GEOLICAL SURVEY OF South Australia

DISCOVERY DAY

ADELAIDE CONVENTION CENTRE

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THURSDAY


FREE ENTRY

DISCOVER

New Data
New Technology
New Insights

Characterisation and mapping of Cu–Au skarn systems in the Punt Hill region, Olympic Cu–Au Province – Adrian Fabris, Laz Katona, Georgina Gordon, Gary Reed, Tim Keeping, George Gouthas and Greg Swain

Roopena Basin: sedimentary basin formation associated with Mesoproterozoic mineralising event in the Gawler Craton – Stacey Curtis, Claire Wade and Anthony Reid

Amata Dolerite, Musgrave Province: connections to Neoproterozoic mantle plume magmatism within Rodinia – Mario Werner, Rian Dutch, Mark Pawley and Carmen Krapf

Important enough to stand alone: the new Department for Energy and Mining – Owen Brown
Introduction

The Coompana Province is an approximately 200,000 km\(^2\) region of crystalline basement that lies between the Gawler Craton to the east, the Musgrave Province to the north and the Madura Province (Spaggiari et al. 2012) to the west (Fig. 1). However, the Coompana Province is entirely buried by Phanerozoic sediments, including the Nullarbor Limestone which forms the foundation for the Nullarbor Plain, one of Australia’s most iconic landscapes. Because of this pervasive sedimentary cover, the Coompana Province is one of the true frontiers of geological knowledge of the Australian continent.

Prior to 2013, the sum of our geophysical knowledge of the Coompana Province was constrained by wide-spaced gravity data acquired in 1965 and 1970, and 1,600 and 3,200 m line-spaced magnetic data acquired in 1970–1972 (Eucla Basin surveys) and 1982 (Officer Basin survey), respectively. Despite the coarseness of this data, a number of interesting geophysical anomalies were identified, including the ~50 km diameter reversely polarised Coompana Magnetic Anomaly (Fig. 1), and became targets for early mineral exploration work. Follow-up ground magnetic and gravity surveys conducted during the late 1970s led to a number of exploration drillholes being sunk during the early 1980s (e.g. Carpentaria Exploration Co. Pty Ltd 1982a, 1982b; Shell Co. of Australia Ltd 1983). Of the drillholes sunk during this period, only two reverse circulation and two diamond drillholes intersected basement. These four drillholes, together with three water bores drilled using a cable tool during the 1890s (Alballa-Karoo, Guinewarra Bore and Nullarbor Plains 6) and two petroleum wells...
(Eucla 1 and Mallabie 1), were the only physical rock samples of the Coompana basement (Fig. 2).

In 2013 the Geological Survey of Western Australia undertook a stratigraphic drilling program in the western Coompana Province (‘FOR’ holes, Fig. 2; Spaggiari and Smithies 2015). This new data began to shed light on the evolution of the region, indicating a complex multiphase history beginning with interpreted Paleoproterozoic oceanic crust formation, followed by a series of magmatic and deformation events, associated with interpreted subduction and crustal reworking throughout the Mesoproterozoic (Dutch et al. 2016a; Kirkland et al. 2017; Spaggiari and Smithies 2015). Integrated with reanalysis of the existing drillholes, this data has begun to build a stratigraphic framework for the western, and parts of the eastern, Coompana Province (Table 1).

Despite this work, understanding of the geology of the South Australian portion of the Coompana Province and its relation to surrounding Proterozoic terranes remains extremely poor. A number of fundamental questions remain unanswered including:

- What are the age and types of lithologies that constitute the basement?
- What is the tectonic and crustal evolution of those rocks?
- What is the relationship between the Coompana Province and the surrounding Proterozoic terranes?
- Are there potential fluid pathways conducive to the formation of mineralisation?
- What is the thickness and geochemical transparency of the cover sediments?

The lack of precompetitive geoscience knowledge and data in the Coompana Province has meant the exploration risk profile was too high for explorers in this frontier province, with no further exploration work conducted since the early 1980s programs.

The Geological Survey of South Australia, together with collaborative partners including Geoscience Australia and CSIRO, have undertaken a program of precompetitive geoscience data acquisition since 2013 to address the data and knowledge gaps in this region.

This process began with the acquisition of the 13GA-EG1 Eucla–Gawler deep crustal seismic and magnetotelluric line (Holzschuh 2015; Thiel, Wise and Duan 2015). In 2015 the Australian

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![Figure 2](image-url) Distribution of existing drillholes in the Coompana Province prior to the Coompana Drilling Project shown over surface geology which is dominated by Phanerozoic-aged cover and basins.
Lithospheric Architecture Mapping Project (AusLAMP) magnetotelluric data acquisition was completed across the Far West of South Australia as a collaboration between the University of Adelaide, Geological Survey and Geoscience Australia (Thiel et al. 2016). Also in 2015, the Geological Survey in collaboration with Geoscience Australia, flew the Coompana Magnetic and Radiometric Survey increasing the magnetic line density to between 400 and 200 m and acquiring a complete radiometric dataset across the Far West (Heath, Reed and Katona 2015). In 2016 a gravity survey acquired over 13,000 new gravity stations at a combination of 2, 1 and 0.5 km spacing across the southern Coompana Province (Heath and Wise 2017).

This regional geophysical data acquisition has provided a wealth of new data to image the Coompana Province in South Australia. However, while the geophysical data provides some insight into the physical properties of the buried basement, the geology still remained largely unconstrained due to a lack of physical samples. Therefore, a program of scientific drilling was undertaken in 2017 with the aim of collecting drill core samples from the crystalline basement beneath the Nullarbor Plain of South Australia.

This article outlines the process undertaken to plan and retrieve new basement samples and describes the rocks retrieved from the $3 million Coompana Drilling Project.

**Drilling program**

**Target selection**

Using newly acquired data from the Coompana airborne magnetic and gravity surveys, the Coompana Province was subdivided into a series of domains with distinct geophysical characteristics (Fig. 3; see Wise, Pawley and Dutch, 2015, for preliminary domain definitions based on the Coompana magnetic survey). These domains are interpreted to represent regions with distinct lithologies and geological histories. The identified domains are consistent with the crustal blocks recognised in the 13GA-EG1 deep crustal seismic profile (Dutch et al. 2016b). The South Australian Coompana Province also hosts a number of intriguing distinct geophysical anomalies including

<table>
<thead>
<tr>
<th>Drillhole</th>
<th>Sample type</th>
<th>Geology</th>
<th>Unit</th>
<th>Magmatic age (Ma)</th>
<th>Metamorphic age (Ma)</th>
<th>Geochron reference</th>
<th>Drillhole reference</th>
</tr>
</thead>
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<tr>
<td>Guinewarra Bore</td>
<td>Cuttings</td>
<td>Granitic basement</td>
<td>Moodini Supersuite?</td>
<td>1158 ± 12</td>
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<td>?</td>
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<tr>
<td>Nullarbor Plains 6</td>
<td>Cuttings</td>
<td>Granitic basement</td>
<td>?</td>
<td>—</td>
<td>—</td>
<td>—</td>
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</tr>
<tr>
<td>FOR004*</td>
<td>Diamond core</td>
<td>Granitic basement</td>
<td>Toolgana Supersuite</td>
<td>1613 ± 4; 1611 ± 7</td>
<td>1179 ± 10</td>
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<td>3</td>
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<tr>
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<td>Toolgana Supersuite</td>
<td>1613 ± 13; 1604 ± 6</td>
<td>1150 ± 10</td>
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</tr>
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<td>1167 ± 7</td>
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<td>5</td>
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<tr>
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<td>Diamond core</td>
<td>Granitic basement</td>
<td>Undawidgi Supersuite</td>
<td>1500 ± 8</td>
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<td>1499 ± 9</td>
<td>—</td>
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<td>3</td>
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<td>—</td>
<td>2</td>
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<td>—</td>
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<td>—</td>
<td>—</td>
<td>11</td>
</tr>
</tbody>
</table>

* Western Australian drillhole

References: 1 Frasier and Neumann (2016); 2 Wingate et al. (2015); 3 Spaggiari and Smithies (2015); 4 Neumann and Korsch (2014); 5 Baily et al. (2012a); 6 Outback Oil Company (1969); 7 Baily et al. (2012b); 8 Travers (2015); 9 Shell Co. of Australia (1983); 10 Carpentaria Exploration Co. (1982a); 11 Carpentaria Exploration Co. (1982b).
the enigmatic Coompana Magnetic Anomaly (Fig. 4a; Wise, Pawley and Dutch 2015). This ~50 km wide, deep-seated, remnant magnetised anomaly is associated with a low-density signature. Drillhole locations were planned to intercept as many of the different geophysical domains as possible (Fig. 3). These domains include:

- Moderate magnetic intensity, low-density domains with a defined NNE-trending fabric which likely represent the oldest protoliths in the region (domain 1).
- A variable, mottled magnetic signature domain with both high and low densities which may represent reworked basement by subsequent granitic intrusions (domain 2).
- A prominent NE-trending line of magnetic intrusions that bisects the province (domain 3).
- The main remnant magnetised Coompana Magnetic Anomaly and a number of possibly associated smaller satellite intrusions located coincident and adjacent to the main anomaly, but which are associated with density highs (domain 4).

Pre-drilling geophysics

Prior to the commencement of drilling, a number of geophysical techniques were trialled to ascertain their effectiveness at determining the thickness and nature of the cover units. This was an important step in the drill planning workflow as it allowed better planning of the proposed drillholes. A combination of audio magnetotellurics (Jiang et al. 2017) and active seismic (reflection and refraction; Holzschuh et al. in prep.) were undertaken at selected proposed drill sites to see if the techniques were able to resolve the cover thickness or any structure within the cover. In addition to trialling the above techniques, depth to magnetic basement estimates were also calculated by modelling individual magnetic sources using the newly acquired Coompana airborne magnetic data (Foss et al. 2017).

The Nullarbor Plain is known for its large and numerous cave systems. Because of this aspect, prior to drilling a series of microgravity surveys were undertaken at each site in an attempt to locate the presence of large, blind cavities that may be in the vicinity of the drill collar (Heath et al. 2017). The surveys were undertaken using two Scintrex CG5 gravity meters on a regular grid pattern with stations spaced at 10 m intervals. The total gravity field was measured and then the regional trend removed in post-processing to highlight the near-surface density variation. The results show areas of lower density in the near surface that may indicate the location of subsurface cavities and allowed for the drill collar to be moved to minimise the potential risk of major drilling problems associated with large cavities.

Drilling methodology

The drilling contract was awarded to South Australian based Boart Longyear Australia via a competitive tender process. Drilling commenced in early April 2017 with the drilling of the first hole CDP001 and was completed in mid-September 2017. Eight holes were drilled for a total of 4,565 m including more than 1,871 m of diamond core (Fig. 4). All holes were drilled at a slight inclination of either –80° or –85° towards 000° (with the exception of CDP007 which was drilled towards 270°), with the core being orientated using Boart Longyear’s Tru-Core™ orientation tool. Because of the likelihood of lost circulation and the potential to damage sensitive cave systems and habitats, drilling used a combination of techniques and multiple casing strings to achieve the desired basement core samples and ensure the best chance for successfully completing each hole with minimal environmental impact (Fig. 5). A primary precollar through the limestone sequences was drilled using air and a combination of hammer and rock rolling until through the area most likely...
Figure 4  Location of the eight Coompana Drilling Project holes shown over: (a) reduction to pole TMI image from the new Coompana magnetic survey; and (b) combination regional and new Coompana gravity survey data. Note the coincidence of the strongly reversely magnetised Coompana Magnetic Anomaly with a large density low in the gravity data.
Geology of the crystalline basement from the Coompana Drilling Project

Drilling has recovered a range of distinct lithologies from the different geophysical domains. Units intersected include migmatitic orthogneisses, felsic intrusions, mafic intrusions and volcanics. These units can be placed in a relative chronology based on observed crosscutting relationships and are described in detail below by this inferred stratigraphy, rather than by drillhole.

Migmatitic rocks

The interpreted oldest rocks are migmatites, including metatexites and diatexites, intersected in geophysical domain 1 both in the north and south of the targeted Coompana Province (Fig. 3). The metatexites, or migmatitic gneisses, were intersected in drillholes CDP001 and CDP006 (Fig. 4). These rocks are well layered with leucocratic continuous layers and discontinuous augen (or lenses) that are separated by a melanocratic groundmass (Fig. 6a–c). The layers are generally defined by recrystallised aggregates of feldspar and quartz. The augen can often be formed by recrystallised feldspar, or recrystallised aggregates of feldspar and quartz that may be the remnants of feldspar phenocrysts, suggesting the protolith was a porphyritic granite (Fig. 6b). The melanocratic component comprises layers of fine-grained mafic minerals (biotite, possibly hornblende and minor magnetite) that are aligned parallel to the layering. The layering is locally folded into open structures with shallowly dipping axial planes (Fig. 6b). In places, the rock is less uniform and can be dominated by either:

- a mafic-rich end-member where isolated leucocratic augen and layers of feldspar and quartz are hosted by a melanocratic groundmass of aligned mafic minerals
- a felsic-rich end-member with remnants of the gneiss and mafic schlieren in a feldspar- and quartz-dominated, massive, granitic groundmass.

The diatexites were intersected in CDP004 (Fig. 4). In drill core, the diatexites are fine to very coarse grained, and composed of variable proportions of feldspar, quartz, hornblende and biotite (Fig. 6d–f). The rocks are compositionally and texturally heterogeneous, comprising a leucocratic, medium to very coarse grained, massive, igneous-textured groundmass that contains a mafic component. This mafic component ranges from blocks of medium- to fine-grained mesocratic foliated rock or gneiss (i.e. schollen; Fig. 6d–e) that are up to 30 cm wide and often back-veined by the groundmass, to irregular bands with greater concentration of mafic minerals (i.e. schlieren; Fig. 6f).

Development of an effective bore hole plan was instrumental to the success of the program. All eight holes were successfully drilled to target depth and retrieved the desired basement intersections. No holes were lost during the program and no environmental incidents occurred.

**Figure 5** Schematic bore hole plan showing the three different levels of casing and hole diameters used for the Coompana Drilling Project.
New geology

Figure 6 Migmatitic rocks, Coompana Drilling Project.

Felsic intrusive rocks

The next package comprises a range of felsic intrusive rocks (Fig. 7a–c). These include the massive, medium to very coarse grained, porphyritic syenogranite to granodiorites that were intersected in CDP003 and CDP005 (Fig. 4). The rocks contain common equant to tabular, poikilitic K-feldspar megacrysts (up to 5 cm across), and plagioclase and quartz phenocrysts in a groundmass of K-feldspar, quartz and plagioclase (Fig. 7a–c). Mafic minerals (biotite, hornblende and magnetite) form small equant to interstitial aggregates. The K-feldspar megacrysts commonly display Rapakivi textures, such as rounding, and more calcic overgrowths (Fig. 7b).

Drillholes CDP003 and CDP005 targeted large, overlapping, ovoidal, magnetic bodies that are prominent on the aeromagnetic images and define geophysical domain 3 (Fig. 3). These bodies were interpreted as plutons which intrude into domain 1 rocks and form a NE-striking well-defined belt that continues to the northeast where it runs along the northwestern side of the Gawler Craton (Fig. 1).

The felsic intrusive suite also includes minor, thin sheets (up to 3 m wide) that range from microsyenogranite to microsyenite in CDP003 and CDP005. These sheets have sharp, irregular contacts that follow the grain boundaries of the host granites, suggesting that the host granites were incompletely crystallised, and the microsyenogranite represents late-stage magmas (Fig. 7b).

Microsyenites are observed within the diatexite in CDP004 (Fig. 6f). The microsyenites are brown to dark green, fine- to medium-grained, weakly
inequigranular to seriate-textured, and contain feldspar, hornblende and biotite. The rock generally has a foliation that is defined by aligned biotite flakes in an equigranular groundmass. The microsyenites contain rare, irregular centimetre-wide feldspar xenocrysts, and in places contain common millimetre- to centimetre-scale leucosomes that are subparallel to the foliation (Fig. 6f).
Mafic rocks

The felsic intrusive rocks are cut by mafic intrusive rocks that correspond to remnant magnetised bodies prominent on aeromagnetic images. Drillholes CDP002 and CDP007 targeted these magnetic features (Fig. 4). CDP002, which targeted geophysical domain 4 (Fig. 3), intersected fine-to medium-grained, inequigranular, massive, dark grey-green to more leucocratic dolerite and gabbro. The dolerite contains randomly oriented prismatic plagioclase intergrown with olivine (often replaced by actinolite and magnetite), clinopyroxene and amphibole (Fig. 7d). The gabbroic rocks are dominated by the mafic minerals, and likely represent cumulate phases (Fig. 7e). These rocks also contain interstitial patches of fine-grained mesostasis composed of K-feldspar, quartz, magnetite and amphibole (Fig. 7d).

CDP007 targeted a small remnant magnetised body along the margin of geophysical domains 1 and 3 (Fig. 3). This drillhole intersected homogenous, aphanitic to medium-grained, inequigranular basalt (Fig. 7f). This rock comprises randomly oriented plagioclase prisms (often with ‘swallow-tail’ terminations), blocky clinopyroxene, and chlorite pseudomorphs (after orthopyroxene) in a groundmass of mesostasis. The mesostasis is composed of plagioclase, clinopyroxene, magnetite and quartz.

Minor metre-scale basalt sheets sharply cut the porphyritic syenogranite in CDP003. The basalt is dark grey-green, fine-grained to aphanitic, porphyritic syenogranite in CDP003. The basalt contains randomly oriented plagioclase prisms that project into cavities. The cavities were filled with massive, very fine grained chlorite and quartz that encloses the fragments, and crustiform aggregates of chlorite–quartz–leucoxene altered rock brecciated (Fig. 8c). The quartz in the cement ranges from angular, with a quartz–chlorite hydrothermal cement (Fig. 8c). The quartz in the cement ranges from fine-grained, massive fragments, bladed subhedral quartz that encloses the fragments, and crustiform prisms that project into cavities. The cavities were then filled with massive, very fine grained chlorite (Mason 2018). These textures indicate progressive fragmentation and fluid flow. A basalt sheet at 480.75–481.92 m has been brecciated and altered. The fluid altered the basalt resulting in an assemblage of albite–chlorite–hematite–leucoxene, and crystallised to form a groundmass of mostly albite–quartz–chlorite between the blocks (Mason 2018).

These observations suggest that the rocks intersected in CDP006 experienced several stages of fault reactivation and generations of fluid flow after the mafic magmatic stage.

Alteration and brecciation

The rocks exhibit common sericitisation, iron alteration, chloritisation and silicification, which are variably developed and range from locally selective to pervasive.

Selective alteration was observed in most of the cores including sericitisation of feldspars, hematite dusting and chloritic alteration of mica and amphiboles (Fig. 8a; Mason 2018). Alteration is particularly well developed in CDP006, which targeted the Palinar Shear Zone, a crustal-scale west-dipping structure that marks the boundary between interpreted geophysical domains 1 and 3 (Dutch et al. 2016b). Sericite–chlorite is the most prominent style of pervasive alteration, which locally resulted in a dark green-grey to black, fine-grained metasomatite rock (Fig. 8b). The metasomatite locally contains ‘worm-like’ early quartz ribbons that are likely remnant leucosomes from the host gneisses (Fig. 8c), angular white quartz blocks that represent an earlier stage of disaggregated quartz veining (Fig. 8d), and blocks of hematite-altered granite.

A breccia zone in CDP006 has intensely sericite–chlorite–quartz–leucoxene altered rock brecciated with a quartz–chlorite hydrothermal cement (Fig. 8c). The quartz in the cement ranges from angular, fine-grained, massive fragments, bladed subhedral quartz that encloses the fragments, and crustiform prisms that project into cavities. The cavities were then filled with massive, very fine grained chlorite (Mason 2018). These textures indicate progressive fragmentation and fluid flow. A basalt sheet at 480.75–481.92 m has been brecciated and altered. The fluid altered the basalt resulting in an assemblage of albite–chlorite–hematite–leucoxene, and crystallised to form a groundmass of mostly albite–quartz–chlorite between the blocks (Mason 2018).

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Summary and current work program

The Coompana Drilling Project was the culmination of a number of years of precompetitive geophysical data acquisition, analysis and interpretation. This project set out to retrieve new basement samples from beneath the Nullarbor Plain and allow us to begin to place new geological constraints on the evolution and prospectivity of this unexplored region.
Metatexite with selective alteration, including the sericite replacement of plagioclase in a leucosome (see lower left of photograph), local hematite-alteration of the leucosomes, and chlorite replacement of the biotite-rich parts of the metatexite. (Photo 416622)

Strong, pervasive sericite–chlorite alteration to produce a relatively homogenous, fine-grained, dark green to black metasomatite. (Photo 416623)

The upper part of the photograph shows the dark green-grey sericite–chlorite metasomatite forming angular blocks within a cement of bladed subhedral quartz, which are then cut by a later stage of white quartz at upper left. The lower part of the photograph shows the ‘worm-like’ quartz-rich aggregates in the metasomatite that are interpreted to represent remnants of the leucosomes in the precursor metatexite. (Photo 416624)

Figure 8 Alteration and brecciation textures, CDP006.

On completion of the drilling program, all core and cutting samples were relocated to the South Australia Drill Core Reference Library and structurally and lithologically re-logged. Non-destructive chemical and mineralogical data has now been acquired on the core using the HyLogger™ and Minalyze™ systems housed at the Core Library. More than 200 physical samples of the different lithologies have been taken and sent off for full suite lithogeochemical data. A total of 35 samples have been submitted for samarium–neodymium isotopic analysis at the University of Adelaide to help constrain the crustal evolution of the province. Twelve samples have been processed for zircon geochronology using the SHRIMP IIe instrument at Geoscience Australia and hafnium isotopic analysis at Curtin University.

These mineralogical, geochemical and isotopic datasets are currently being compiled and analysed. The results of this analysis program will be presented at an open day hosted at the South Australia Drill Core Reference Library on 1 August 2018.

Acknowledgements

The Geological Survey of South Australia acknowledges the Mirning People, and the members of the Far West Coast Aboriginal Corporation, who are the traditional owners of this land. In particular, Clem Lawrie, James Peel, John Mungee, Neville Miller and Peter Miller are thanked for undertaking on-country site inspections. The Geological Survey would also like to acknowledge the hard and constructive work undertaken by staff of the Department of Environment, Water and Natural Resources and the Alinytjara Wiluraga Natural Resources Management, including the members of the Nullarbor Parks Advisory Committee who provided the necessary approvals to undertake this project within the Nullarbor parks.

A huge amount of time and effort from Geological Survey staff was required to undertake this project. Ian Hopton, Lyn Broadbridge, Trevor Boswell and John Stephenson are thanked for field and logistical support.
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FURTHER INFORMATION


PACE Copper Coompana Drilling Program 2017 video https://www.youtube.com/watch?v=ixzLVKnjIEE&list=PL77aEODq4UsID7xR_SJ-aKhU0uOUd4k

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Characterisation and mapping of Cu–Au skarn systems in the Punt Hill region, Olympic Cu–Au Province

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Introduction

South Australia hosts one of the world’s great iron oxide – copper–gold (IOCG) terranes. Termed the Olympic Cu–Au Province (Skirrow et al. 2007), this belt is renowned as the host to Olympic Dam, the type example of breccia-hosted, hematite-rich IOCG deposits (Groves et al. 2010). The same thermal event resulted in variants of this deposit class throughout the Olympic Cu–Au Province and includes skarn-dominated mineralisation where hydrothermal fluids interacted with carbonate-rich lithologies.

Punt Hill is the name given to a series of Cu–Au skarn prospects, located 105 km NNW of Port Augusta (Fig. 1; Swain et al. 2017), and has been shown to be part of the ~1.6 Ga thermal event that formed other well-known IOCG deposits in the region, in particular Carrapateena which is located a further 40 km north (Reid et al. 2011). The Punt Hill project includes some of the best examples of widespread skarn development in the eastern Gawler Craton. Although highly prospective, exploration in the region is both expensive and technically challenging owing to hundreds of metres of post-mineralisation cover.

As part of a broader study aiming to characterise proximal to distal footprints of IOCG-type deposits in the eastern Gawler Craton (Fabris et al. 2013; Fabris et al. 2015), the Geological Survey of South Australia, in collaboration with the then tenement holders Monax Mining, used the Punt Hill region to develop a multidisciplinary approach for characterising, mapping and predicting alteration associated with skarn-hosted Cu–Au mineralisation. A particular focus was given to progressing the understanding of skarn development and generating exploration criteria and predictive models to aid future exploration in the region. This article provides an overview of the main outcomes of the project and is a summary of results provided in Fabris et al. (2018).

Geology

The Punt Hill region is located in the central Olympic Cu–Au Province (Fig. 1). The oldest unit known in the study area is granite of the c. 1850 Ma Donington Suite (Reid et al. 2011; Jagodzinski 2005; Schwarz 2003). Donington Suite locally forms basement to a sequence of laminated silty and variably calcareous metasedimentary rocks thought to be equivalents of the Wandearah Formation of the c. 1760 Ma Wallaroo Group (Cowley, Connor and Zang 2003). To the east of the Elizabeth Creek Fault, these low metamorphic grade metasediments (Reid and Fabris 2015) are preserved within a series of NW-trending half-grabens (Fig. 2) and host the majority of known mineralisation in the Punt Hill region. Variably altered Wallaroo Group within these half-grabens is thought to be the primary control on similarly aligned residual gravity anomalies evident in the region (Fig. 1).

Drillhole intersections indicate that east of the Elizabeth Creek Fault, Wallaroo Group metasediments are typically <250 m thick. Preserved thickness increases to the west of the Elizabeth Creek Fault (e.g. 663 m intersected in drillhole PN-07-09; Giles 2002). Wallaroo Group is thin to absent in the northern part of the Punt Hill project area (e.g. absent in drillholes FTDD01, HL002, NHD1) and along up-faulted basement blocks (e.g. drillholes NNDD1, BLDD01, SDDD01).
Figure 1  Location of the Punt Hill study region shown over residual gravity image. Prominent features include high magnitude and amplitude gravity anomalies within the southwestern and western portion of the project region and a series of NW–SE-orientated linear gravity anomalies through the central Punt Hill region. Drillholes utilised in the project are shown.
Over the Punt Hill series of prospects, the Wallaroo Group is variably overlain by felsic volcanioclastics and lavas of the Gawler Range Volcanics (Allen et al. 2008; Allen et al. 2003). Drilling to date has intersected thicknesses of <180 m of these volcanics.

Proterozoic crystalline units are unconformably overlain by arenaceous redbeds of the c. 1490 Ma Pandurra Formation (Beyer et al. 2018; Cowley 1991). Variation in accommodation space controlled by continental extension (Beyer et al. 2018) and post-depositional erosion led to significant differences in thickness of Pandurra Formation across the project area (Fig. 2), from being completely absent to some areas with intersections up to 306 m (drillhole NNDD1). The Pandurra Formation and underlying units are intruded by mafic dykes of the c. 800 Ma Gairdner Dolerite (Cowley and Flint 1993). The Gairdner Dolerite can be recognised in regional aeromagnetic datasets as long, subparallel, linear anomalies, with a characteristic northwest orientation.

Overlying the Pandurra Formation is the Beda Basalt, which consists of amygdaloidal, layered, subaerial basalts and are the extrusive equivalent of the Gairdner Dolerite. Unconformably overlying the Beda Basalt, are the flat-lying lithologies of the Adelaidean Stuart Shelf (Preiss 1987), comprising the Umberatana (Tapley Hill Formation and Whyalla Sandstone) and Wilpena (Nuccaleena Formation; and Tregolana Shale, Corraberra Sandstone and Simmons Quartzite members) groups. The thickness of Adelaidean units ranges from ~250 m in the northwest to >1,000 m in the southeast of the project area. A thin veneer of Quaternary and Recent sediments cover the project area.

The interpreted stratigraphic relationships and inferred fault architecture are illustrated in Figure 2.

### Alteration and mineralisation

The Punt Hill region incorporates several Cu–Au (Ag–Zn–Pb) prospects associated with calcic-dominated, garnet–pyroxene skarn within metasedimentary units of the Wallaroo Group (Table 1; Fig. 3; Swain et al. 2017). To date, only minor copper mineralisation has been intersected within the underlying Donington Suite granite or overlying Gawler Range Volcanics. Both these units host variably intense K-feldspar, white mica, chlorite, hematite and carbonate alteration. Notably, elevated copper values in these units are associated with an increased degree of hematite alteration.

Petrographic studies of the skarn system describe a prograde garnet- and pyroxene-dominant mineral assemblage, overprinted by a diverse retrograde assemblage of amphibole, calcite, talc, chlorite, K-feldspar, hematite, sulfide (chalcopyrite, bornite, chalcopyrite, sphalerite, galena, pyrite), fluorite, apatite, barite, anhydrite, epidote, tourmaline, titanite, biotite and native gold (Fig. 3; Mason 2012). Although mineralisation is commonly associated with increased iron content (up to 20 % Fe₂O₃), iron oxides form only a minor component of the alteration assemblage. Instead, a significant proportion of iron is as silicate in iron-rich garnet (andradite). Sulfide precipitation is associated with the later paragenetic or retrograde phase of the skarn system, which is similar to that described for other skarn systems worldwide (Meinert 1992). The specific processes and fluid source driving the prograde–retrograde evolution of the alteration system in the Punt Hill region have not been studied in detail. Typically, alteration and mineralisation result from either a single fluid source generated during cooling of an intruding pluton, and then progressing through a heating and cooling event, or, mixing of magmatic–hydrothermal fluids with distinct fluid sources in chemical disequilibrium (Einaudi, Meinert and Newberry 1981).

At Punt Hill, sulfides predominantly form in veins that crosscut early prograde alteration (commonly containing quartz, calcite, hematite, amphibole and chlorite) and as interstitial growth between garnet and pyroxene grains (Fig. 3e). The copper sulfide tenor is controlled by the degree to which retrograde fluids are oxidised, where bornite (and rare native gold) occurs within hematite-bearing zones and chalcopyrite occurs within more chlorite-bearing zones (relatively reduced; Mason 2012). Importantly, since higher copper grades are associated with retrograde alteration, mapping the retrograde zones is of significance for exploration targeting.

The ore environment is interpreted to represent an oxidised calcic copper skarn. This is based on the well-developed calc-silicate exoskarn assemblage including andradite-rich assemblages, presence of
Table 1  Summary table of selected mineralised prospects and intercepts for the Punt Hill project (Swain et al. 2017)

<table>
<thead>
<tr>
<th>Prospect</th>
<th>Drillhole</th>
<th>Depth (m)</th>
<th>Interval (m)</th>
<th>Copper (%)</th>
<th>Gold (g/t)</th>
<th>Silver (g/t)</th>
<th>Zinc (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whistle Pig</td>
<td>WPDD1</td>
<td>788–848</td>
<td>60</td>
<td>0.13</td>
<td>0.03</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Woodchuck</td>
<td>WDDD1</td>
<td>683–753, including 28</td>
<td>70</td>
<td>0.41</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Groundhog</td>
<td>GHDD1</td>
<td>837–963, including 14</td>
<td>126</td>
<td>0.4</td>
<td>—</td>
<td>0.25</td>
<td>4.5</td>
</tr>
<tr>
<td></td>
<td>GHDD2</td>
<td>888–1,050, including 28</td>
<td>162</td>
<td>0.34</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>GHDD3</td>
<td>826–902</td>
<td>76</td>
<td>0.22</td>
<td>—</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td></td>
<td>GHDD4</td>
<td>840–962, including 48</td>
<td>122</td>
<td>0.47</td>
<td>0.1</td>
<td>6.6</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>GHDD6</td>
<td>846–1,005, including 17</td>
<td>159</td>
<td>0.47</td>
<td>0.12</td>
<td>5.3</td>
<td>0.48</td>
</tr>
<tr>
<td></td>
<td>PHDD1402</td>
<td>903–999, including 26</td>
<td>96</td>
<td>0.47</td>
<td>0.12</td>
<td>5.3</td>
<td>0.37</td>
</tr>
<tr>
<td>Prairie Dog</td>
<td>PDDD1</td>
<td>754–782</td>
<td>29</td>
<td>0.12</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>811–821</td>
<td>11</td>
<td>0.22</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>888–900</td>
<td>13</td>
<td>0.55</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>985–997</td>
<td>13</td>
<td>0.33</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>PDDD2</td>
<td>856–1,014</td>
<td>152</td>
<td>—</td>
<td>—</td>
<td>0.32</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>876–975, including 1</td>
<td>99</td>
<td>0.24</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Marmot</td>
<td>MMDD1</td>
<td>1,009–1,029</td>
<td>20</td>
<td>0.2</td>
<td>0.04</td>
<td>1.9</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>1,034–1,050, including 6</td>
<td>16</td>
<td>0.52</td>
<td>0.12</td>
<td>2.2</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Hoary</td>
<td>HODD3</td>
<td>1,075–1,094</td>
<td>19</td>
<td>0.28</td>
<td>0.05</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>

Oxidised minerals in the retrograde assemblage (e.g. hematite, anhydrite, barite), dominance of bornite, chalcopyrite and chalcocite as the principal copper sulfides, and presence of consistent additional base metal sulfides (sphalerite, galena; Einaudi and Burt 1982; Mason 2012).

The best mineralised intersection is from the Groundhog prospect, returning 159 m at 0.47% Cu, 0.12 g/t Au, 5.3 g/t Ag, 0.48% Zn and 0.12% Pb (from 846 m), including 17 m at 1.1% Cu, 8.5 g/t Ag and 1.2% Zn (from 853 m) in drillhole GHDD6 (Swain et al. 2017).

Methods

Geochemical, spectral and petrophysical data were acquired in the Punt Hill and Red Lake region using historical drillholes and drill core provided by Monax Mining, who also gave access to >$6 million worth of data collected during their tenure. Spectral scans of drill core, in the visible to thermal infrared wavelength range, were made using the HyLogger-3™ hyperspectral core scanner. These data enabled consistent and subjective drill core logging of mineralogy at centimetre scale. Selected sample intervals were analysed for 65 elements by inductively coupled plasma methods, and fluorine by specific ion electrode. Geochemical data was used to establish trace element associations with mineralisation and surrounding alteration. Both regional- and prospect-scale inversions of aeromagnetic and gravity data were generated to improve the understanding of the 3D distribution of magnetic susceptibility and density in the region. Magnetic susceptibility and density measurements were collected on drill core to provide petrophysical constraints and aid interpretation of the magnetic and gravity inversion models.

The co-location of sample intervals where possible enabled data to be integrated and relationships between data types to be investigated, e.g. relationships between geochemistry, mineralogy, lithology and petrophysical properties. Details of how each of these data were collected and integrated can be found in Fabris et al. (2018).

Project summary

Spectral mineralogy

Spectral logging of drill cores using the HyLogger-3™ enabled high spatial resolution downhole mapping of mineralogy in the Punt Hill region. Spectral mineralogy derived from HyLogger-3™ compared well with minerals identified in thin section (Mason 2012; Fabris et al. 2018). Spectral results from >3,000 m of skarn across the different prospects in the Punt Hill region indicate that garnet...
compositions are primarily andraditic with lesser grossular garnet. Pyroxene species are dominated by diopside and lesser augite and hedenbergite. Retrograde minerals identified spectrally include chlorite, talc, amphibole (hornblende), K-feldspar, white mica (muscovite and illite), carbonate (calcite and siderite), epidote, barite and hematite. There is only minor serpentine, rare magnetite (few holes only) and no known pyrrhotite or olivine. These mineral assemblages and compositions are consistent with an oxidised copper skarn classification (Einaudi and Burt 1982). Skarn mineralogy can be used to interpret proximity to the source of hydrothermal fluids (Meinert 1992), which is vital for mapping a skarn system and predicting the likely location of mineralisation. Protolith composition imposes a primary control on the skarn assemblage and can complicate the interpretation of the mineralogy, where interpretation should be restricted to similar lithological units and along fluid flow paths. In an attempt to develop an internal stratigraphy within the Wallaroo Group which hosts the skarn alteration in the Punt Hill region, lithologies in more distal and less altered

Figure 3 Alteration and mineralisation styles within Wallaroo Group, Punt Hill prospects. Photomicrographs and petrographic descriptions from Mason (2012).
drillholes were used with correlation of observed mineralogy between closely spaced drillholes (particularly at Groundhog prospect). As a result, Wallaroo Group sediments (Wandearah Formation equivalent) in the region are interpreted to originally be composed of three broad units:

1. variably calcareous sandstone and siltstone, over,
2. a series of alternating silty carbonate and fine-grained, laminated carbonaceous units (now dominated by K-feldspar; Fig. 3d), over,
3. dolomitic siltstone.

Copper mineralisation is mostly associated with the central, more calcareous units.

Using this primary lithology as context, garnet to pyroxene ratios were measured from spectral data. The results are presented in Figure 1 and Table 2, and give a likely vector towards the source of high temperature fluids or, in other words, causative intrusion.

Skarn systems are generally limited to within a few kilometres from an intrusive heat source (Meinert, Dipple and Nicolescu 2005). This necessitates Hiltaba Suite intrusions to be present in relatively close proximity to prospects in the Punt Hill region. Given Hiltaba-age units have not been observed in drill core, the implication is that they occur below or proximal to each group of prospects. Several possibilities have been interpreted based on residual gravity data and include the Red Lake region, beneath the Hoary prospect, and a more discrete body south of the Prairie Dog prospect (Fig. 1). To satisfy garnet:pyroxene ratios measured at each prospect, both the large gravity low in the south of the Punt Hill region and the smaller gravity low south of the Prairie Dog prospect are likely Hiltaba-age intrusions which have mobilised hydrothermal fluids up and along NW–SE-trending regional faults. In this scenario, the skarn mineralisation at Punt Hill represents relatively shallow alteration from fluids derived from these bodies.

**Geochemistry**

Spectral mineralogy was used to map alteration mineralogy within drillholes, and also to characterise alteration assemblages of each drill core sample submitted for assay. The classification method is explained in Fabris et al. (2018), and enabled trace element relationships to specific alteration minerals and assemblages to be established. While copper mineralisation at Punt Hill was found to be associated with a diverse range of alteration minerals, it was most frequently associated with partially retrogressed samples containing amphibole and/or talc, commonly with garnet and/or pyroxene (Fig. 3).

Elements associated with copper mineralisation in the Punt Hill region were Au, Ag, Cd, Co, Ni, Pb, S, Se, Te and Zn. In addition, the elements As, Bi, Ce, La, Mo, W and U have both highly anomalous values in the region and an association with prograde and retrograde mineral assemblages, and therefore relate to the mineralisation process. Interestingly, antimony values in the Punt Hill region are extremely high (commonly >100 x the average crustal abundance), but with high values related with a range of alteration assemblages and intensities, including a strong correlation with white mica-dominated alteration evident in both the Gawler Range Volcanics and Wallaroo Group (Fig. 4). This correlation with alteration minerals associated with weakly as well as intensely altered units supports it

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**Table 2** Relative garnet:pyroxene ratio gained from HyLogger-3™ spectral data at individual prospects in the Punt Hill region

<table>
<thead>
<tr>
<th>Prospect</th>
<th>Drillhole</th>
<th>Garnet:pyroxene*</th>
<th>Vector</th>
</tr>
</thead>
<tbody>
<tr>
<td>Groundhog</td>
<td>GHDD7</td>
<td>Gar&gt;&gt;pyx (5.30)</td>
<td>High temperature fluid source from south</td>
</tr>
<tr>
<td></td>
<td>GHDD5</td>
<td>Gar&gt;&gt;pyx (4.42)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>GHDD4</td>
<td>Gar&gt;&gt;pyx (4.06)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>GHDD3</td>
<td>Gar&gt;&gt;pyx (4.04)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>GHDD6</td>
<td>Gar&gt;&gt;pyx (2.82)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>GHDD1</td>
<td>Gar&gt;&gt;pyx (2.18)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>GHDD2</td>
<td>Gar = pyx (1.07)</td>
<td></td>
</tr>
<tr>
<td>Woodchuck</td>
<td>WDDD1</td>
<td>Pyx&gt;&gt;gar</td>
<td>High temperature fluid source from southwest</td>
</tr>
<tr>
<td></td>
<td>WDDD2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Whistle Pig</td>
<td>WPDD1</td>
<td>Gar&gt;&gt;pyx</td>
<td>High temperature fluid source from southeast</td>
</tr>
<tr>
<td></td>
<td>WPDD2</td>
<td>Gar&gt;&gt;pyx</td>
<td></td>
</tr>
<tr>
<td>Prairie Dog</td>
<td>PDDD1</td>
<td>Gar&gt;&gt;pyx</td>
<td>High temperature fluid source from southwest</td>
</tr>
<tr>
<td></td>
<td>PDDD2</td>
<td>Gar = pyx</td>
<td></td>
</tr>
<tr>
<td>Hoary</td>
<td>HODD1</td>
<td>No garnet or pyroxene</td>
<td>High temperature fluid source from east</td>
</tr>
<tr>
<td></td>
<td>HODD3</td>
<td>gar &gt;pyx</td>
<td></td>
</tr>
</tbody>
</table>

* Measured ratios indicated in brackets for the GHDD series of drillholes were derived using “The Spectral Assistant.”
Figure 4 Probability plot for antimony showing that high values (>10 ppm) are associated with most alteration assemblages and within Gawler Range Volcanics and Wallaroo Group. Samples dominated by white mica alteration have the highest median antimony values.

Figure 5 3D perspective view of drillholes in the Punt Hill region coloured by (a) antimony and (b) copper values overlaid on residual gravity. Antimony values are significantly high (>10 x the average crustal abundance) over a wide area and across a range of stratigraphic units. By comparison, the distribution of high copper values (>10 x the average crustal abundance) is more restricted.
Figure 6 Plot of the prospectivity index calculated using a threshold of 10 x average crustal abundance for the elements Au, Ag, As, Bi, Ce, Cu, La, Mo, Pb, Sb, U and Zn from available downhole geochemistry in the Punt Hill region. Hotter colours and increasing size represent increasing prospectivity.

Figure 7 Cross-plot of magnetic susceptibility versus density classified by stratigraphic units in the Punt Hill region. Data is limited to samples with measurements of both properties. Only Geological Survey generated petrophysical properties are shown.

Relationship of petrophysical properties with stratigraphy, alteration and mineralisation

Petrophysical properties measured on drill core in the Punt Hill region (Fig. 7) indicate negligible magnetite (mostly <0.001 SI) content, and a range from average crustal densities (~2.67 g/cm³) to moderately high density values of ~3.5 g/cm³. The increase in density is a result of skarn alteration, and is primarily developed within Wallaroo Group. While significantly elevated, the density values are lower than those associated with hematite- or magnetite-dominated IOCG deposits (e.g. hematite-dominated IOCG deposits have density ranges of 2.7–4.5 g/cm³; Ehrig et al. 2012; Fabris et al. 2013).

Observed relationships between magnetic susceptibility, density, mineralogy and copper values demonstrate that highest copper grades are most commonly associated with zones of low magnetic susceptibility, moderate density, and which record both prograde and retrograde alteration events, the latter event giving rise to lower density minerals such as talc, amphibole, chlorite and white mica.
models of inferred retrograde and prograde density distributions across the Punt Hill study area (Fig. 9). These modelled regions represent the location of rocks of similar properties to known skarn alteration and therefore can be used to predict the possible extension of mineralisation outside of that identified from drilling. Although inversion results are non-unique, extensive skarn alteration can be used to explain residual gravity highs in the Red Lake region (mostly prograde skarn) and the three NW–SE-trending gravity highs in the Punt Hill region (Fig. 1). Our models indicate that there are large areas of prospective ground that remain untested by drilling.

Petrophysical data from Punt Hill drill cores shows no indication of significantly elevated magnetic susceptibility within the mineralised zones, yet residual magnetic anomalies are present in the aeromagnetic data (Fig. 10). Magnetic susceptibility data captured from drill core places the highest magnetic susceptibility values in the Beda Basalt. However, the aeromagnetic data reveals discrete residual magnetic features, which is not consistent with the flat-lying Beda Basalt being the source of these features. The discrete magnetic anomalies are often coincident with residual gravity anomalies and are present at most of the mineralised sites drilled at Punt Hill, including Groundhog, Hoary, Woodchuck, Prairie Dog, Wiarton Willy and Marmot (Fig. 1). The exception is at the Whistle Pig prospect (drillholes WPDD1 and 2), where mineralisation was intersected in a magnetic low. While residual magnetic anomalies are one of the key targeting criteria in the Punt Hill region, no connection had previously been established between magnetic anomalism and mineralisation. Magnetic inversion results from this study model the magnetism as being sourced from beneath the Wallaroo Group (Fig. 11). The deeply sourced magnetism appears to represent magnetite growth along fluid pathways, with discrete anomalies at individual prospects associated with relatively shallow upflow zones of fluids (where fluids are magnetite-stable), with the skarn mineralisation at Punt Hill therefore representing the upper level alteration from these fluids. This result is significant as it demonstrates a genetic relationship to more traditional IOCG mineralisation, where early magnetite alteration is observed below the lower temperature and more oxidised part of the alteration system (Apukhtina et al. 2017). The implication is that in the right conditions (host rock, crustal depth, structural setting), other IOCG styles (breccia-hosted, hematite-dominated, magnetite-dominated) may also exist in the region.

Inversion models
Modelling of gravity and magnetic data was used to develop predictive maps of regions containing similar petrophysical properties to those measured in skarn alteration zones in drill core. Property value ranges within the inversion results tended to be lower than measured values. It was taken that the loss of density or magnetic susceptibility within the distribution was inherent in the inversion codes and prompted the technique of rescaling values to fit the range gained from measured density values. Alternative explanations include that petrophysical properties measured on drill core are not adequately representative of volumes modelled in inversions, or, that the background density of 2.67 g/cm$^3$ used in the model was too high. Although it is uncertain whether rescaling of density and magnetic susceptibility values derived from the inversion results is valid, it produced geologically plausible

**Figure 8** Plot of density and magnetic susceptibility of drill core samples, Punt Hill region. Each sample is coloured using a simplified alteration classification scheme and sized by copper values. At Punt Hill, prograde altered rocks have a moderately high density in the range of approximately 3.1–3.4 g/cm$^3$. Retrograde overprinted rocks have a density range of approximately 2.8–3.1 g/cm$^3$. Reasonable discrimination is observed between prograde- and retrograde-dominated assemblages. Densities below 2.8 g/cm$^3$ are considered to be background.
**Conclusion**

The Punt Hill region is prospective for Cu–Au ± Pb–Zn skarn and IOCG style deposits, lying within the Olympic Cu–Au Province of the eastern Gawler Craton. To date, the most significant copper intersections have been associated with partly retrogressed zones within garnet–pyroxene skarn developed in Wallaroo Group metasediments. Mineralised zones typically include amphibole and/or talc, commonly with garnet and/or pyroxene, and have low magnetic susceptibility (mostly <0.001 SI) and moderate densities (2.7–3.3 g/cm$^3$). The reduction in density associated with the retrograde alteration phase means that exploration targeting should be offset from peak gravity values.

Informed by measurements of magnetic susceptibility and density from Punt Hill drill cores, regions with similar properties to areas of known mineralisation were identified within gravity and magnetic inversion models. The modelling supports the existence of broad areas of skarn alteration in Wallaroo Group which remain to be tested by drilling.

Antimony was identified as an element that shows an association with both proximal and distal alteration minerals, and is a useful element for identifying kilometre-scale geochemical ‘footprints’ in the region. A geochemical index derived using elements associated with known mineralisation indicates that prospects in the central Punt Hill region, including Groundhog, Prairie Dog, Woodchuck and Marmot, have geochemical attributes that are most similar to that expected in a significant mineral system.

In addition to providing detailed characterisation of the mineralogy within the Punt Hill region, spectral mineralogy through the HyLogger$^\text{TM}$ system enabled semi-quantitative estimation of the garnet to pyroxene ratio, which in skarn systems provides an indication of proximity to the source of hydrothermal fluids (temperature vector). When coupled with regional gravity data and magnetic inversion results, garnet to pyroxene ratios support a causative intrusion proximal but to the south of the Punt Hill prospects. These data support a mineralisation model where magmatic–hydrothermal fluids sourced from deep-seated Hiltaba Suite intrusions moved up NW–SE-trending faults in a generally northward direction and into calcareous strata, forming prograde skarn assemblages. Either cooled and evolved fluids, or a separate shallowly sourced fluid, resulted in retrograde alteration and Cu–Au ± Ag–Zn–Pb mineralisation.

Complete descriptions of results and interpretations are available in Fabris et al. (2018). Datasets have been incorporated into a 3D Gocad model which is the ideal method to view results of this project. This model serves as a 3D mineral potential map that displays components of mineral systems developed in the Punt Hill region down to ~5 km depth.
Figure 10  Residual aeromagnetic image of the Punt Hill study region. Dominant features include NW–SE- and NNW-orientated linear residual magnetic highs, and high magnitude and amplitude magnetic anomalies west of the Elizabeth Creek Fault. Most prospects are associated with residual magnetic anomalies.
Figure 11  Magnetic susceptibility inversion model for the Punt Hill region, looking northeast. The z plane of the model is located at 3,000 m depth. The x and y planes have been positioned to cut through the Groundhog prospect and show areas of increased magnetic susceptibility from ~1.3 km (see Fig. 10). Existing drillholes are displayed (white lines from surface). Base of model is at 5,240 m. Vertical exaggeration is 5 times. Areas in red represent values greater than 0.036 SI units.

Acknowledgements
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FURTHER INFORMATION

3D Gocad model
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Roopena Basin: sedimentary basin formation associated with Mesoproterozoic mineralising event in the Gawler Craton

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Introduction
Iron oxide–copper–gold (IOCG) mineralisation within the eastern Gawler Craton formed synchronous with emplacement of a silicic large igneous province—the Mesoproterozoic (1595–1575 Ma) Gawler Range Volcanics and Hiltaba Suite. A causal link between the hydrothermal breccia systems and this high-temperature mafic and felsic magmatism in the Olympic Cu–Au Province has been demonstrated (e.g. Skirrow et al. 2007). However, the two largest currently mined IOCG deposits, Olympic Dam and Prominent Hill, are both also spatially associated with sedimentary rocks deposited synchronous with volcanism (Belperio, Flint and Freeman 2007; Bull et al. 2015; McPhie et al. 2016). It has been suggested that the presence of an active sedimentary basin may have also been significant in the formation of IOCG mineralisation (McPhie et al. 2011) by potentially providing the saline groundwaters that are a key component of the fluid-mixing model for the formation of the Olympic Dam orebody (Haynes et al. 1995).

One of the best preserved sedimentary successions to have formed during this early Mesoproterozoic event occurs on northern Eyre Peninsula. The volcano-sedimentary succession within the Roopena Basin (Fig. 1) provides a unique window into the types of sedimentary processes that were operating during this major igneous and metallogenic event. In addition, the Roopena Basin remains an exploration target for IOCG-type deposits.

Recent work by the Geological Survey of South Australia has redefined the stratigraphy of the Roopena Basin, which was previously considered to be part of the Corunna Conglomerate (Daly 1993). The aim of the work program was to determine the extent, architecture and sedimentological and volcanic evolution of the Roopena Basin. Work completed included re-logging of available drill core, including drill core obtained from the recent Mineral Systems Drilling Program (Fabris et al. 2017), remapping the exposed portions of the Roopena Basin in the vicinity of Roopena Homestead, and detrital zircon geochronology.

The first results of this work program were published in a departmental report book, which presented detailed core logging and lithostratigraphic correlation within the basin (McAvaney and Wade 2015). Recently, the final interpretations and broader regional implications from the work were published as an Open Access article in the Australian Journal of Earth Sciences (Curtis, Wade and Reid 2018). Here we summarise the significant aspects of the work as an overview of the geology of the Roopena Basin.

Roopena Basin geology
The Roopena Basin is a north–south-trending basin ~6 km wide, bound by the Roopena and Wizzo Well faults (Fig. 1). It has a preserved extent of 75 km² based on outcrop and intersections in drillholes; however the original extent of the basin may have been significantly larger, given the thickness of the preserved volcano-sedimentary succession is up to 330 m. The basin contains three units of the lower Gawler Range Volcanics: the Angle Dam Dacite1; upper and lower Fresh Well Formation; and upper and lower Roopena Basalt (Fig. 2). The evolution of the basin consisted of alternating phases of volcanic-dominant and sedimentary-dominant activity (Fig. 3).

1 Originally defined as Angle Dam Volcanics (McAvaney and Wade 2015). The Geological Survey of South Australia has initiated the process to formally change the name to Angle Dam Dacite to reflect the dominant lithology.
Figure 1  (a) Surface geology (adapted from Krapf et al. 2016) and (b) aeromagnetic expression (TMI 1VD) of the Roopena-Myall Creek area, showing the preserved outcrop and subsurface extent of the Roopena Basin between the Roopena and Wizzo Well faults. Reprinted from Curtis, Wade and Reid (2018; fig. 2) with added locality map.
New geology

The Angle Dam Dacite (Fig. 4a) is a porphyritic volcanic which forms the oldest unit of the Gawler Range Volcanics in the Roopena area, and is overlain by alluvial conglomerates (Fig. 4b) and sandstones of the lower Fresh Well Formation which mark the first phase of sedimentation within the basin (Fig. 3a). Sedimentation was interrupted by extrusion of the lower Roopena Basalt (Fig. 3b), which contains local hyaloclastite breccia (Fig. 4c), indicating rapid quenching of lava due to interaction with water or wet sediment within the basin.

The overlying upper Fresh Well Formation marks the major period of sedimentation within the Roopena Basin (Fig. 3c). It comprises a succession of volcaniclastic claystone (Fig. 4d), siltstone and sandstone deposited in a fluviolacustrine setting. The upper Fresh Well Formation contains three coarsening-upwards prograding sedimentary packages with sharp basal contacts (Fig. 2), suggesting rapid flooding events occurred within the basin. Three tuffaceous beds within this formation provide evidence of extra-basinal explosive felsic volcanism during sedimentation (Fig. 2). Detrital zircon geochronology of a sandstone within the Fresh Well Formation yielded a maximum depositional age of c. 1580 Ma, with provenance dominated by magmatic zircons of the c. 1635–1605 Ma St Peter Suite (Fig. 5; Curtis, Wade and Reid 2018). Significant sedimentation within the basin was terminated by extrusion of the upper Roopena Basalt (Fig. 3d), which is the uppermost unit preserved within the succession and contains up to 11 distinct lava flows. Thin sedimentary intervals and peperite development within the upper Roopena Basalt indicate that minor sedimentation occurred during volcanism (Fig. 2).

The Fresh Well Formation and underlying Paleoproterozoic basement locally contain hematite–chlorite–sericite alteration, permissive of hematite-style IOCG deposits, which have been the focus of a number of exploration programs in the Roopena area, including Australian Selection in the 1980s (Samedan of Australia and Esso Australia Ltd 1985) and more recently Renascor Resources (2018).

**Implications**

The development of sedimentary basins synchronous with extrusion of the Gawler Range Volcanics at Roopena, Olympic Dam and Prominent Hill all occur within the eastern Gawler Craton. The coincidence of sedimentation and mafic volcanism suggests that this region underwent at least localised extension in the early Mesoproterozoic. This is consistent with the overall extensional tectonic environment envisaged to be a factor in the formation of IOCG deposits (Hitzman, Oreskes and Einaudi 1992).

It is possible that these sedimentary packages preserved now as relics within either hematite breccia systems (e.g. Olympic Dam) or as fault bound domains could have originally formed a much larger sedimentary basin system across the eastern Gawler Carton. If this was the case, it raises
example in the Myall Creek (Simpson 2017) and Peltabinna areas (Werner et al. 2017), supporting the relatively local, restricted nature of sedimentation at this time.

Narrow fault-bound basins can be found in regions undergoing limited extension, or also in regions undergoing transpression or transtension, in which zones of lateral faulting form pull-apart basins. Where such lateral movements are connected to deeper, lithospheric structures, the often vertical or subvertical nature of these deformation zones can facilitate the transport of mantle-derived magmas and fluids into an upper crustal setting. Steep structures are identified in some interpretations of the seismic and magnetotelluric surveys across Olympic Dam (Heinson et al. 2018; Wise et al. 2016). It is probable that strike-slip, normal or oblique-slip faulting synchronous with emplacement of the Gawler Range Volcanics may have contributed to the formation of localised sedimentary basins. If these basins are structurally controlled (McPhie et al. 2011) it is possible that these same structures may have facilitated magmatic emplacement and fluid flow that contributed to the formation of the IOCG deposits.

However, we favour the concept that these basins were more likely to have been relatively restricted in extent. While the Roopena Basin was undoubtedly larger than the currently preserved area, the immaturity of sediments suggests that the basin was unlikely to have been orders of magnitude larger than what is preserved. Indeed, the detrital zircon age patterns recovered from the sample of the Fresh Well Formation in the Roopena Basin are significantly different from those derived from the Olympic Dam deposit (Fig. 5), which certainly supports the notion that these two packages were not part of a connected basin. In addition, sedimentary rocks preserved elsewhere in the Gawler Range Volcanics tend to form relatively thin interlayers within the dominantly volcanic units, for questions about the possible significance of a larger, water-rich sedimentary basin interacting with deep-sourced magmatic hydrothermal fluids across the eastern Gawler Craton. Indeed, the concept that the sedimentary rocks at Olympic Dam were part of a previously larger basin was suggested by McPhie et al. (2011) based on interpretation of a distal source for detrital chromite and volcanic quartz in the bedded sedimentary facies rocks at the deposit.

Figure 3  Stylised block diagrams illustrating the temporal evolution of the Roopena Basin. (a) Emplacement of the Angle Dam Dacite and deposition of the lower Fresh Well Formation. (b) Emplacement of the lower Roopena Basalt. (c) Deposition of the upper Fresh Well Formation. (d) Eruption of the upper Roopena Basalt. Reprinted from Curtis, Wade and Reid (2018; fig. 10).
Figure 4  Units of the lower Gawler Range Volcanics, Roopena Basin. Reprinted from Curtis, Wade and Reid (2018; figs 5a, 5b, 5d and 5g).

Figure 5  Probability density distribution of detrital zircons from (a) a sample of the Fresh Well Formation (Curtis, Wade and Reid 2018) and (b) bedded clastic facies at Olympic Dam (data from McPhie et al. 2016). Probability density plots drawn using AgeDisplay (Sircombe 2004). Reprinted from Curtis, Wade and Reid (2018; fig. 9).
The Roopena area lies within the Olympic Cu–Au Province, connecting the hematite-style IOCG deposits in the broader Olympic Dam area with the skarn-style IOCG deposits on Yorke Peninsula. We note that the presence of localised hematite–chlorite–sericite (white mica) alteration within the Fresh Well Formation and underlying basement within the Roopena Basin is characteristic of other hematite-style IOCG deposits and prospects within the Gawler Craton (Skirrow 2009). In addition, directly to the west of the Roopena area the presence of quartz veins associated with fluorite, barite, muscovite, feldspar, kaolinite, halloysite and smectite and enrichment in elements such as Ag, Sb, Te, Bi, Cu, Pb and Zn, are consistent with low-sulfidation, argillic alteration (Wade et al. 2014), suggesting that the upper crustal part of this lithosphere-scale hydrothermal system is also preserved. Nevertheless, no significant IOCG-style mineralisation has yet been discovered in the Roopena Basin.

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Amata Dolerite, Musgrave Province: connections to Neoproterozoic mantle plume magmatism within Rodinia

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Introduction

The Amata Dolerite is a mafic dyke suite that intruded the late Paleoproterozoic to Mesoproterozoic basement rocks of the Musgrave Province during the early Neoproterozoic at c. 800 Ma. Dykes of the Amata Dolerite occur within the Musgrave Province together with dykes of the older c. 1080 Ma Alcurra Dolerite and differentiating between these two mafic dyke suites poses a major challenge to geological mapping and mineral exploration in this area. The Amata Dolerite is enriched in economically important metals such as copper and gold, and thus potentially forms a significant source rock for sediment-hosted or fault-controlled hydrothermal mineral deposits. The Alcurra Dolerite is associated with coeval Giles Complex mafic–ultramafic intrusions that are prospective for orthomagmatic Ni–Cu – platinum group elements (PGE) mineralisation (Howard et al. 2009) and forms part of the Warakurna Large Igneous Province (Wingate, Pirajno and Morris 2004). This article describes the key characteristics of the Amata Dolerite within the eastern Musgrave Province of South Australia based on mapping within the Alcurra 100,000 map sheet area (Krapf et al. 2017, 2018) and provides criteria to distinguish these two mafic igneous suites.

Recognising the differences between the Amata and Alcurra dolerites has geological significance. The Amata Dolerite is considered an equivalent of the Gairdner Dolerite (Goode 1970; Maboko 1988; Glikson et al. 1996; Sheraton and Sun 1997; Wingate et al. 1998; Edgoose, Scrimgeour and Close 2004; Howard et al. 2011), and along with the Willouran Basic Province (Hilyard 1990; Crawford and Hilyard 1990) and other coeval mafic igneous rocks, forms the Gairdner Large Igneous Province (Zhao, McCulloch and Korsch 1994; Foden et al. 2002; Claoué-Long and Hoatson 2009). The Gairdner Large Igneous Province extends from the Adelaide Geosyncline and Curnamona Province northwards to the Paterson Orogen in northwest Western Australia.

Wang et al. (2010) extended this province to the Willouran–Guibei Large Igneous Province in order to include coeval mafic rocks of the South China Block, which, according to the ‘Missing Link’ model of Li, Zhang and Powell (1995), was connected to southeastern Australia in the early Neoproterozoic as part of the Rodinia supercontinent. Magma formation and emplacement of coeval early Neoproterozoic mafic igneous rocks have been related to a major phase of mantle plume activity, which caused widespread decompression melting of asthenospheric mantle and the establishment of this large igneous province. Magmatism was accompanied by intracontinental rifting that ultimately led to the breakup of Rodinia at c. 720 Ma (Crawford and Hilyard 1990; Zhao and McCulloch 1993b; Zhao, McCulloch and Korsch 1994; Wingate et al. 1998; Li et al. 2006; Ernst et al. 2008; Li et al. 2008; Wang et al. 2009; Wang et al. 2010).

Consequently, understanding the timing, distribution, and processes associated with the Amata Dolerite in the eastern Musgrave Province is important for understanding global-scale geological processes and plate reconstructions. The distribution, lithology, geochemical characteristics and age constraints of the Amata Dolerite, as well as its broader significance, are discussed.
**Distribution**

The distribution of the Amata Dolerite in the eastern Musgrave Province is deduced from outcrop mapping and from interpretation of orthophoto, satellite and total magnetic intensity (TMI) images (Fig. 1). Dykes of the Amata Dolerite commonly form prominent linear magnetic anomalies due to their magnetite content and high magnetic susceptibility (Dutch, Pawley and Harvey 2014). The Amata Dolerite dykes can be traced along strike for up to 10 km in length and their thickness ranges from <1 m up to ~100 m. Larger dykes locally split up into several smaller dyke segments and en echelon offsetting of dyke segments is relatively common.

**Figure 1** Outcrop distribution and geochemistry sample locations of dykes of the Amata and Alcurra dolerites shown over TMI image.
The Amata Dolerite occurs mainly in the southern half of the study area as several ESE- to SE-trending dyke swarms. The main outcrops are located in the southwestern part of the Alcurra map sheet area (Fig. 1). An ~5 km wide, SE-trending dyke swarm occurs south of Mundy Dam. About 5 km farther north is an overall ESE-trending, wedge-shaped area of dyke intrusions with individual dykes clearly visible in TMI images as linear positive magnetic features (Fig. 1). This dyke swarm is ~8 km wide in the area west of Kangaroo Well and Guy Fawkes Bore but narrows to ~2 km around Agnes Creek Homestead and continues eastwards as a magnetic lineament to the Marryat Railway Station area, where the Amata Dolerite is sporadically exposed.

An ~2 km wide zone of prominent ESE-trending high-magnetic intensity lineaments between Guy Fawkes Bore and the Marryat Fault probably represents an unexposed dyke swarm of the Amata Dolerite, which can be traced from the One Tree Bore area in the east to the confluence of the Alcurra and Marryat creeks in the west (Fig. 1). Another prominent positive magnetic lineament, which is also interpreted as an unexposed Amata Dolerite dyke, occurs directly to the north and parallel to the Marryat Fault.

Farther north, a prominent ESE-trending positive magnetic lineament is traceable between Sundown Outstation and Wallaby Rock. It represents another Amata Dolerite dyke or dyke set, which crops out at Wallaby Rock crosscutting the small Wallaby Rock pluton of the Piti tournaments Super Suite. North of Gosse’s Lineament, within the outcrop area of the Alcurra Dyke Swarm, dykes of the Amata Dolerite are virtually absent. An exception forms a narrow set of east- to ESE-trending dolerite dykes, exposed to the southwest of Holy Water Well, that belong to the Amata Dolerite as indicated by geochemistry.

Overall, the Amata Dolerite intruded older basement rocks in the study area as SE- to ESE-trending dyke swarms or dyke complexes. This contrasts with the strike directions of dispersed dykes of the Alcurra Dolerite south of the Alcurra Dyke Swarm (Figs 1, 2).

**Lithological and mineralogical characteristics**

Exposures of Amata Dolerite dykes in the study area range from scattered low rubbly to more prominent larger bouldery outcrops (Fig. 3a). Dolerite boulders often show onion-shell weathering and some outcrops are characterised by bread crust like weathering forms (Fig. 3b). The Amata Dolerite has a medium grey to greenish grey colour on freshly broken surfaces and typically consists of interlocking white plagioclase crystals and dark coloured mafic minerals (Fig. 3c). The dolerite is typically massive and samples with ophitic or subophitic texture display a conspicuous spotty pattern on polished surfaces (Fig. 3d). Thicker dykes commonly have fine-grained chilled margins and a coarse-grained gabbroic interior. Dolerite as well as adjacent basement rock is locally strongly epidotised along dyke margins giving the rock a greenish colour. Intensively weathered dolerite is exposed in some places as a light brown to white clayey saprolite, as dark brown ferruginised rock, or as greyish calcite-altered rock.

Thin sections show that the Amata Dolerite is mainly composed of plagioclase and clinopyroxene. Igneous textures range from intergranular in the core of wider gabbroic dykes, to (sub-)ophitic and porphyritic at the chilled dyke margins (Fig. 4a–c). Plagioclase (~40–60%) typically forms randomly oriented laths and prisms up to 2 mm and the
Figure 3  Outcrop and sample photos of the Amata Dolerite.

typical pale fawn-brown colour is probably due to minute hematite inclusions. Plagioclase is also variably altered to sericite, zoisite and albite. Clinopyroxene (~30–55%) occurs as colourless to pale pinkish (Ti-augite) subhedral blocky crystals and crystal aggregates up to 1.5 mm in size and shows alteration to hornblende and actinolite. Clinopyroxene also occurs as subradiating sheaves of groundmass quench crystals (0.4–1.0 mm long) intergrown with acicular plagioclase microlites in a chilled dyke margin sample (Fig. 4d).

Olivine occurs in some samples in small amounts (<1%) as inclusions in clinopyroxene but is usually completely altered to a yellowish brown phyllosilicate–goethite assemblage (Fig. 5a). Opaques (1–5%, mainly Fe–Ti oxides) form blocky crystals up to 2 mm in size with some magnetite showing skeletal crystal forms. Primary Fe–Ti oxides show alteration to secondary Fe–oxides and sphene. Pleochroic bluish green to yellowish brown hornblende (commonly <1–5%) marginally replaces and overgrows earlier formed clinopyroxene (Fig. 5b) and is commonly intergrown with late crystallising interstitial quartz, K-feldspar and apatite. Hornblende also occurs in some Amata Dolerite samples in significant amounts (~10%) as dark green grains occupying interstices between plagioclase and clinopyroxene. Biotite typically forms pleochroic dark brown to straw yellow to green flakes commonly in association with Fe–Ti-oxides (Fig. 5c) or as small inclusions within late interstitial quartz–feldspar. Quartz, K-feldspar and apatite fill late-formed interstices. Quartz and K-feldspar form small angular grains and minor micrographic intergrowths within these interstices (Fig. 5d) or are
sparsely scattered through the rock. Apatite occurs as tiny prisms and acicular crystals as inclusions in quartz, feldspar, or amphibole (Fig. 5d).

The Amata Dolerite can be distinguished mineralogically from the Alcurra Dolerite, with the latter typically having a much higher olivine content of ~5–20%. However, this difference is commonly only visible in thin sections but not in hand specimens. The fact that some samples of the Amata Dolerite contain small amounts of both primary olivine (as phylllosilicate-altered pseudomorphs) and late interstitial quartz suggests that the basaltic magma was slightly silica undersaturated to allow early crystallisation of olivine, with the latest residual melt fractionating towards a silica- and iron-rich composition typical of the tholeiitic magmatic association.

**Basement contacts and contamination**

Dykes of the Amata Dolerite intrude gneisses of the c. 1.7–1.5 Ga Birksgate Complex and c. 1.15 Ga granites of the Pitiŋatjaṯara Supersuite. Locally they also crosscut dykes of the c. 1080 Ma Alcurra Dolerite, although contacts are rarely exposed. Larger dykes of the Amata Dolerite locally split up into several smaller dyke segments enclosing rafts of basement host rocks. About 5.5 km northwest of Agnes Creek Homestead, an ~80 m wide Amata Dolerite dyke encloses an ~20 m wide felsic gneiss sliver, which is crosscut by a number of 5–10 cm wide dykelets that splay off the main dyke. Macroscopically visible contamination of the Amata Dolerite with smaller basement xenoliths is relatively uncommon. This contrasts with the Alcurra Dolerite, which frequently displays evidence for contamination by the host rocks.

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**Figure 4**  Photomicrographs showing igneous textures of the Amata Dolerite.

4(a) **Intergranular texture of coarse-grained dyke interior with interlocking clinopyroxene and plagioclase crystals.** (Sample 2014852; plane-polarised light; photo 416690)

4(b) **Subophitic texture with clinopyroxene crystal enclosing plagioclase crystals.** (Sample 2014847, cross-polarised light; photo 416691)

4(c) **Porphyritic texture of chilled dyke margin with plagioclase and clinopyroxene phenocrysts in fine-grained groundmass.** (Sample 2014963, plane-polarised light; photo 416692)

4(d) **Subradiating sheaves of clinopyroxene quench crystals intergrown with acicular plagioclase microlites.** (Sample 2014963, plane-polarised light; photo 416693)
Despite the lack of macroscopic evidence for contamination in the Amata Dolerite, clear signs of basement contamination and assimilation can be seen in thin sections and in the geochemistry of some samples. In thin sections, such samples show abundant large patches (up to 1 mm in diameter) of radiating micrographic quartz–feldspar intergrowths (Fig. 6a). Some of these nucleate on plagioclase crystals or fill interstices between plagioclase crystals (Fig. 6b). These micrographic quartz–feldspar intergrowths probably originated from melting of small felsic gneiss or granite fragments entrapped by the intruding dolerite. Geochemically, the basement contamination is reflected in elevated SiO₂, K₂O, Rb, Cs, Ba and Th concentrations, as well as in high La/Nb ratios and increased light rare earth elements (REE) fractionation.

**Geochemistry – a powerful tool to distinguish between the Amata and Alcurra dolerites**

It is usually very difficult to macroscopically distinguish the Amata Dolerite from the Alcurra Dolerite. Thin sections can help to identify the Alcurra Dolerite as it is typically more olivine-rich. However, geochemistry is the best tool to distinguish these two dolerite suites (Table 1). The Amata Dolerite is a high-Fe–Ti and low-Mg tholeiitic mafic rock with Mg number mainly below 55, which contrasts markedly with the low-Fe–Ti and high-Mg Alcurra Dolerite with Mg number mainly above 55 (Fig. 7). Due to the olivine-poor nature of the Amata Dolerite, it has generally low concentrations of the compatible trace elements Ni, Co and Cr,
whereas the olivine-rich Alcurra Dolerite is enriched in these elements. The Amata Dolerite shows elevated concentrations for some trace elements including Cu and Au (Fig. 7). These enrichments make the Amata Dolerite an important source rock for potential mineralisation, e.g. in fault zones where hydrothermal fluids can mobilise these elements and subsequently precipitate them to form Cu–Au deposits.

The Amata Dolerite is characterised by high contents of high field strength elements (HFSE) such as Zr, Nb and REE, which are depleted in the Alcurra Dolerite. Chondrite-normalised REE plots clearly show the high REE abundance of the Amata Dolerite in comparison to the Alcurra Dolerite (Fig. 7). Subtle differences in the overall shape of REE patterns can also be used to discriminate these two dolerite suites. Light REE fractionation as indicated by (La/Sm)N ranges mainly between 1 and 2 for both suites. However, the heavy REE are slightly more fractionated in the Amata Dolerite ((Gd/Yb)N 1.5–2) than in the Alcurra Dolerite ((Gd/Yb)N mainly 1–1.5). La/Nb ratios are the most powerful distinguishing features between the younger Amata Dolerite and the older Alcurra Dolerite in the eastern Musgrave Province. The Amata Dolerite has smooth positively sloped REE patterns and trace element characteristics that are similar to those of continental flood basalts. These features and juvenile isotopic signatures indicate that the Amata Dolerite is largely derived from decompression melting of upwelling depleted asthenospheric mantle or a rising mantle plume (Zhao and McCulloch 1993b; Zhao, McCulloch and Korsch 1994; Foden et al. 2002). In contrast, pronounced HFSE depletions (especially Nb), selective large ion lithophile element enrichments (K, Sr, Ba), and evolved isotopic signatures for the Alcurra Dolerite appears to reflect partial melting of a metasomatised, subduction-modified subcontinental lithospheric mantle (Zhao and McCulloch 1993a, b; Glikson et al. 1996; Sheraton and Sun 1997). Furthermore, our studies in the eastern Musgrave Province have shown that emplacement of the Amata Dolerite was accompanied by only minor crustal contamination, whereas this was a significant process for the Alcurra Dolerite.

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Age – implications from the record of early Neoproterozoic mantle plume magmatism within Rodinia

Attempts to extract zircon or baddeleyite from samples of the Amata Dolerite collected in the eastern Musgrave Province were unsuccessful and thus no precise age dates are available from its type area. Imprecise Sm–Nd isochron ages of 790 ± 40 and 797 ± 49 Ma were reported for NW-trending dolerite dykes near the town of Amata.
Figure 7  Binary variation diagrams of Fe$_2$O$_3$T, MgO, Cu and Au vs Mg number, chondrite-normalised REE patterns and Nb vs La plot for the Amata and Alcurra dolerites.
New geology

(Zhao and McCulloch 1993b; Zhao, McCulloch and Korsch 1994). A dyke sample with Amata Dolerite-like geochemistry, collected within the Tieyon map sheet area at the eastern outcrop margin of the Musgrave Province, yielded an imprecise age of c. 760 Ma, with the Sm–Nd age of 766 ± 53 Ma in good agreement with its Rb–Sr age of 758 ± 21 Ma (Dutch et al. 2013; Werner et al. 2014). A similar age uncertainty is also reported for the west Musgrave Province, where a sample from an unnamed mafic dyke suite yielded a Sm–Nd isochron age of 747 ± 48 Ma. Howard et al. (2011) suggested that these c. 750 Ma mafic rocks are either part of the c. 825 Ma Gairdner magmatic event, or represent a slightly younger suite, possibly contemporaneous with the c. 755 Ma Mundine Well Dolerite Suite of northwestern Australia (Wingate and Giddings 2000; Li et al. 2006).

Based on the correlation of the Amata Dolerite with the Gairdner Dolerite (see introduction), the age of the Gairdner Dolerite should also apply to the Amata Dolerite. The Gairdner Dolerite is constrained by SHRIMP U–Pb age of 827 ± 6 Ma from baddeleyite and zircon extracted from a dolerite dyke sample from drillhole RL 1 (Reedy Lagoon, northwestern Stuart Shelf, SA Geodata drillhole number 16695; Wingate et al. 1998). This early Neoproterozoic age was confirmed by LA-ICPMS U–Pb dating of magmatic apatite as well as hydrothermal apatite and titanite from Gairdner Dolerite dykes at Olympic Dam, which yielded ages of c. 825–820 Ma (Huang et al. 2015, Apukhtina et al. 2016). A similar age was also reported for the Little Broken Hill Gabbro in the Curnamona Province (Pb–Pb zircon 827 ± 9 Ma; Wingate et al. 1998). Furthermore, a sample of the Gairdner Dolerite equivalent type B mafic dykes of the Tomkinson Ranges in the western Musgrave Province yielded a U–Pb baddeleyite age of 824 ± 4 Ma (Ss Sun, unpublished data in Glikson et al. 1996).

The apparently slightly younger Neoproterozoic ages of mafic rocks from the eastern Musgrave Province, derived from Sm–Nd dating, raise an important question. Were these rocks, including samples of the Amata Dolerite, indeed part of the Gairdner Dolerite magmatism, or do they represent a distinct episode of mafic magmatism? Post-825 Ma early Neoproterozoic magmatism in South Australia is sporadically documented for the Adelaide Geosyncline, including the Rook Tuff (802 ± 10 Ma; Fanning et al., 1986), the Oodla Wirra Volcanics (798 ± 5 and 799 ± 4 Ma; Fabris et al., 2005), the Burra porphyry (794 ± 4 Ma) and volcaniclastics within the Skillogalee Dolomite (788 ± 7 Ma; Preiss, Drexel and Reid 2009).

It is possible to examine this issue by looking at South China, which has one of the best-preserved and best-documented records of early Neoproterozoic, c. 825–760 Ma giant plume-driven mafic magmatism in the world (Li et al. 2008; Wang et al. 2009). This is highly relevant to the early Neoproterozoic magmatic record of the Musgrave Province and the Gawler Craton because in some reconstructions of the Rodinia supercontinent, southeastern Australia was potentially connected to the South China Block at that time (Li, Zhang and Powell 1995) (Fig. 8). The period 825–800 Ma represents the first major phase of basaltic magmatism in South China (Li et al. 2003; Li et al. 2008, Wang et al. 2009, 2010), which occurred before and during early intracontinental rifting and is comparable to the early Neoproterozoic magmatism and rifting recorded for the Adelaide Geosyncline and surrounding crustal provinces. A subsequent second phase of major mafic magmatism associated with major rifting is well documented in South China for the period 790–750 Ma (Li et al. 2003; Lin, Li and Li 2007; Zhou et al. 2007; Li et al. 2008; Wang et al. 2009). A potential equivalent of this slightly younger Neoproterozoic magmatic phase is the c. 780 Ma Gunbarrel mafic magmatic event (Harlan et al. 2003) (Fig. 8). It is recorded along the western margin of Neoproterozoic Laurentia, which was connected to the South China Block on the opposite side of the contact to Australia (Li, Zhang and Powell 1995).
Precise U–Pb zircon or baddeleyite dating of the Amata Dolerite and other potentially coeval mafic intrusions in the Musgrave Province and surrounding crustal provinces would be necessary to verify that distinct phases of early Neoproterozoic mafic magmatism existed over an extended period of time also in central-southeastern Australia.

Summary

The Amata Dolerite intruded Palaeo- to Mesoproterozoic basement units of the Musgrave Province. These include dykes of the Alcurra Dolerite, which form part of the Warakurna Large Igneous Province. Differentiating between these two similar, but unrelated, mafic dyke suites can be challenging but is important for geological mapping and mineral exploration. Major differences are geophysical properties as well as mineralogical and geochemical characteristics. Magnetic susceptibility of the Amata Dolerite is high due to its magnetite-richness and results in excellent visibility of its dykes in TMI images as linear positive magnetic anomalies. Geochemistry is the best tool to distinguish these two mafic suites. The Amata Dolerite is low in Mg but high in Fe, Ti, V, Zn and HFSE. This contrasts with the high-Mg–Cr–Ni and low-Fe–Ti nature of the Alcurra Dolerite, which is further characterised by strong HFSE depletions. Low La/Nb ratios (<2) are indicative of the Amata Dolerite, whereas the Alcurra Dolerite typically has high La/Nb ratios (>2). Enrichments in Cu and Au make the Amata Dolerite an important source rock for potential sediment-hosted or fault-controlled hydrothermal mineral deposits, whereas the Alcurra Dolerite is prospective for magmatic Ni–Cu–PGE deposits.

Age constraints for the Amata Dolerite show that it forms part of the Gairdner–Willouran–Guibei Large Igneous Province, which formed in the early Neoproterozoic due to giant mantle plume activity. These regions were subsequently dismembered and dispersed during the breakup of the supercontinent Rodinia (Wang et al. 2010). The older c. 825 Ma Gairdner Dolerite and age-equivalent mafic rocks correspond to the first magmatic cycle (c. 825–800 Ma) in the South China Block. In the light of the well-documented early Neoproterozoic history of mafic magmatism in South China, it appears plausible that some of the mafic dykes in the Musgrave Province, including parts of the Amata Dolerite, record the second, younger cycle of magmatism (c. 790–750 Ma), as tentatively indicated by the above mentioned Sm–Nd ages. This is further supported by the fact that this younger phase of early Neoproterozoic magmatism is well documented in mafic rocks located paleogeographically both to the west (northwestern Australia) and to the east (South China and western Laurentia) of the Amata Dolerite region within Rodinia (Fig. 8).
References


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FURTHER INFORMATION
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South Australia is now home to the Department for Energy and Mining. Minister for Energy and Mining, Dan van Holst Pellekaan, told an official launch he aspired for the agency to be the best government department in Australia, one that earns a reputation for delivery on stakeholder expectations and partners with industry to make an ever-growing contribution to the South Australian economy.

Headed by Dr Paul Heithersay PhD, BSc (Hons), PSM, the new department has been tasked with reducing energy costs to create more jobs and grow exports. The department will also work to improve energy reliability and reduce emissions from generation. The department will ensure mineral and energy companies can responsibly access and develop the state’s mineral and petroleum resources.

The former Department of Mines and Energy had a long history in South Australia, a remnant of which was retained in the name of this publication, MESA Journal. The Geological Survey of South Australia began as the Geological Office of the South Australia Colony in 1882. For most of its 136-year history, the Geological Survey resided within the department responsible for mines, although its ambit extends beyond the search for minerals for commercial extraction to collecting, managing and delivering knowledge of our state’s geology.

In 1997, the Department of Mines and Energy was merged with Primary Industries. In the 21 years since that decision, resources were first grouped with agriculture, then combined in a broad industry portfolio within the Department for Manufacturing, Innovation, Trade, Resources and Energy (DMITRE). Skills and training were added to create a Department of State Development (DSD) before resources and energy were spun off to the Department of the Premier and Cabinet (DPC) in 2017.

Energy trod a different path. From 1946 until the 1990s, generation, transmission and distribution was the responsibility of the Electricity Trust of South Australia. In the 1990s, ETSA’s generation, transmission and distribution elements were disaggregated and privatised in 2000. Sagasco, the state’s upstream, distribution and retail business, was sold to Boral, which merged the distribution businesses into ASX-listed Envestra. Origin Energy acquired the upstream and retail interests.

Post-privatisation, South Australia’s energy division focused on managing the state’s participation in the National Energy Market and regulating electrical, plumbing and gas fitting services through the Office of the Technical Regulator. Many years with the Department of Transport, Infrastructure and Energy ended with the division’s transfer to DMITRE, DSD and then DPC. In the latest changes, the Low Carbon Economy Unit and Energy Plan Implementation Team have been incorporated into the Energy and Mining portfolio.

The new department is already providing input into the National Energy Guarantee discussion, the Commonwealth review of Woomera Prohibited Area access arrangements and the Resources 2030 Task Force. Work on updating the Mining Act 1971 continues with a Bill due in Parliament this year.

A new name means a new website and a new logo. Much of the department has relocated to a central office in Waymouth Street, Adelaide, and phone numbers were recently updated to Skype for Business. Access to SARIG, the South Australian Resources Information Gateway, the general inquiries phone number and GPO Box remain unchanged.
Department for Energy and Mining

Mineral Resources
- Resource Policy and Engagement
- Resource Information
- Mining Projects
- Mineral Tenements and Exploration
- Mining Regulation
- Geological Survey of South Australia

Energy Resources
- Resource Royalties and Commercial
- Geoscience and Exploration
- Engineering Operations

Energy and Technical Regulation
- Energy Policy and Projects
- Energy Programs and Services
- Technical Regulation

Energy Implementation
- Energy Implementation
- Low Carbon Economy

Resources Infrastructure and Investment Task Force

Corporate Services

Chief Executive
Paul Heithersay

Alex Blood
Barry Goldstein
Vince Duffy
Sam Crafter
Peter Bradshaw
Julianne Cirson

Barry Goldstein

Vince Duffy

Sam Crafter

Peter Bradshaw

Julianne Cirson