal pathway that branches up from C1 reaches the surface beneath the Wooltana–Poontana Fault (which has most likely been active since the Pliocene, Wülser et al. 2011) and the Beverley uranium mine (Fig. 2). The crustal architecture may therefore have some control on the location of uranium in near-surface sedimentary layers. Mobile reducing fluids may provide the required redox conditions near the neotectonic displacement along the Wooltana–Poontana Fault for uranium emplacement. The results indicate the significance of understanding the full crustal architecture when exploring for near-surface economic mineral deposits.

Conclusion
This study is another example of how geophysical surveys contribute to the scale-reduction process that is critical for mineral exploration success (e.g. McCuaig, Beresford and Hronsly 2010). Starting from the regional scale of the AusLAMP surveys, the follow-up high density MT surveys, such as that over the Beverley uranium mine, resolve crustal-scale faults that can control the location of mineral deposits.

As an outcome of the insights gained from this study and the AusLAMP survey, $500,000 will be invested through the PACE Copper initiative to acquire over 300 broadband MT stations across the Olympic Domain. The site layout will cover a 100 x 100 km area to map low conductivity zones to the surface in 3D. The data collection will likely commence in October/November 2017. Further in-fill surveys are planned to maximise the impact of MT methods in the process of unlocking the mineral potential of South Australia.

Acknowledgements
Petratherm provided MT data for the southern profile. Heathgate provided logistical support during the data acquisition of the northern profile. Anthony Reid (Geological Survey of South Australia) reviewed the article.

References


---

**FURTHER INFORMATION**

Stephan Thiel

Stephan.Thiel@sa.gov.au
Introduction

The Mineral Systems Drilling Program (MSDP) was a $3.5 million cash and $4.11 million in-kind collaborative drill program managed by the Geological Survey of South Australia in partnership with the Deep Exploration Technologies Cooperative Research Centre (DET CRC), Minotaur Exploration, Kingston Resources and several service providers. The objective of the MSDP was to further the understanding of mineral systems developed during c. 1590 Ma magmatism, with particular emphasis along the southern Gawler Ranges. From July 2015 to April 2016, 14 diamond drillholes were completed for a total of 7,868 m (Fig. 1). The following is a summary of the geological outcomes of the project and is complementary to outcomes of DET CRC technology trials also summarised in this edition of the MESA Journal. The reader is referred to Fabris et al. (2017) for a more comprehensive review of project results and outcomes.

Drillholes by region

Carriewerloo: MSDP01–04

MSDP drillholes in the Carriewerloo region were sited to aid subsurface mapping and assess the mineral potential in what is a mostly covered terrain. Geophysical imagery, in particular the magnetic data, shows considerable variation in texture and intensity that can be related to geology (Fig. 1). Drillholes were located above coincident high magnetic and gravity features on a local scale, but within distinct geophysical domains (Fig. 2):

- MSDP01 and MSDP03 within the Olympic Domain on a NE-trending, narrow linear magnetic feature, that is bound by the Roopena and Wizzo Well faults, but potentially separated by a ENE-trending unnamed fault.
- MSDP02 within the Olympic Domain on the southern margin of a broad gravity high and in a moderate magnitude magnetic anomaly.
- MSDP04 within the Spencer Domain on a broad gravity high, containing numerous high frequency magnetic features.

Prior to the program, it was uncertain whether geophysical anomalies were related to units of the Gawler Range Volcanics (GRV) or to pre-GRV basement. This was predominantly due to having very few constraints on the depth to basement in the region and the overall lack of understanding of the distribution of mafic units within the GRV. In MSDP01, 03 and 04, modelled depths to basement can now be related to the uppermost basaltic unit in each hole (Roopena Basalt). Significant thicknesses of mafic units were intersected in the drillholes and were both magnetic (upper basalt, $-7 \times 10^{-3}$ SI; lower basalt, $-12 \times 10^{-3}$ SI) and relatively dense (upper basalt, 2.75 g/cc; lower basalt, 2.82 g/cc). In MSDP02, the modelled target zone defined through inversion of magnetic and gravity data could be explained by a thick sequence of Tapley Hill Formation (2.72 g/cc) and/or the underlying Beda Basalt (2.84 g/cc). MSDP drillholes demonstrated that high frequency geophysical features are controlled by units within the GRV, and therefore regions of high magnetic susceptibility and density can be used to approximate the distribution of thick mafic units (Fig. 2). High magnitude and high frequency magnetic features most closely correspond with the known distribution of the upper basalt (Roopena Basalt). Gravity highs do not always coincide with regions of high magnetic susceptibility and are therefore interpreted to represent either...
thickened mafic units or dense bodies below the upper basalt (i.e. lower basalt or mafic units below). Extensive mafic units, both intersected in drilling and interpreted through geophysics, highlight the difficulty in targeting geophysical features below volcanic flows of the GRV.

Although there is limited deep drilling through the GRV with which to compare, one overarching observation is the large volume of basaltic units encountered in the Carriewerloo region. On a regional scale, Carriewerloo is situated at the southern end of an approximately NNE-trending broad gravity high (Fig. 3). The western margin of this feature coincides with the likely extension of the Uno Fault. The broad gravity high continues north along the eastern margin of the Olympic Domain where it coincides with the approximate position of Lake Torrens. Forward modelling along the 08GA-A1 seismic line by Geoscience Australia (Fig. 3; Carr et al. 2012) reconciled this feature as relating to thick mafic units (>2 km) at the base of the GRV within an extensional setting. Basaltic units intersected in MSDP drillholes and seismic interpretations permit this explanation, although significant ambiguity remains. Of interest, magnetotelluric models indicate a lithospheric-scale linear conductivity anomaly to the immediate west of the gravity feature (Thiel 2016). Crustal features represent first-order fluid pathways and, in this case, may have a direct link to mafic volcanism in this portion of the eastern Gawler Craton.
The drilling was also aimed to extend knowledge of the Spencer–Olympic domain boundary and determine whether it acts as an important fluid pathway. While the drilling failed to penetrate the GRV, which meant that basement geology and its mineral potential could not be assessed directly, MSDP01 and MSDP03 in combination with seismic surveys by Curtin University (Fig.1) provided useful information on the Roopena and Wizzo Well faults (Figs 2, 4). MSDP01 and MSDP03 were drilled close to the interpreted trace of the Roopena and Wizzo Well faults, but only samples from MSDP03 showed the degree of fracturing indicative of significant brittle displacement. Fracture-fill was common, particularly in MSDP03; however, there was a distinct lack of alteration away from fractures suggesting the absence of a significant hydrothermal system in this region during or post GRV time. Rare crustiform banding was evident, but with no surrounding alteration. This makes it more likely that fracture fills are related to late-stage fluids derived during cooling of the GRV. Overall, the lack of alteration intensity in the region indicates that fracturing intersected in the drillholes is likely to be related to post GRV-cooling tectonic movement (reactivation post 1590 Ma). Based on all MSDP drillholes, alteration zones within the GRV are associated with demagnetisation. On a regional scale, this points towards a different exploration focus than the accepted practice of drilling on or adjacent to...
Magnetic highs. Demagnetised dilational zones associated with the Roopena and Wizzo Well faults offer an alternative exploration model for targeting epithermal/hydrothermal systems within this region.

For exploration models that include basement targets, a fundamental control on the exploration search space is depth to basement. The MSDP has provided new constraints on the thickness and depth to base of the GRV, based on several deep drillholes and two reflection seismic profiles that were part of the broader program (Fabris et al. 2017, p. 25). These indicate that the GRV is >1.4 km thick along the southeastern margin of the Gawler Ranges (Fig. 4). A thickened succession of volcanic units in this region is interpreted to have resulted from local extensional tectonics active during the extrusion of the GRV, particularly between the Roopena and Wizzo Well faults. The depth estimates have economic implications for exploration where the modelled target is at or below the base of the GRV, and underlines the importance of identifying and targeting topographic paleohighs in the pre-GRV landscape.

The MSDP drillholes have provided stratigraphic control and an improved understanding of the depositional environment of the GRV. While the full GRV sequence was not penetrated, the drillholes contained exceptionally well preserved volcanic textures, enabling identification of hyaloclastite, pillow textures and peperite, demonstrating that at least some flows were deposited in a subaqueous setting (Figs 5 and 6; Simpson 2017). In addition to the GRV, MSDP02 is a rare cored hole through the Adelaidean stratigraphy in this region and provides a new reference hole for several units, including a thickened sequence of dolomitic and carbonaceous shales of the Tapley Hill Formation. Of economic interest, elevated copper and silver values were associated with the base of the Tapley Hill Formation over both the Spearfelt Rhyodacite and Beda Basalt, highlighting its widespread potential for sedimentary copper. Notably, grades were higher over the Beda Basalt (Beda Basalt contained average values of 176 ppm Cu; n = 19) and mineralisation continued into the upper Beda Basalt (up to 1% Cu), suggesting this unit provides a source of copper that might be remobilised and concentrated under suitable geological conditions.

**Figure 4** Interpreted migrated seismic section for Curtin University transect alongside MSDP01.

**Figure 5** Peperitic mixing between basalt (red-brown to green) and grey sediment, MSDP04, 108.1 m. (Photo 416125)
Peltabinna: MSDP05–07
MSDP drillholes in the Peltabinna region were sited to investigate the mineral potential of two separate regional demagnetised structures, the Eurilla and Progress faults, interpreted to be splays of the Yarbrinda Shear Zone, which may have been reactivated during the extrusion of the GRV (Fig. 1). In what is one of the key findings of the program, MSDP05 intersected a zone of epithermal veining with several veins displaying colloform texture with fine sulfide banding (ginguro veins; Fig. 7). Veining is associated with a ~200 m wide alteration zone which was demagnetised and contains variably intense white mica, chlorite and carbonate (veins and infill). While there were no significantly high gold and silver values recorded over the interval, the veins contain anomalous Ag, As, Bi, Mo, Sb, Cs and S, which is typical of epithermal mineral systems. The stratigraphic position of the alteration zone is important. Mineral exploration in the region has been focused mainly at the base of the GRV, yet this zone of epithermal alteration is developed within the upper GRV, between the Pondanna Dacite Member and Eucarro Rhyolite. This opens up the potential for mineralisation across the GRV, rather than just at its margins.

While drilling in the Peltabinna region intersected mostly coherent lavas, both MSDP05 and MSDP07 intersected a newly defined sequence of volcaniclastic sediments within the upper GRV (Mount Friday Formation; Werner et al. 2017). It is postulated that the regional demagnetised features visible in aeromagnetic data are related to extensional faulting and are associated with low lying corridors that accommodated the deposition of thickened epiclastic deposits during periods of GRV extrusion. Evidence for extension comes from the greater thickness of Pondanna Dacite Member (>345 m) and Eucarro Rhyolite (>600 m) intersected in MSDP06 and MSDP07, respectively, than that observed in outcrop in the central Gawler Ranges (200–300 m). In both drillholes, white mica alteration is associated with the volcaniclastic stratigraphic level, and our interpretation is that underlying faults acted as upflow zones and focused fluids into these more permeable units. The presence of permeable volcaniclastics and underlying structures are indicated to be important ingredients in the localisation of the epithermal mineral systems, such as that intersected in MSDP05. High water content of these units may be a factor in controlling zones of boiling during influx of hot fluids. It is uncertain whether alteration in MSDP05 took place during the extrusion of the GRV or was related to a later discrete hydrothermal event. The lack of volcanic facies indicative of a proximal vent suggests that the hydrothermal system developed post-deposition. Granite sills intersected at the base of MSDP07 provide evidence of an intrusive phase that may have been the thermal driver for post-depositional fluid flow.

Black Eagle Rock: MSDP08–10
Several mineral occurrences are known along the southern margin of the Gawler Ranges (Reid 2017; Schwarz et al. 2006). Discoveries such as Parkinson Dam (Smith 2006), Diomedes and Uno are proximal to faults that are broadly subparallel with the margin of the GRV and are outboard of the current GRV margin. While exploration in this region is ongoing and continues to identify evidence of a widespread mineralising event, potential for mineralisation associated with similar but inboard structures within or beneath the upper GRV is largely unknown. These bounding faults are likely to provide major upflow zones. This model is analogous with major silver deposits developed in the Imiter district, Morocco (Fig. 8; Cheilletz et al. 2002; Nicolson and McAvaney 2015). Drillholes MSDP08–10 are the first holes in this area to directly investigate the potential for this style of mineralisation.
A 4 km long, low-impact seismic survey conducted with Curtin University across the current GRV margin (Fig. 1) infers compartmentalised deposition of volcanics close to the margin but largely failed to define basement contacts or likely structures, possibly due to a less than ideal line orientation (Fabris et al. 2017). Ground electromagnetic data (EM) collected by Minotaur Exploration produced several narrow but very high magnitude EM conductors (up to 100,000 s) in the Black Eagle Rock area. None of the modelled EM conductors were satisfactorily explained by the drilling. The target depths in all holes corresponded to massive and weakly altered dacitic and rhyolitic coherent facies with only minor fracturing. In hindsight, additional ground EM lines were needed to correctly determine the geometry of the conductors.

MSDP08 and 09, drilled within a few hundred metres of the current GRV margin, penetrated ‘basement’ below the GRV, while MSDP10 did not reach pre-GRV units by the end of hole depth of 567 m. MSDP08 and 09 intersected Archean–Paleoproterozoic gneiss and metagranite at a vertical depth of 146 and 234 m, respectively. These units have lower magnetic susceptibility than...
the overlying GRV but comparable specific gravity values. This indicates that it will not be possible to model depths to the base of the GRV from the magnetic data in this region.

The most significant mineralisation intersected in these holes was in MSDP10 and included elevated zinc values (up to 1,940 ppm from 493 to 494 m) corresponding with intervals containing irregular, late-stage quartz veins with fluorite and sphalerite. Rare to trace galena was evident, associated with quartz veining, but maximum lead values were only 758 ppm. Nevertheless, demagnetisation associated with moderate to intense sericite–chlorite ± pyrite alteration and common chlorite–pyrite veining in the last ~200 m of the hole (within Bittali Rhyolite) does suggest a broad alteration zone and the potential for more significant mineralisation nearby (Fig. 9).

Drillholes MSDP08 and 09 lacked the degree of fracturing and alteration expected close to a significant fluid pathway, although a feeder dyke with a fault breccia at its margin was intersected at the base of MSDP08 and provides evidence of stitching of a pre-existing structure.

Overall, drilling in the Black Eagle Rock region indicates the most likely position for a mineralised fault zone is between MSDP10 and 08 where both holes, which were angled towards each other, ended with evidence of alteration and faulting.

Paney and Tin Hut Well prospects: MSDP11 and 12

MSDP11 and 12 were sited on potential traps caused by reactive lithologies of the Hutchison Group, located at the margin of Pennas Granite (Fig. 8; informal name of Hiltaba Suite pluton located southeast of Paney Homestead). The porphyritic texture of the Pennas Granite in drill core (MSDP11 and 14) and GRV dykes evident in MSDP11 and 12, indicate the Paney and Tin Hut Well prospects were at an upper crustal level during the 1590 Ma event, but below shallow-level volcanism (part of likely feeder systems).

MSDP11 intersected a fascinating series of rocks that included skarnified Hutchison Group over augen gneiss of presumed Sleaford Complex. These are intruded by foliated intermediate and felsic units. Metadioritic units intersected have not previously been described in this region, although they appear similar to units described within the Peter Pan Supersuite (Moola Suite) on the eastern Eyre Peninsula (Wade and McAvaney 2016). Geochronology on these rocks is pending, but the foliation and dating of similar felsic units in nearby holes supports a Kimban age. In addition to Kimban intrusives, porphyritic dykes of presumed 1590 Ma age are common, particularly above the skarn-altered zone.

The skarn zone is characterised by magnesium-rich minerals (including diopside, serpentine, talc, tremolite) together with iron oxide (magnetite with subordinate hematite; 33% Fe from 320–377 m). This assemblage suggests a protolith of dolomitic sediments poor in iron (Hall, Cohen and Schiffman 1988; forming magnetite in preference to widespread andradite garnet), and supports a stratigraphic correlation with dolomitic units of the Hutchison Group. Both endo- and exo-skarns are evident (Fig. 10). Endo-skarn appears to be
developed within Kimban granite. Significant quantities of pyrite occur over narrow intervals and are associated with magnetite, commonly proximal to Kimban felsic intrusives. Anomalously but uneconomic intersections of Ag, Pb and Zn in MSDP11 were recorded throughout this zone.

The timing of the alteration and mineralisation is uncertain. Regional evidence indicates widespread skarnification (pyroxene, amphiboles, serpentine, talc) of similar stratigraphic units elsewhere, and it is inferred that this took place during amphibolite facies metamorphism of the Kimban Orogeny (Parker et al. 1993). However, it is likely that there is a 1590 Ma overprint, and the common occurrence of galena in veins and fault zones that crosscut the foliation suggests at least some of the lead mineralisation is related to the 1590 Ma event. This is supported by preliminary analysis of Pb/Pb isotopes in pyrite samples taken from MSDP11 (Jeff Steadman, University of Tasmania, pers. comm. 2017). Remobilisation is likely to be linked with the intrusion of the nearby Pennas Granite.

Although located along strike from MSDP11, the reactive metadolomitic units of the Hutchison Group appear to be absent from MSDP12 (although a highly altered equivalent may now be masked by intense silica alteration). Instead, a narrow graphitic breccia zone, possibly equivalent to graphitic units of the Hutchison Group elsewhere, hosts elevated values of precious and base metals including 1 m at 42 ppm Ag, 29 ppb Au, 0.54% Cu, 0.35% Pb and 0.96% Zn (410–411 m).

In addition to mineralisation associated with skarn and graphitic breccia, a distinct mineralisation style is evident within MSDP12 and at the base of MSDP11 which is not controlled by reactive lithologies. Alteration zones characterised by intense silica and lesser sericite–chlorite overprint pre-1590 Ma units. In places, alteration is so intense that the original rock texture has been almost entirely overprinted (Fig. 11). These zones contain up to 20% pyrite as veins, stringers and disseminations. These mainly overprint felsic igneous units, but also appear to be associated with mafic units where the highest copper and silver values were reported. The timing and style of this mineralisation is unknown and requires further investigation.

Mount Allalone and Pennas Granite: MSDP13 and MSDP14

MSDP13 was drilled into a fault zone between outcrop of the Corunna Conglomerate and the Pennas Granite (intersected by MSDP14), also inferred as the margin of the Nuylt and Coulta–Cleve domains (Fig. 8). A sequence of metasandstone and calc-silicate units were intersected, with the uppermost metasandstone unit returning a maximum depositional age of 1717 ± 4 Ma (n = 39; age range of detrital spectra between c. 1780 and 1680 Ma; SHRIMP; Liz Jagodzinski, Geological Survey of South Australia, pers. comm. 2016), which indicates a temporal relationship with conglomeratic units at Mount Allalone (Corunna Conglomerate). Based
on the lack of any obvious depositional break above 492.8 m, it is inferred that sediments in the remainder of the hole are of similar age. Calc-silicate units are composed predominantly of diopside (clino.pyroxene), wollastonite, prehnite and quartz, which are common products of skarnified or thermally metamorphosed dolomitic and/or silty limestones. The units are variably mylonitised, which is a record of the high strain accommodated along this domain boundary and indicates significant post-Kimban tectonic movement (likely to have occurred during the Kararan Orogeny, 1620–1575 Ma). This is supported by field observations of a tectonic fabric in outcrop on the eastern margin of Mount Allalone. The close proximity to Pennas Granite implicates the emplacement of this large Hiltaba Suite granite as a driver for the thermal metamorphism and/or metasomatism.

The sequence of alternating calc-silicate and metasandstone below medium- to coarse-grained sandstone and conglomerate observed at Mount Allalone suggests that the Corunna Conglomerate was deposited in a localised shallow-water evaporitic basin, which was subsequently infilled by coarse conglomeratic fluvial units.

Geochemical associations and vectors

Several distinct styles of mineralisation were identified in samples from the MSDP. Trace element associations with each of these are summarised below and provide a regional benchmark for comparison. Although mineralised intersections were subeconomic, trace element associations may still be useful as pathfinders and for identifying geochemical vectors.

**Epithermal, colloform quartz–sulfide veining, MSDP05**

Epithermal veining identified in MSDP05 is associated with a ~200 m wide alteration zone that is characterised by magnetite destruction and variably intense sericite, chlorite and carbonate (veins and infill) alteration (Fig. 12). Chemical associations include broad Ca, Cs and Sb anomalism over the entire alteration zone, and individual veins containing elevated Ag, Au, As, Bi, Mo and S values.

**Phylllic alteration zone, MSDP10**

MSDP10 hosts strong pervasive sericite ± chloride–silica–sulfide alteration from 378.95 m to end of hole (Fig. 9). Alteration is most intensely developed along vein networks and within breccia matrices. Sulfide zones are generally minor (<5% sulfide) but are associated with elevated Au, Ag, As, Cd, Cu, F, Li, Mo, Pb, Sb, Te and Zn values. Chlorite alteration in this hole is iron-rich which contrasts with a background Fe–Mg composition seen in similar units in other drillholes.

**Magnesian skarn, MSDP11**

Intervals of magnesian skarn intersected in MSDP11 (Fig. 10) are associated with selective to massive magnetite (with subordinate hematite; up to 52% Fe) and several pyritic zones. Trace element association includes elevated but insignificant levels of Au, As, Bi, Cu, Pb, Sb, S, Sn, W and Zn.

**Silver mineralisation, MSDP12**

Silver and minor base metal mineralisation over the interval 392–415 m in MSDP12 is associated with moderate to strong silica, sericite and chlorite alteration of presumed Hutchison Group (Fig. 13). Silver values average 7.8 ppm but are up to 42 ppm. The interval is also associated with elevated Au, Co, Cr, Li, Mo, Ni, Pb, S, Sb, Te, W and Zn values. Copper is also highly anomalous within a graphitic breccia at 410–411 m.

**Intense silica–sericite–pyrite alteration zones, MSDP11 and MSDP12**

Intense silica–sericite alteration zones evident in MSDP11 and 12 are generally associated with depletion in trace elements. Within pyritic zones (up to 40%), several trace elements are enriched (Fig. 11). In addition to silver, which ranged from 0.09 to 5.29 ppm in the intervals assayed, the following trace elements were elevated: As, Bi, Cd, Co, Mo, Pb, Sb, Te, W and Zn.
**Geological outcomes**

**Regional implications**

The Pennas Granite is interpreted to have been a source of heat and fluids that remobilised Pb–Ag–Zn at the Tin Hut prospect and facilitated thermal metamorphism and/or metasomatism of the Corunna Conglomerate. Similar Hiltaba Suite intrusions can be interpreted from regional gravity and magnetic images across the southern margin of the GRV. Known and interpreted granites are proximal to identified mineralisation that includes various mineralisation styles (Fig. 14). Hiltaba Suite intrusives are inferred to be crucial in either upgrading existing mineralisation or in forming new mineral deposits in the region. Reactive units (e.g. carbonates, graphitic units) of the Hutchison Group provide significant chemical contrast and are a likely source of metals. The Hutchison Group is therefore regarded as an important ingredient for localising mineralisation. Interpretive mapping of the subsurface distribution of reactive rocks of the Hutchison Group would refine regional prospectivity mapping.

**Alteration trends**

The MSDP intersected numerous lithologies and stratigraphic units across the southern Gawler Ranges, all of which have been characterised through whole rock geochemistry and spectral mineralogy (HyLogger™). The degree of alteration in drillholes varied greatly, providing examples of both unaltered to highly altered variants of many units. Of most significance were trends observed

---

**Figure 12** Summary plot for MSDP05 of spectral mineralogy from HyLogger™, lithology logging, selected whole rock geochemical results, magnetic susceptibility and specific gravity. Alteration zone associated with epithermal veining is associated with intense white mica alteration, demagnetisation and elevated Cs, Ca and Sb values across the entire alteration zone, with individual veins containing elevated Ag, Au, As, Bi, Mo and S values.

**Figure 13** Pyrite-rich alteration zone within variably brecciated, chloritised and silica-altered, fine-grained rock, MSDP12, 392.8 m. (Photo 416132)
within felsic volcanic units in the region. While white mica alteration was common within intersections of felsic volcanic rocks, spectral analyses have shown that white mica composition changed from a mixture of phengite and muscovite in background rocks, to dominantly muscovite close to mineralisation. Where chlorite is present in alteration assemblages, the chlorite composition is more iron-rich close to sulfide mineralisation. Along with demagnetisation, which is observed within alteration zones, these compositional variations of alteration minerals provide a potential vector to mineralisation.

Conclusion
The MSDP sought to address technical and scientific challenges present along the southern Gawler Ranges. Contributions to scientific objectives have been made through improvements to geological knowledge of the regional stratigraphy and lithological variation, deposit models, alteration styles, regional controls on fluid flow and mineralisation, and in providing new constraints on the depth to base of GRV. These data contribute to a growing understanding of the geology and mineral potential of the region, and provide stimulus to future exploration.

Acknowledgements
The MSDP was part of South Australia’s PACE Frontiers and PACE Copper initiatives which form part of South Australia’s Copper Strategy. Valuable contributions (technical, staffing and financial) were received from collaborative partners Minotaur Exploration, Kingston Resources and DET CRC.

Technology deployment was supported by DET CRC whose activities are funded by the Australian Government’s Cooperative Research Centre Program.

Curtin University managed seismic acquisition and processing.
References


FURTHER INFORMATION

Adrian Fabris
Adrian.Fabris@sa.gov.au
Mineral Systems Drilling Program – testing and delivering tomorrow’s mineral discovery technologies

Adrian Fabris
Geological Survey of South Australia, Department of the Premier and Cabinet

Introduction

There has been a dramatic decline in the discovery of major new mineral deposits in Australia since around the early 2000s (Guj and Schadde 2013). The decline is generally attributed to most outcropping mineral deposits having been found, driving the need to develop new techniques and methods to improve discovery rates through cover sediments and rocks. This is of particular relevance to South Australia where much of the state’s prospective geology is covered by younger sediments which significantly impede exploration and discovery. The good news for South Australia is that if exploration success rates through cover can be improved, the full potential of our likely mineral wealth can be achieved.

The Mineral Systems Drilling Program (MSDP), which took place between July 2015 and April 2016 along the southern Gawler Ranges, was a collaborative drilling project between the Geological Survey of South Australia (GSSA), Deep Exploration Technologies Cooperative Research Centre (DET CRC), mineral explorers, service providers and research institutes, namely:

• mineral explorers Minotaur Exploration and Kingston Resources
• services companies Boart Longyear, Imdex, Globaltech, Olympus, Epslog and Bureau Veritas
• researchers from CSIRO, the University of Adelaide and Curtin University.

The primary aim of the MSDP was to develop new geological knowledge across the southern Gawler Ranges; however, progressing the development of new technologies that will contribute to improving exploration beneath cover was an important aspect, and involved trials of technologies being developed within DET CRC (DET CRC 2017b; Hillis et al. 2014). The ‘pull through’ and learnings from the MSDP trials are relevant to the entire minerals industry. The emphasis on high-calibre geoscience collaborations across geoscience sectors, and commitment to the application and testing of new exploration technology within the program, sets the MSDP apart from other government-run drilling programs. The MSDP was world-first in adopting this type of collaborative arrangement between government, researchers, mining industry and service companies. The MSDP provided the platform for engaging and drawing together diverse and innovative research in the minerals sector. It also provided the opportunity to showcase and test precommercial products in a semi-commercial environment. A through-chain collaboration of this type is virtually unknown in the world of geoscience and mineral exploration.

This article is intended as complementary to a summary of geological outcomes from the MSDP, also presented in this edition of the MESA Journal. This article focuses on outcomes of technology trials and the collaborative benefits of the MSDP. The reader is referred to Fabris et al. (2017) for a more comprehensive review of the background and aims for each technology deployment.

Technology trials

DET CRC was established with the objective of developing transformational technologies for successful mineral exploration through thick cover rocks to be utilised and commercialised by the mineral exploration industry. DET CRC technologies were deployed in most of the 14 MSDP drillholes
over a nine-month period, representing a significant opportunity for research, development and testing during the program (Fig. 1). These technologies aim to deliver real-time information and data analysis during a drill program (Hillis et al. 2014). The technologies featured in the MSDP included downhole and top-of-hole sensors.

**Wireless Sub**

The Wireless Sub is attached to the top of the drill string and accurately measures drilling parameters such as the downward force on the drillbit, rate of penetration, fluid pressure and rotation speed, enabling the driller to optimise drilling performance and maximise productivity (Fig. 2). The objective of the MSDP trial was to demonstrate the reliability and robustness of the technology and facilitate the rapid development of the Wireless Sub towards commercialisation. The extended period of testing in a harsh drilling environment allowed the technology to be thoroughly evaluated, and provided an opportunity to validate its reliability and precision.

During trials, the Wireless Sub progressed from a 1st generation prototype through to a more robust and reliable 2nd generation unit which underwent significant testing. A real-time rig display was designed and deployed during the MSDP. The Wireless Sub was licenced for commercialisation shortly after the conclusion of the MSDP (DET CRC 2016b), with testing on the program critical in convincing the licensee, Boart Longyear, that the technology was both useful and reliable.

**AutoSonde and AutoShuttle**

The AutoSonde and AutoShuttle collect geophysical wireline log type data (gamma, magnetic susceptibility and resistivity) without separate mobilisation of a wireline logging crew or additional time requirements at the drill site (Fig. 3). The AutoSonde is deployed into the hole by the driller and analyses the drilled profile as the drill rods are pulled out of the hole. The AutoShuttle sits behind the core barrel and acquires measurements while drilling, returning data every time the core barrel...
The MSDP was the first full field trial of the AutoShuttle outside of the Brukunga Drilling Research & Training Facility in the Adelaide Hills. A comparison of total count gamma results showed the fidelity possible by using the AutoShuttle due to the increased reading time. Following the MSDP trials, DET CRC has accepted a commercialisation proposal from Boart Longyear for the magnetic susceptibility and resistivity sensors on the AutoSonde and for the AutoShuttle.

Lab-at-Rig®

Lab-at-Rig® enables state-of-the-art on-site analysis of drill cuttings, and provides near real-time XRF geochemistry and XRD mineralogy (Fig. 4). These data can be used to aid geological logging and allow greater confidence in assessing the prospectivity of drill core. The focus of testing during the MSDP was on improvement and development of design configurations, sample capture and sample preparation techniques. This also involved better integration with a solids removal unit. Delivery of data to clients was also tested, and involved data streaming via a dedicated satellite system and delivery through to ReflexHub, which was launched during the program. Workflows for real-time data analysis were trialled. Lab-at-Rig® operated for the majority of the drill program and had no issue with 24-hour operation.

Geochemical data from drill cuttings were available within a few hours of being drilled and provided an extraordinary ability to remotely assess lithology and mineral prospectivity while drilling was in progress. In the field, having geochemical analyses at ~1 m resolution for an entire hole was a rare luxury and was used to aid core logging (including subtle intraformational variation as well as major breaks) and highlight mineralised intersections.

While a commercialisation agreement was reached with Boart Longyear for the AutoSonde with total count gamma sensor before the start of the MSDP (January 2015), the MSDP provided an ideal precommercial test environment with learnings fed back into future product design which has assisted with bridging the so called ‘commercialisation valley of death’ (being the gap between research and commercial worlds). The AutoSonde, rebadged the TruProbe™ by Boart Longyear, was recently deployed during the GSSA Coompana drill program (April–September 2017).
It also enabled correlation with mineralogy to provide a more thorough understanding of influences on elemental variation (protolith vs alteration). Contamination from excessive bit wear (Cu, W ± Ag) and rod grease (Zn) was evident in results, however, could be corrected using known ratios from drillbit compositions.

**Fluid Management System**

The Fluid Management System (FMS) utilises a series of ion selective electrodes to provide real-time information on the chemistry of the drilling fluids (Fig. 5). Sulfide intervals and changes in aquifer chemistry can be detected. Significant learnings and development made during the MSDP resulted in design changes and a practical workflow for use in field conditions. Dramatic changes in drill fluid chemistry resulting from additives highlighted the possible commercial application of using the system to maintain optimal fluid condition for efficient drilling.

**Real Time Drill Site**

The objective of the Real Time Drill Site (RTDS) was to develop and deliver ICT architecture to integrate geoscience data generated by DET CRC’s analytical technologies during the MSDP, and allow those data to be interrogated, analysed and visualised. This was in support of the vision of real-time data analysis and exploration in the mineral industry that is currently in its infancy. Software development was facilitated by funding gained from the South Australian Mining Industry Participation Office and utilised South Australian based developers. A demonstration of the RTDS ‘dashboard’ was held towards the end of the MSDP and enabled Wireless Sub and AutoSonde data to be integrated and viewed through a secure portal (utilising Reflex Hub), anywhere in the world (Fig. 6).

**Seismic acquisition for the minerals industry**

Several targeted, cost-effective surface seismic surveys and downhole vertical seismic profiles (VSP) were conducted by Curtin University and DET CRC to aid depth to basement estimation around MSDP drillholes and refine the methodology for using seismic in hard rock terrains. To contain costs, inexpensive sources and sparse geophone spacing with small crews were used. Different geometries, acquisition systems and imaging methodologies were trialled. Most novel were the evaluation of a draggable receiver string seismic system and the use of optic fibre as receivers during VSP surveys. It was concluded that the draggable receiver string could be effective at imaging to 100 m depth. In-hole optic fibre distributed acoustic sensors delivered faster and higher quality data than hydrophone VSP (DET CRC 2017a). This indicates the potential to gain velocity characterisation in drillholes at very low cost, opening up the possibility that it will become part of routine petrophysical data acquired during a drill program.

**RoXplorer® trial**

Following completion of the 14 MSDP diamond drillholes, DET CRC’s new coiled tubing drilling rig, the RoXplorer®, was deployed on the same drill pad as MSDP02 (Fig. 7; Fabris 2017; DET CRC 2017b). The site provided an example of thick cover...
Figure 6  Real Time Drill Site ‘dashboard’ module within ReflexHub-IQ. (Courtesy of DET CRC)

Figure 7  RoXplorer® on deployment at Port Augusta field site as part of the broader MSDP project. (Courtesy of DET CRC; photo 416155)
of sedimentary rocks typical of the Stuart Shelf and a target zone of ~1% Cu at the contact between Tapley Hill Formation and Beda Basalt at 398 m. In addition to these geological attributes, inclusion of the RoXplorer® trial as a component of the broader MSDP provided permitting and logistics advantages, which enabled researchers to focus on achieving a successful drillhole, in what was the first full field trial of RoXplorer®. At completion of this trial, DET CRC had realised the milestone of drilling a 20 m interval in under one hour and demonstrated that the RoXplorer® could retrieve cuttings that sharply define geological boundaries. Furthermore, assays of cuttings collected during drilling closely matched those obtained from the diamond core in MSDP02. The trial was a significant demonstration that DET CRC’s flagship technology, a coiled tubing drill rig designed for mineral exploration, was a viable method of addressing their objective of cheaper, faster drilling. It also meant all key technology developments within DET CRC were tested during the MSDP.

Trials during the MSDP have played a tangible role in moving these technologies closer to commercial products. All technologies were demonstrated or successfully adapted to meet the challenges provided by remote and sometimes harsh climatic conditions. One measure of success is through progress along Schild’s (2014) technology readiness levels (TRL). All technologies progressed at least one level against TRLs (Table 1).

Explanations, demonstrations and benefits of technology trials have been presented in a video series available through the DET CRC TV channel.

The benefits of collaboration

A core principle of the MSDP was to foster collaboration. Thirteen organisations collaborated: 8 industry, 4 research and the South Australian Government. The program accessed a range of expertise from across government to ensure activities followed best practice. These included the areas of Aboriginal heritage, community engagement, safe work practices, land access and rehabilitation. Within the GSSA, regional mapping and data collection projects were modified and integrated with the drill program to maximise the benefits from coordinated activities across a range of disciplines. The South Australian Government’s investment of $2.5 million from the PACE Frontiers and PACE Copper initiatives was leveraged into an overall ~$8 million cash and in-kind program. This leverage was achieved due to integrated research required to achieve the program, which grew as project parties fully realised the potential benefits. The collaborations increased the leverage of financial and in-kind contributions, significantly improving outcomes.

Industry participants, Minotaur Exploration and Kingston Resources, achieved additional metres of drilling and access to near real-time data in which to make assessments of the geology and prospectivity. DET CRC and associated researchers and service providers gained access to a semi-commercial environment in which to deploy, test, improve and redeploy technology over a nine-month period. Not only did the GSSA leverage ~$1 million in cash and at least $2 million in-kind from collaborators, but also gained access to industry knowledge and expertise, and additional sample analyses to add to the evaluation of an emerging new mineral district.

In excess of 100 South Australian based suppliers were used during the program (DETCRC 2016a) from trucking water and grading roads to preparation of 3,225 meals. This represents a flow on of the broader benefits of the program to regional South Australia.

### Table 1

<table>
<thead>
<tr>
<th>Technology readiness level stages (Schild 2014)</th>
<th>TRL 0</th>
<th>TRL 1</th>
<th>TRL 2</th>
<th>TRL 3</th>
<th>TRL 4</th>
<th>TRL 5</th>
<th>TRL 6</th>
<th>TRL 7</th>
<th>TRL 8</th>
<th>TRL 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Idea. Unproven concept, no testing has been performed.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basic research. Principles postulated and observed but no experimental proof available.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technology formulation. Concept and application have been formulated.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Applied research. First laboratory tests completed; proof of concept.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Small-scale prototype. Built in a laboratory environment ('ugly' prototype).</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Large-scale prototype. Tested in intended environment.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prototype system. Tested in intended environment close to expected performance.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Demonstration system. Operating in operational environment at precommercial scale.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>First of a kind commercial system. Manufacturing issues solved.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Full commercial application. Technology available for consumers.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**The benefits of collaboration**

A core principle of the MSDP was to foster collaboration. Thirteen organisations collaborated: 8 industry, 4 research and the South Australian Government. The program accessed a range of expertise from across government to ensure
Conclusion

The MSDP provided an opportunity to showcase and test precommercial technology within a supportive real-life exploration program. All technologies were successfully deployed during the MSDP with significant progress made, not only to hardware and software, but also deployment procedures and protocols. An improved understanding of skills and training requirements was identified for routine use of these technologies in future drilling programs. The technologies deployed during the MSDP provide the wider exploration community the opportunity to gain an early insight of how data from new technologies will better inform future exploration geoscientists, accelerate decision-making and eventually lower the cost of exploration.

The success and impact of technology trials during the MSDP is due largely to the successful model deployed by DET CRC, which supports the progress of research and development through to commercial products that are aligned with the objectives of DET CRC. While the technologies alone will not transform the exploration success rate beneath barren cover, they provide a step change in the approach to acquiring data in a cost-effective and timely manner. This will permit more test holes to be drilled based on evaluation of real-time data; both are widely acknowledged as essential to improving success of mineral exploration through cover.

The program served as a model for collaboration in the way that it brought together mineral explorers, DET CRC, the mining equipment, technology and services (METS) sector, government and research organisations. The outcomes include improved understanding of the state’s geology and an impetus to grow the state’s METS sector through leveraged activity from the licence of new intellectual property.

Acknowledgements

The MSDP was part of South Australia’s PACE Frontiers and PACE Copper initiatives which form part of South Australia’s Copper Strategy. Valuable contributions (technical, staffing and financial) were received from collaborative partners Minotaur Exploration, Kingston Resources and DET CRC.

Technology deployment was supported by DET CRC whose activities are funded by the Australian Government’s Cooperative Research Centre Program.

Curtin University managed seismic acquisition and processing.

The measure of improvement of DET CRC technology using the TRL scale was prepared by Robbie Rowe (GSSA).

References


DET CRC – see Deep Exploration Technologies Cooperative Research Centre


FURTHER INFORMATION

Adrian Fabris
Adrian.Fabris@sa.gov.au

DET CRC
detcrc.com.au

DET CRC TV
www.youtube.com/user/DETCRCTV
Characterisation of the Samphire granite, Hiltaba Suite, northeastern Eyre Peninsula

Russel Bluck and Callan Brown
Samphire Uranium Pty Ltd

Peer reviewed (Geological Survey of South Australia)

Introduction
The Hiltaba Suite Samphire granite lies south of Whyalla on the northeastern Eyre Peninsula, underlying the eastern coastal plain and adjacent Spencer Gulf (Fig. 1). Uranium exploration in the area commenced in 2007 and resulted in the discovery of sediment-hosted uranium mineralisation in Eocene paleochannels eroded into the fractionated and uranium-rich Samphire granite.

Exploration has generated datasets from drilling, airborne magnetics, airborne electromagnetics (AEM) and gravity surveys over the onshore part of the Samphire granite. An integration of the available data has enabled the granite intrusion to be subdivided into five generalised geological domains and identified metasedimentary carapaces across the top of the intrusive.

Background
The Samphire granite is known only from mineral exploration drilling and geophysical surveys. In the 1980s BHP explored for lignite along the western margin of the Pirie Basin, finding extensive Eocene Kanaka beds sediment on a metasediment/granite basement; one radiometric profile had a possible ‘redox’ signature (Hole PP-15, BHP Minerals 1982, p. 37). In 2006 UraniumSA Limited, an ASX listed junior exploration company, modelled the Kanaka beds in the Samphire area as permissive for fluid circulation and the development of redox systems, and postulated the underlying circular aeromagnetic anomaly as a potentially uranium-endowed Hiltaba Suite granite. The first exploration hole in 2007 intersected a typical redox profile leading to the discovery of the Blackbush deposit and the geologically similar Plumbush deposit in Eocene Kanaka beds sediment with JORC-compliant resource estimates aggregating 21,100 tonnes U₃O₈ at a 100 ppm cutoff (UraniumSA 2012, 2013).

Figure 1 Regional setting of the Samphire granite shown on total magnetic intensity (TMI) image.
Regional setting

The Samphire granite appears as a north–south elongate, irregular ellipsoidal body ~55 x 23 km (795 km\(^2\)) in aeromagnetic imagery, delineated by peripheral high-amplitude, positive-linear to curvilinear magnetic responses in Paleoproterozoic country rocks and enclosing fabrics of moderate-low amplitude magnetic response. Country rocks to the intrusion are Warrow Quartzite (c. 2005 Ma; Geoscience Australia, GA, 2017) along the western margin, Broadview Schist (1791–1750 Ma; GA 2017) and Wandearah Formation (1763–1750 Ma; GA 2017) along the northern margin, with undifferentiated Hutchison Group (1964–1850 Ma; GA 2017) interpreted on the eastern and southern margins. The western margin underlies the eastern coastal plain of the Eyre Peninsula, with the remaining portion below the Spencer Gulf (Figs 1, 2). The northwestern onshore portion has been divided into the five granite domains that are the focus of this paper (Fig. 3).

The Samphire granite has been dated at c. 1585 Ma (Jagodzinski and Reid 2017) and forms part of the Hiltaba Suite lying on the boundary between the Spencer and Olympic domains in the southern Gawler Craton (Fig. 1; Ferris, Schwarz and Heithersay 2002). The Roopena Fault Zone, which is interpreted as the Spencer–Olympic domain boundary, extends north from the Samphire granite with a linear demagnetised zone (DMZ) extending south through the intrusion (Fig. 3).

Methodology

Datasets used in the study comprise exploration drilling data (791 holes, 9 with diamond core), aeromagnetics (25 m to 200 m line separation), AEM (500 m to 1,000 m line separation), and gravity surveys (25 m to 200 m station separation). A descriptive ‘domain’ designation has been adopted in the interpretation to reflect the heterogeneity inherent in the geology and accommodate the disconnect between point observations and kilometre-scale geophysical datasets and derived grid surfaces.

In the regional interpretation, geological domain boundaries were constructed on magnetic amplitude/frequency signatures constrained by mapped outcrop. Within the Samphire granite geological domain boundaries were constructed on magnetic amplitude/frequency signatures cross-collated with AEM and gravity responses with geological input from drillhole lithology. Geochemical data was interrogated on the basis of the interpreted domain boundaries (Fig. 3).

Clay alteration

Exploration rotary mud drilling targeted the prospective uranium mineralised Kanaka beds and holes were terminated either in recognisable pre-Eocene basement or at bit refusal. Petrology of end-of-hole (EOH) samples, called clay-altered granite in the field, range from variably friable clearly recognisable granite with incipient to extensive sericite, clay and chlorite alteration (Fig. 4), through to materials comprising angular quartz grains in a groundmass of kaolinite–illite with ghost granitic fabric (Fig. 5).
The origin of the clay alteration is not conclusively established. In regional exploration drilling, significant clay-alteration of basement below the Eocene unconformity was recognised only within the boundaries of the Samphire granite. At the Blackbush deposit, solid 3D models show envelopes of clay alteration extend down into the granite within corridors formed by post-emplacement structures in granite. A pan concentrate of radiometrically active clay-altered material from drillhole MRC167 north of Blackbush contained primary bassanite pseudomorphically replaced by a metamict-altered monazite, potentially during a saline hydrothermal/epithermal alteration (Pontifex 2012).

The pervasive clay-alteration was initially assumed to be a pre-Eocene saprolite. However, given it is restricted to the Samphire granite it is now considered most likely to be an intrusion or post-emplacement-related hydrothermal event.

### The Samphire granite

The Samphire granite has an internal magnetic morphology subdividing it into:

- **a southern portion** comprising two-thirds of the area (522 km²) and distinguished by linear-textured low amplitude/frequency responses
- **a northern portion** comprising one-third (243 km²) of the area and distinguished by curvilinear-textured moderate amplitude/frequency magnetic responses.

The two portions are in contact along an indistinct northwest trend discernible in amplitude/frequency textures and indistinct terminations. The northern portion has been subdivided into five granite domains and is overlain by an incompletely preserved carapace of altered metasediments.

### Granite margins

On the western margin of the Samphire granite, geophysical profile inflexions are coincident with a change from granite to metasediment in drill samples indicating a near-vertical attitude for the intrusive contact with Warrow Quartzite below Eocene cover. Subtle geophysical variations in the country rock west of the contact are indicative of post-emplacement metasomatic alteration.

North of the margin of the Samphire granite, Broadview Schist and Wandearah Formation country rocks exhibit a moderate- to high-amplitude magnetic anomalism which steadily diminishes northwards along strike. In this area EOH samples from exploration rotary mud holes frequently return anomalous Cu–Co values.

The metasomatic alteration and geochemical anomalism of country rock along the Samphire granite margins is interpreted to be the result of thermal gradients and fluid flow more or less contemporaneous with emplacement.

### Metasediment carapace

Inside the northern margin of the Samphire granite clay-altered material is sporadically recognised as a subhorizontal layer below Eocene cover and overlying clay-altered granite. Drill cuttings comprise pink, red, brown, grey variegated silt/clay materials, with minor erratic angular lithic fragments with siliceous–quartzitic or gneissic textures, and are commonly Cu–Co anomalous. The materials are interpreted as the eroded remnants of a concave-south carapace of clay-altered Wandearah Formation and Broadview Schist overlying Samphire granite. They are thin and apparently discontinuous and are not shown in Fig. 3.
In the more sparsely drilled southwestern part of the Samphire granite within the study area, two areas of clay-altered metasedimentary rock are associated with diffuse magnetic responses. These are interpreted as probable roof pendants of country rock overlying stock-like phases of the Samphire granite (labelled 1 in Fig. 3).

**Granite domains**

Only the northwestern, onshore, portion of the Samphire granite where there is adequate exploration data is considered in this interpretation (Fig. 3). Integration of geological, geochemical and geophysical data has enabled five granite domains to be recognised and interpretation of geophysical imaging has been used to trace discordant relationships and infer an intrusive sequence:

- east granite domain
- green granite domain
- mottled granite domain
- red granite domain
- west granite domain.

**East granite domain**

The east granite domain extends over 16 km² and is inferred with less confidence over an area of 189 km². The domain is characterised as a unit by moderate-high amplitude magnetics which show an internal domal northwest-elongate, low-frequency fabric.

The east granite was intersected in 62 rotary mud holes with drill cuttings comprising light-grey and grey clay/silt with dispersed angular quartz. Gneissic textured fragments in cuttings may represent entrained country rock or xenoliths. There are no core samples.

**Green granite domain**

The green granite domain extends over 39 km² and is characterised as a unit by moderate-high amplitude magnetics which show an internal open northwest-oriented ellipsoidal fabric which occurs at a higher frequency than in the east granite domain. From geophysical imaging the domain is interpreted lying west of the east granite, extending along the eastern margin of the mottled granite, terminating to the north against the DMZ, and in the south partially enclosing a lobate portion of the red granite (Fig. 3).

Across the green granite domain Eocene sediments pinch out and the Miocene section thins significantly. The area is interpreted as a paleotopographic high, potentially replicating a domal feature in the upper surface of the Samphire granite.
Green granite was intersected in 23 rotary mud holes with drill cuttings comprising cream, grey and off-white clay/silt with dispersed angular quartz. Petrology from core hole MRC005 describes a coarse- to medium-grained granite composed of coarse K-feldspar crystals intergrown with medium-grained quartz and sericite-altered plagioclase, and lesser biotite with trace zircon and apatite (Jagodzinski and Reid 2017). In hand specimen the granite is visually similar to the mottled granite, though with less apparent sericite alteration.

**Mottled granite domain**

The mottled granite domain extends over 5.6 km² and is characterised as a unit by high amplitude/ frequency magnetics with a coherent internal linear northeast- to southwest-trending texture and an overprint of linear northwest-trending cross features. From geophysical imaging it is interpreted west of the green granite, extending along the eastern margin of the red granite, terminating to the northeast against the DMZ, and to the southwest thinning and terminating against a lobate feature of the red granite which is partially enclosed by the green granite (Fig. 3).

Mottled granite was intersected in 109 rotary mud holes with drill cuttings comprising cream, grey, off-white clay/silt with dispersed angular quartz. In hand sample granite intersected in MRC007A is green and white mottled, coarse to medium grained and visually dominated by coarse K-feldspar crystals intergrown with medium-grained quartz, plagioclase and visually dominated by coarse K-feldspar crystals intergrown with medium-grained quartz, plagioclase, and lesser dark brown biotite. It is variably sericite altered, particularly the plagioclase.

**Red granite domain**

The red granite domain extends over 16 km² and comprises a coherent unit of north-northeast striking, concave-east low-moderate amplitude/frequency magnetics with a subtle overprint of northwest-trending cross features. The domain is interpreted in geophysical imaging extending along the eastern margin of the west granite domain, with a lobate body terminating the southern end of the mottled granite domain and a lobate portion surrounded by the green granite domain (Fig. 3).

Red granite was intersected in 336 rotary mud holes with drill cuttings comprising cream, grey and off-white and occasionally pinkish clay/silt with dispersed angular quartz. Drill core of the red granite is available from nine drillholes; eight of which were drilled in a restricted ~150 m diameter area underlying the Blackbush deposit.

Petrology from core hole MRC009 drilled on the southern edge of the Blackbush deposit describes red-coloured medium-grained granite composed of approximately equal proportions of quartz- and sericite-altered and hematite-dusted plagioclase with lesser K-feldspar, minor biotite, zircon and opaques which may be magnetite (Jagodzinski and Reid 2017).

Cored tails from below the body of the Blackbush deposit and ~500 m north of MRC009 intersected similar granites but with micro- and macro-scale differences. Petrology identified a range of rare earth element (REE) minerals associated with finely hematite altered granite. Synchysite is a common accessory in association with fluorite, acicular bastnasite is often included in synchysite, and monazite is uncommon. In isolated sections of some core K-feldspar is displaced by up to 30% fluorite in a medium-grained evenly textured rock. In the majority of cored tails, subtly different granite textures/compositions are juxtaposed either side of fine linear to curvilinear fractures and veins, commonly with chlorite–hematite selvedge, occasionally quartz–hematite or rarely quartz–fluorite. Core in MRM893 intersected subvertical, centimetre-wide fluorite–quartz–hematite veins with colloform or crustiform laminar banding and ‘dog tooth’ crystal forms which are characteristic of epithermal systems (Goldsmith 2014). The juxtaposition of rock type and vein textures are interpreted to reflect block brecciation of the red granite, probably by hydraulic fracturing along zones para-conformable to shallow east-dipping fabrics in the granite (Fig. 6).

In drill core from the red granite domain a textural fabric dips ~45°; there is no strike orientation (Fig. 7). Downhole radiometric profiles from drillholes across the Samphire granite frequently show stepped profiles indicative of compositional banding across widths of a few to over 10 metres. At the granite domain level, interpretation of magnetic profiles indicates the contact between the red and green granite domains has an overall easterly dip ~45° with a northeasterly strike.

The red granite domain is interpreted to have been emplaced as a series of northeast-trending east-dipping phases which, in the area of the Blackbush deposit, are block-brecciated and hydrothermally veined.

**West granite domain**

The west granite domain extends over 29 km² and comprises a coherent arcuate north-northeast-trending, concave-east unit of relatively low-amplitude, low-frequency magnetic and gravity signatures which extend parallel with the western margin of the Samphire granite. In geophysical imaging a lobate portion of the west granite domain extends south along the indistinctly defined contact between the northern and the southern portions of
the Samphire granite. The west granite is intruded into Warrow Quartzite to the west and is interpreted in contact with the red granite domain to the east, terminating to the northeast against the DMZ (Fig. 3).

The west granite was intersected in 41 rotary mud holes with drill cuttings comprising pink, off-white, cream and grey clay/silt with dispersed angular quartz. There are no core samples.

**Geochemical data**

Exploration rotary mud drilling was sampled at 2 m intervals with the gravity-settled portion of drilling mud return flow collected. An archetype of each interval was grab-sampled into chip trays and the entire EOH sample retained for assay. A total of 134 rotary mud EOH samples were laboratory assayed from four of the five granite domains (Australian Laboratory Services Pty Ltd, ME-ICP61, ME-MS62S). Subsequently, portable X-ray fluorescence (p-XRF) readings were taken on the EOH chip-tray compartment from drillholes without assays (503 holes). While p-XRF instrumentation has acceptable precision within recognised limits, in this application the physical inhomogeneity of the material in the chip trays and the instrument’s small field of view resulted in a relatively low reproducibility.

At a whole-of-population level and across the range of values, the distribution of K and Ca assay data overlaps the p-XRF chip-tray data. This similarity of distribution of values indicates that for the purpose of the present work the methods are comparable, and that patterns and trends in values most probably reflect variability in the geology/geochemistry of the granite domain materials (Fig. 8).

**Geochemical trends**

The assay and p-XRF data are grouped together, subset by granite domains and treated as populations rather than individual values. While there is a high variability of individual values forming significant noise envelopes for each domain, at a population level there are interpretable patterns within the data.

A scatter plot of K vs Ca data by granite domain indicates bi-modal populations with the east, green, mottled and red granite domains showing high and low K subsets either side of 10,000 ppm, with significant overlap between the domains. Visually, the east and green granite domain data plot predominantly below the 10,000 ppm K level, the red granite domain data plot predominantly above that level, and the mottled domain values appear
more evenly spread. The west granite domain exhibits a relatively even spread of K values with a possible bi-modal tendency to a high/low Ca spread (Fig. 9).

Trends within the noise envelopes are more readily discernible when domains are represented by their average values (Table 1). The limitations of this approach are obvious given the uncertainties inherent in the geochemical datasets and the interpretive limitation of the geological domains. As a general proposition, increases in K, Rb/Sr and U/Th ratios are indicators of fractionation, though ion substitution for K in crystal lattices is a significant constraint on interpreting Rb/Sr ratios in isolation (Table 2).

Line plots of average values of the domains show systematic changes indicative of increasing fractionation from the east through to the west granite domain. Average K is similar for both the east and green domains, increasing for the mottled before peaking for the red and declining somewhat for the west granite domain. There is a reverse trend for average Ca which is at a high in the east and declines through the green, mottled and red to a low in the west granite domain (Fig. 10).

Line plots of domain average values for U ppm, U/Th and Rb/Sr show a similar pattern as K average values. The consistencies of trends in the rock-forming metals and in ratios indicative of fractionation are consistent with the inferred sequential emplacement from east to west of domains of increasingly fractionated granite (Fig. 11).

Ternary plots of normalised K:Ca:Na have been compiled from assay data available for four of the five granite domains; there is no Na data for the west granite domain. Trends which are apparent in the line and scatter plot data from the east granite domain through the red granite domain are exhibited in the Ternary plots. Where there is sufficient data, notably for the red and mottled granite domains, the tendency for bi-modal populations seen in the scatter plot of all K vs Ca data remains apparent (Fig. 12).

Across the Samphire granite within the east, green and west granite domains, the drillholes with high K values are randomly distributed without any apparent underlying geological control. Within the area of the red granite domain, the distribution of high K values is biased by the concentration of drilling at the Blackbush deposit.

**Discussion**

Geological and geochemical data generated during uranium exploration has been used to interpret the geology and emplacement history of the Samphire granite. The area is overlain by a relatively consistent 50–80 m of Eocene, Miocene and younger sedimentary rocks and the following discussion is of the geology below the Eocene unconformity, or the Miocene unconformity where Eocene is absent.

The Hiltaba Suite Samphire granite was intruded into Warrow Quartzite, Broadview Schist, Wandearah Formation and undifferentiated Hutchison Group metasedimentary country rocks. The outer western contact is essentially subvertical while the upper
alteration and Cu–Co anomalism. The alteration and mineralisation is interpreted to be the result of thermal gradients and fluid flow contemporaneous with emplacement.

Across the upper surface of the intrusion both the granite and overlying carapace are clay-altered with sporadic Cu–Co anomalism associated with the metasediments. Clay-alteration and mineralisation is interpreted to post-date granite emplacement and magnetic-positive metasomatic alteration.

In parts of the Samphire granite where the metasediment carapace has been removed, clay-alteration of the granite is associated with linear northeast- and northwest-trending structures which are interpreted to post-date lithification. In the Blackbush area 3D models show envelopes of clay-alteration extend 80–100 m below the top of granite within a north-trending fault-bounded corridor.

The five granite domains comprising the northern portion of the Samphire granite are each delineated by coherent geophysical signatures, but are internally heterogeneous with geochemical and geological variability.

**East granite domain** material is typically more sodic and less potassic than all other domains and has the lowest Rb/Sr and U/Th ratios and U geochemistry. Gneissic/banded materials in drill cuttings may be unidentified carapace, roof-pendant remnants or protolith xenoliths.

**Green granite domain** material is similar to the east granite domain with broadly comparable sodium, potassium and Rb/Sr, U/Th ratios and U geochemistry, but with its own distinct geophysical signature. To the south and west, the green granite domain is intruded by the red granite domain.

**Mottled granite domain** material is less sodic than the east and green granite domains, transitional to those of the west and red granite domains. Its Rb/Sr, U/Th ratios and U geochemistry overlap the other domains, tending to be lower than the west and red granite domain materials and higher that the green and east granite domain populations. The mottled granite domain is intruded by the red granite domain.

Table 1  Geochemical values, Samphire granite domain

<table>
<thead>
<tr>
<th>Domain</th>
<th>Ca (ppm)</th>
<th>K (ppm)</th>
<th>U (ppm)</th>
<th>Th (ppm)</th>
<th>Rb (ppm)</th>
<th>Sr (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Range</td>
<td>Average</td>
<td>Range</td>
<td>Average</td>
<td>Average</td>
</tr>
<tr>
<td>West</td>
<td>7,084</td>
<td>857–58,659</td>
<td>21,575</td>
<td>1,853–50,487</td>
<td>25</td>
<td>76</td>
</tr>
<tr>
<td>Red</td>
<td>8,652</td>
<td>531–106,510</td>
<td>25,664</td>
<td>1,449–49,830</td>
<td>44</td>
<td>62</td>
</tr>
<tr>
<td>Mottled</td>
<td>9,327</td>
<td>991–254,000</td>
<td>15,147</td>
<td>1,258–67,471</td>
<td>22</td>
<td>49</td>
</tr>
<tr>
<td>Green</td>
<td>3,783</td>
<td>1,000–10,599</td>
<td>11,039</td>
<td>1,400–41,878</td>
<td>15</td>
<td>73</td>
</tr>
<tr>
<td>East</td>
<td>12,697</td>
<td>228–213,691</td>
<td>11,322</td>
<td>1,000–47,044</td>
<td>17</td>
<td>50</td>
</tr>
</tbody>
</table>

Table 2  Fractionation indicators, Samphire granite domain

<table>
<thead>
<tr>
<th>Domain</th>
<th>K (ppm)</th>
<th>U (ppm)</th>
<th>Rb/Sr</th>
<th>U/Th</th>
</tr>
</thead>
<tbody>
<tr>
<td>West</td>
<td>22,000</td>
<td>25</td>
<td>11.0</td>
<td>0.49</td>
</tr>
<tr>
<td>Red</td>
<td>26,000</td>
<td>44</td>
<td>12.1</td>
<td>0.90</td>
</tr>
<tr>
<td>Mottled</td>
<td>15,000</td>
<td>22</td>
<td>3.6</td>
<td>0.59</td>
</tr>
<tr>
<td>Green</td>
<td>11,000</td>
<td>15</td>
<td>3.7</td>
<td>0.21</td>
</tr>
<tr>
<td>East</td>
<td>11,000</td>
<td>17</td>
<td>3.7</td>
<td>0.58</td>
</tr>
</tbody>
</table>

Figure 10  Ca and Na average value, Samphire granite domains.
**Red granite domain** material shows a step change in geochemical trends being less sodic and significantly more potassic with significantly higher Rb/Sr and U/Th ratios and U geochemistry than the mottled, green and east domains. At its north end the red granite domain has a linear east-dipping contact with the mottled granite domain. To the south the red granite domain intrudes the east–green–mottled series, terminating the extent of the mottled granite and forming a semi-circular lobe within the green granite domain.

Block brecciation and hydrothermal veining of the red granite is associated with alteration and elevated U-REE mineralisation in the area of the Blackbush deposit.

**West granite domain** material is similar to the red granite domain with comparable potassium values but with lower calcium; there is no sodium data available. The domain has Rb/Sr, U/Th ratios and U geochemistry which is lower than the red but higher than the mottled, green and east granite domains. The west granite domain is emplaced between the red granite and country rock to the west. To the south it is in contact with the southern portion of the Samphire granite along an indistinct northwest trend.

**Carapace** of altered country rock is present over the northern margins of the Samphire granite intrusion. Two isolated areas of clay-altered country rock in the south of the west granite domain on the western margin of the Samphire granite are interpreted as intact carapace overlying stocks of the Samphire granite.

The uranium-mineralised Eocene fluvial channel which hosts the Blackbush deposit eroded through the shallow-dipping carapace and incised into underlying clay-altered uranium-rich red granite domain materials.

**Conclusion**

The Samphire granite is a fractionated Hiltaba Suite intrusion with an areally larger southern portion and a smaller northern portion. Within the onshore part of the northern portion, five increasingly fractionated granite domains are interpreted to have been sequentially emplaced in the form of an inverted cone-like body. The least fractionated east granite domain is close to the centre with sequentially more fractionated green and the east-dipping mottled and red domains westwards. The west granite domain has vertical country rock contacts.

Country rock metasomatic alteration contemporaneous with emplacement of the Samphire granite is associated with base metal anomalism. Clay-alteration extends across the top of the Samphire granite and remnants of clay-altered...
metasediment carapace are metal anomalous. In the Blackbush area there is a localised zone of more intense alteration with U-REE mineralisation associated block brecciation, epithermal veining and clay-alteration of the uranium-rich red granite domain.

Acknowledgements
Samphire Uranium Pty Ltd, the owners of the Samphire project, provided access to the data. Our concepts are built on the contributions of the geoscientists who worked on the project, in particular Edward Keys, Wade Bollenhagen, Nicole Galloway-Warland, Marco Scardigno and Faith Gerhard. The data and intellectual contributions of Nigel Cook at the University of Adelaide and his students Sam Goldsmith and Urs Domnick have been invaluable. Stacey McAvaney and Mark Pawley (Geological Survey of South Australia) ensured logical rigor.

References


GA – see Geoscience Australia


Remediating the Leigh Creek coal mine

Remediation overview

Leigh Creek coal mine is a major mine that has played a key role in South Australia’s energy history for over 70 years. Credited with enabling post-war industrialisation, remediating the Leigh Creek coalfields was always going to be a significant undertaking for operator Flinders Power Partnership.

The series of open pits and surrounds cover around 70 km² (Figs 1, 2). A key site challenge, which is common to remediating most coal mines, is the inherent risk of spontaneous combustion arising from the coal itself and the associated surface water management requirements.

In addition to technical challenges, the site poses a number of significant social considerations: there is a cemetery next to one of the mine pits – on what was the original site of Leigh Creek township – there are Aboriginal heritage sites within the area, and a community preference to maintain the man-made dam for water recreational pursuits and to preserve it as a bird habitat.

The challenge of mine closure has come a long way in recent decades. Environmental managers and regulators can now consider the balance between competing or complementary technical, safety, environmental and social interests, through a strategic planning approach that integrates a suite of methodologies to tackle the risks at hand.

Mine closure planning pulls together a systematic performance-based approach, to identify key risks and management needs, develop ongoing monitoring to track the success of mitigation, and modify approaches over time to adapt to performance needs. For Leigh Creek’s remediation, the public safety and environmental risks were detailed in a comprehensive closure and works plan of more than 4,000 pages, developed over 20 months by Flinders Power.

Figure 1 Location of the Leigh Creek coal mine shown over satellite imagery.

Figure 2 Aerial view over a section of the Main Series pit. (Courtesy of Flinders Power; photo 416240)
Bringing to life closure related activities, is a team managed by Flinders Power and overseen by South Australian mining and environmental regulators. The team is committed to ensuring the closure plan and works are well managed, consider the potential for post-mining landuse and executed to highest quality standards.

As the mine closure operation reaches its final stages, regulators are pleased with the progress and outcomes delivered by Flinders Power. The vetting process required Flinders Power to submit its Mine Closure Plan, which regulators assessed and collaborated with Flinders Power to identify refinements to the closure methodology. This collaboration will not only improve expected closure outcomes but raise the likelihood of successful relinquishment of the site by Flinders Power to government. The challenge for any operator is closing a site to a suitable standard that the mining lease can be relinquished and the site handed back to government.

Lead regulators have indicated that:

‘While there are many aspects to the Leigh Creek closure and rehabilitation works, the major focus is on reducing the risk of spontaneous combustion which interplays heavily with surface water management, as well as public safety, environmental values, the amenity for the local community and visual amenity for people passing through.

‘At the current rate of progress, Flinders Power expects to wind up much of the on-ground remediation works by mid 2018 and, subject to government assessments and sign off, there will be a period of monitoring – five years likely – to ensure any residual risks continue to be monitored, managed and addressed prior to relinquishment.

‘From the significant works to re-profile the waste rock dumps which will revegetate naturally and blend into the surrounds, we can look forward to a day when tourists may make their way to the attractive post-landuse dam for fishing and water sports.’

Rich history

The former Leigh Creek mine is located 550 km north of Adelaide in a picturesque part of the northern Flinders Ranges.

Long before European settlement, the Aboriginal people referred to the coal deposits in the area as Yulu’s (Kingfisher Man) charcoal. Colonist John Henry Reid came across the coal-bearing shale during the sinking of a railway dam in 1888 in the Leigh Creek area. Leigh Creek coal is considered low-grade sub-bituminous black coal, colloquially called ‘brown coal’. Geologists have dated the coal to the Triassic age (240–200 million years old), occurring as saucer-shaped sedimentary deposits laid down on a pre-Cambrian basement of limestone and shales, and overlain by Quaternary sediments (Flinders Power 2017).

Various early attempts to scale up profitable mining of Leigh Creek’s brown coal were thwarted by technical and logistical difficulties (Klaasse 1997, chs 1, 2). It wasn’t until 1941 when coal supply to South Australia proved precarious that serious prospects for mining the coalfield were advanced successfully.

Former premier Tom Playford championed the cause to define the coal deposit’s extent and work out how best to proceed to mine it – drawing on public sector capabilities – in the Department of Mines, Engineering and Water Supply Department, South Australian Railways, the Factories and Boilers Department, Treasury through to the Chief Storekeeper (Klaasse 1997, p. 63; Fig. 3).

Following the start-up of production in 1944, coal was successfully tested in the Whyalla steelworks and used for trams, government institutions, including the Royal Adelaide Hospital, and an increasing array of industrial applications, dispelling criticism of Leigh Creek’s brown coal. When interstate shortages of coal prevailed, Leigh Creek coal kept the Osborne Power Station running, entrenching its value to the South Australian economy and community.

In 1946 Playford succeeded in nationalising the Adelaide Electric Supply Company Ltd when he secured support for the Electricity Trust of South Australia (ETSA) Bill. Continuing on a swell of political support, the government-owned ETSA
took control of the coalfield in 1948 to secure coal supplies for power generation. In 2000, just over half a century later, operations at the power station and coalfield were privatised.

In 1954, the first ETSA-owned Port Augusta power station (90MW) purpose built for Leigh Creek coal was commissioned, followed by another in 1963 (240 MW) and yet again in 1985 by a further expansion with the installation of the Northern Power Station. This culminated in the delivery of 544 MW of power from Leigh Creek coal.

With the expanded power plant, came the need to enlarge the coalfield and construct a retention dam to prevent flooding. Associated with this the township had to be relocated, and a new site for Leigh Creek was selected 22 km south at Windy Creek. Construction commenced in 1979, and by 1980 the first home was occupied.

Roughly 100 Mt of coal was mined from Leigh Creek, to a depth of 200 m using traditional open-cut mining methods. The early years of Leigh Creek saw a dramatic increase in production from 9,000 tpa in 1943 to around 444,000 tpa in 1949–1950. At full-scale operations the mine produced between 2 to 4 Mtpa of brown coal using conventional truck and shovel methods as well as terrace mining in the 1990s. Coal ore was crushed and stockpiled on site, then transported 250 km south by rail to the power stations.

In June 2015 Flinders Power’s parent company, Alinta Energy, announced it would cease mining by November 2015 as the operation had become uneconomic.

Formulating closure plan

The closure announcement in June 2015 set in motion an intensive period of planning towards mine closure and remediation, which was assigned to Flinders Power, then a subsidiary of Alinta Energy (Figs 4, 5).

Current and future potential environmental and social impacts had to be identified, risks assessed and prioritised for control, roles and responsibilities made clear, and a comprehensive program of works documented. The Leigh Creek closure plan documented culturally significant heritage sites and artefacts, and set out a robust community engagement plan and a management strategy.

In formulating its approved Mine Closure Plan, Flinders Power conferred with South Australia’s applicable regulatory authorities – mining regulators from the Department of the Premier and Cabinet (DPC), the Environment Protection Authority (EPA), SafeWork SA, the Department of Environment, Water and Natural Resources (DEWNR) through to Aboriginal Affairs and Reconciliation (AAR), and more.

Flinders Power credits the collaborative effort during the risk assessment phase as bringing essential clarity to the closure plan:

‘The joint risk assessment process enabled all parties to focus their attention on key risks associated with the closure, so clarifying the necessary resources to manage those risks.’

Brad Williams, Program Director.
This has translated into a series of detailed mitigation plans for public safety, pit wall stability, spontaneous combustion risk, retention dam integrity, surface water and groundwater management, preservation of Indigenous and non-Indigenous heritage sites, and a means of dealing with existing infrastructure.

To reduce the safety risk of public access into mine areas, barriers or earth-based bunds will be constructed around mine pits, with the design incorporating surface water management. Careful planning will enable controlled access to the original town cemetery.

**Reducing coal combustion risk**

Each coal seam has a unique propensity to spontaneously combust depending on the complex interplay of variables. To tailor solutions for Leigh Creek, Flinders Power has drawn on their extensive site expertise and rich archive of historical mine information, and sought the counsel of leading industry experts (Flinders Power 2017, pp. 149–169) and independent advice by authorities.

Limiting the access of oxygen to coal is key to lowering the risk of spontaneous combustion. At Leigh Creek technical teams have achieved this by re-profiling waste dump slope in areas at high potential and likelihood for combustion, and then by applying and covering with non-combustible material (Fig. 7).
Re-profiling to reduce the angle of slopes acts to significantly reduce the ability of oxygen to permeate the dump, curtailing its ability to establish a convection cell. The cut-and-fill methodology inherently reduces particle sizing of the outer overburden layer and provides a compacted surface. Subsequently applying inert cover with a fine, clay-rich material further reduces the potential for water and oxygen ingress.

Controlling surface water movement is the next key step to reduce the potential for erosion of protective cover and maintain the short- and long-term stability of the rehabilitated areas.

Infrared thermal monitoring is being used to gauge the success of the rehabilitated profile (Fig. 8), and this will continue as a post-closure monitoring procedure, aided by the use of aerial drone technology.

**Next step**

While the majority of on-ground excavation and landform works are on target by Flinders Power to be completed by mid 2018, the team expect an active monitoring process to accurately demonstrate the closure strategies have been effective, with five years the likely period.

Mining regulator’s comments:

‘Casting to the future in five to ten years, the success of this project will be judged by the successful management and control of associated offsite risks, the preservation of mine history, including cultural sites, while maintaining public safety.

‘Leigh Creek mine has been so much a part of South Australia’s living memory and energy history, but in future the nearby surrounds will also be better appreciated for its rich Aboriginal heritage, diverse flora and fauna, like the yellow-footed rock wallaby along with emus and reptiles, 40 species of birds, and the native aquatic life that now inhabit the retention dam.’

**Acknowledgements**

Flinders Power, in particular Brad Williams, Peter Kelly and Paul Jones, are acknowledged for assistance with the article and supplying many photographs.

**References**

