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Abstracts for the 2009 Conference

Edited by R.J Korsch

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Fluid sources and processes in the Wernecke IOCGU Breccias, Canada, and comparisons with Australian examples

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Introduction

Recent research on hydrothermal fluids in Proterozoic iron oxide-copper-gold±uranium (IOCGU) deposits and occurrences in the Wernecke Mountains, Yukon, Canada, and the Cloncurry district, Australia, has identified distinct differences between the two regions, which relate to the geological setting and evolution of their respective terranes and which potentially have significant implications for determining the key ingredients in IOCGU deposits (Hunt et al., 2005; Hunt et al., 2007; Baker et al., 2008; Kendrick et al., 2008; Gillen et al., 2009; Figure 1). The terranes are characterised by metasedimentary host rocks that contain evidence for evaporite successions and mafic magmatic activity. Mafic magmatism is more widespread and long lived in the Cloncurry district, however, culminating in the late orogenic emplacement of major felsic and mafic magmatism of the Williams-Naraku batholiths (1550-1500 Ma). Furthermore, the Cloncurry district, which has undergone multiple metamorphic and deformation events, is characterised by low pressure-high temperature conditions. The Wernecke Mountains experienced only low-grade, greenschist facies metamorphism during the Racklan Orogeny and lack any significant late-orogenic, felsic-mafic magmatism. Deposits and prospects in the two regions share some similarities such as similar age (1600-1500 Ma), similar mineral alteration assemblages (e.g., albite, magnetite, hematite, chalcopyrite, carbonate), enrichment in distinct elements (e.g., Cu, Au, Fe, U, Co, Ni, F, Mo), and similar structural settings (faults) and deposit styles (breccias). Importantly though, there are no known major economic deposits in the Wernecke Mountains. This paper compares and contrasts the geology and fluid types, sources and conditions of IOCG mineralisation in the Wernecke and Cloncurry regions, in order to highlight the critical ingredients in the formation of IOCG deposits. Comparison is also drawn with the limited fluid data available from IOCG deposits in the Gawler Craton of South Australia.

Wernecke Mountains, Canada

The Wernecke Breccia is found in areas of the north-central Yukon Territory that are underlain by the Paleoproterozoic Wernecke Supergroup. The Supergroup consists of the Fairchild Lake, Quartet and Gillespie Lake Groups that together form an approximately 13 km-thick package of fine-grained, marine sedimentary rocks and carbonate that were deposited as two clastic to carbonate grand cycles (Thorkelson, 2000; Thorkelson *et al.*, 2001a, 2000b). The Fairchild Lake Groups represents initial subsidence and infilling, and the Quartet and Gillespie Lake Groups

represent subsequent subsidence and infilling. The grand cycles may reflect continental rifting and equate to two stages of lithospheric stretching followed by thermal subsidence of the basin (Thorkelson, 2000).

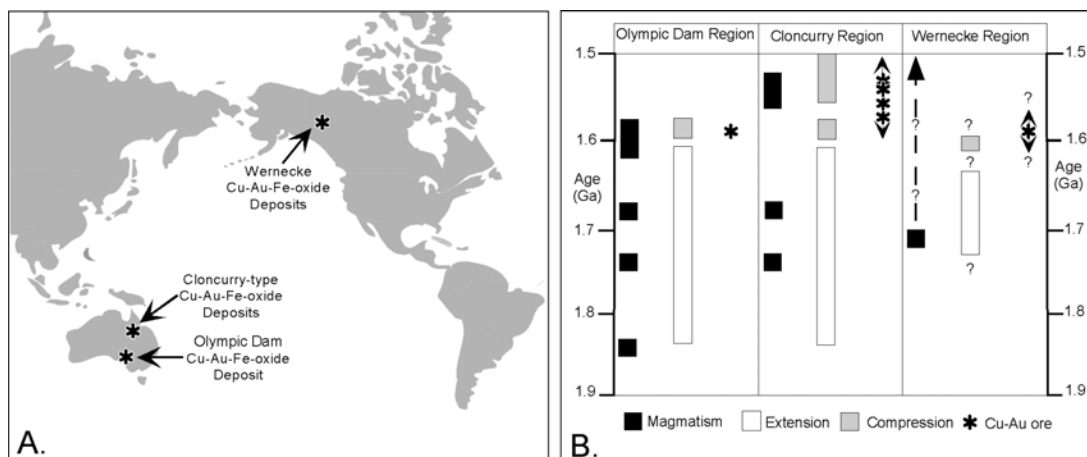


Figure 1. (A) Location of Wernecke, Cloncurry and Gawler IOCGU deposits. (B) Summary diagram of known magmatic, deformation (extension and contraction) and metallogenic (Cu and Au) events from the three IOCGU regions (modified from Partington and Williams, 2000; Thorkelson, 2000).

The Wernecke Supergroup was metamorphosed to greenschist facies and multiply deformed during the Proterozoic Racklan Orogeny (Thorkelson, 2000). Bodies of the Wernecke Breccia cross-cut the Supergroup and are made up largely of clasts of the Supergroup in a matrix of rock flour and hydrothermal precipitates. At least 65 bodies of Wernecke Breccia are known, and all are associated with IOCGU mineralisation. Mineralisation occurs as disseminations and veins within Wernecke Breccia and surrounding rocks of the Wernecke Supergroup, and is largely made up of early magnetite and/or hematite and later chalcopyrite and pyrite (Hunt et al., 2005). Gangue is dominantly composed of carbonate (calcite, dolomite, siderite), quartz, albite and K-feldspar, with lesser biotite, muscovite, chlorite and fluorite, and locally includes minor titanite, rutile, epidote, apatite, tourmaline and monazite. Extensive sodic alteration occurs locally within the Fairchild Lake Group and potassic alteration occurs within the overlying Quartet and Gillespie Lake Groups; the alteration is spatially associated with the breccia bodies. The breccia bodies occur proximal to faults on a regional (Richardson Fault array) and local scale, and were emplaced into weak zones, such as fault and shear zones, fold axes and lithological contacts, during the expansion of over-pressured fluids (Hunt et al., 2005). Cross-cutting relationships indicate multiple phases of brecciation, and mineralisation occurred after peak metamorphism and syn- to post-deformation (Thorkelson, 2000; Hunt et al., 2005). The Wernecke Breccia occurs throughout the Wernecke Supergroup, but is most abundant in the lower part of the stratigraphy, where there is a transition from calcareous sedimentary strata that contain halite facies meta-evaporites to overlying, locally pyritic, carbonaceous shale (Fairchild Lake Group to Quartet Group). Fluid pressures, calculated from fluid inclusion data for breccias at this stratigraphic level, range from approximately 2.5 to 3 kb indicating a depth of emplacement of about 7.5 to 9.0 km, approximately equivalent to the thickness of overlying strata of the Wernecke Supergroup (Hunt, 2005).

A single U-Pb date on titanite from alteration in Wernecke Breccia has an age of ~1595 Ma (Thorkelson, 2000). The breccia prospects are commonly spatially associated with the volumetrically minor Bonnet Plume River intrusions. These intrusions are mafic to intermediate in composition, and occur predominantly as clasts within Wernecke breccias, but previously were also interpreted to have formed as narrow (< 1 to 5 m) dykes and sills that cut the Wernecke Supergroup (Thorkelson et al., 2001a). U-Pb (zircon) dating of four Bonnet Plume River bodies shows they are ca. 1710 Ma old (Thorkelson et al., 2001b); nevertheless, recent

detrital zircon analysis indicates the Wernecke Supergroup contains zircons as young as 1610 ± 30 Ma (Furlanetto et al., 2009). Therefore, the Bonnet Plume River intrusions appear to be older than the host Wernecke Supergroup.

Fluids that formed the Wernecke Breccia and the associated mineralisation were moderate temperature ($185\text{--}350$ °C), moderate to high salinity (24–42 wt. % NaCl eq.) NaCl–CaCl₂ brines (Hunt, 2005; Gillen et al., 2009). Carbon isotopic compositions for hydrothermal carbonates range from: $\delta^{13}\text{C}_{\text{carbonate}} \approx -7$ to $+1$ ‰ (V-PDB) and $\delta^{18}\text{O}_{\text{carbonate}}$ values are between -2 and 20 ‰ (V-SMOW). Calculated $\delta^{18}\text{O}_{\text{fluid}}$ values derived from carbonate range from approximately -8 to $+14$ ‰. Sulphur isotope values for hydrothermal pyrite, chalcopyrite and barite range from: $\delta^{34}\text{S}_{\text{pyrite/chalcopyrite}} \approx -13$ to $+14$ ‰ (CDT) and $\delta^{34}\text{S}_{\text{barite}} \approx 7$ to 18 ‰ (CDT). The $\delta^{18}\text{O}$ values for hydrothermal carbonates generally reflect those of strata from the host Wernecke Supergroup, and $\delta^{13}\text{C}$ values indicate that carbon was derived in large part from the Supergroup. The $\delta^{34}\text{S}$ values of pyrite, chalcopyrite and barite point to a seawater (or sediments/evaporites deposited from seawater) as a likely source for much of the sulfur with possible additional sulfur from the leaching of biogenic pyrite and/or sulfides in local igneous rocks (Hunt, 2005). The carbon, oxygen and sulfur isotopic compositions, combined with limited hydrogen isotope data, indicate that the fluids were likely derived from formation/metamorphic water, mixed with variable amounts of low δD (e.g. organic) water \pm evolved meteoric and/or evolved seawater (Hunt, 2005).

Halogen chemistry (Cl, Br, I) has identified bittern brine signatures (low Cl/Br basal fluids) and halite dissolution signatures (high Cl/Br fluids), suggesting that halite dissolution within the Wernecke Supergroup was variable (Kendrick et al., 2008; Gillen et al., 2009). Noble gas compositions have low $^{40}\text{Ar}/^{36}\text{Ar}$ ratios (<2000) in fluids identified by halogens as bittern brines. Similarly, the majority of halite dissolution fluids also returned low $^{40}\text{Ar}/^{36}\text{Ar}$ ratios. Higher ratios (up to 40,000) were detected in fluids from the Hoover prospect, which suggests that a basement-derived, or possible magmatic fluid, component may have been present in that system. Results from thermometry experiments, and detailed chemical analyses by Proton Induced X-ray Emission (PIXE) and Laser Ablation-Inductively Coupled Plasma Mass Spectrometry (LA-ICPMS), also support an origin that is typical of evaporite-derived basal fluids. The vast majority of fluid inclusions present are liquid-vapour±halite and their major element chemistry is typical of basal fluids with $\text{Ca} > \text{K}$ and low metal levels (particularly Cu and Fe; cf. Yardley, 2005). There is an absence of very high temperature (>600 °C), ultrasaline brines (>50 wt%), carbon dioxide-bearing fluid inclusions, and also of fluids of low salinity.

Cloncurry District, Australia

The Cloncurry district in northwest Queensland, Australia, hosts several major Proterozoic IOCG deposits, including Ernest Henry, Starra, Osborne and Eloise, which are the products of a complex terrane history and multiple genetic processes. The major host rock package formed during early extension and is subdivided into two major cover sequences. Cover sequence 2 (Leichardt and Calvert Superbasins) contains both mafic and felsic metavolcanic rocks and mixed clastic-carbonate-evaporite metasedimentary rocks (ca 1780–1690 Ma). Cover sequence 3 (Isa Superbasin) consists of metamorphosed siliciclastic and basic volcanic rocks (ca 1655–1600 Ma; Page and Sun, 1998; Foster and Rubenach 2006). Major thickness changes in both sequences are localised over regional scale north-south trending structures, suggesting that the faults were basin-margin structures. Low pressure metamorphism occurred during east-west extensional basin formation, and coincided with widespread albitisation. Subsequently, the region underwent a protracted period of deformation and metamorphism during the Isa Orogeny (ca 1600–1500 Ma). Regional low pressure, high temperature, greenschist to upper amphibolite facies metamorphism peaked at ca 1595–1580 Ma, followed by episodic metamorphic events which coincided with voluminous mafic and felsic potassic magmatism (1550–1500 Ma; Foster and Rubenach, 2006). Syn- and post-peak metamorphic albitisation was associated with magmatism and the large scale north-south structures. Many of the IOCG

deposits in the region formed post peak metamorphism and synchronous with granite emplacement (1550-1500 Ma, e.g., Ernest Henry, Mount Elliott, Swan, Mount Dore and Eloise). U-Pb and Re-Os dates from titanite associated with albitisation and molybdenum from the Cu-Au ore at the Osborne deposit, however, indicate a peak metamorphic age (1595 Ma) that does not coincide with a major period of magmatism (Gauthier et al., 2001). More recently a 1568 Ma Re-Os date on molybdenite at Starra also indicates a late peak metamorphic age, pre-Williams-Naraku age for mineralisation (Duncan et al., 2009). The IOCG deposits occur within north-, north-northeast- and north-northwest-trending structures at bends and fault intersections within strongly albitised rocks, distal from granites, but commonly spatially associated with mafic rocks and the contact between cover sequence 2 and cover sequence 3. The deposits are mineralogically diverse, with examples that contain mostly hematite, hematite and/or magnetite, magnetite-dominant and magnetite-pyrrhotite. The ores are enriched in a variety of elements including K, Mn, U, Ag, Mo, Co, Ni, As, Zn, F and Ba in addition to Fe, Cu and Au (Williams et al., 2005).

Fluid inclusion studies, including microthermometry and advanced microanalysis, were carried out in barren, regional albite alteration, barren granitic environments that display evidence of the magmatic-hydrothermal transition, and IOCG deposits (Baker et al., 2008). Four main fluid inclusion types are recognised:

- multi-solid inclusions (with homogenization temperatures (Th) ~200 to >550 °C, and salinity ~30 to >60 wt. % total salts),
- three-phase halite-bearing inclusions (Th ~120 to 350 °C, ~30 to 40 wt. % NaCl equiv.),
- two-phase aqueous inclusions (Th ~100 to 250 °C, <5 to 35 wt. % NaCl equiv.), and,
- carbon dioxide (\pm solid phases) inclusions.

Multi-solid inclusions occur primarily in IOCG deposits and granite-hosted environments, but are mostly absent in barren, regional albite alteration. PIXE analyses indicate that these inclusions contain the highest copper concentrations (>400 ppm), particularly in inclusions in granite-hosted settings and/or with Br/Cl ratios consistent with a possible magmatic origin. Non-magmatic fluids with Br/Cl ratios consistent with bittern-derived and halite-dissolution sources are also important, and are likely more abundant than magmatic-derived fluids; nevertheless, fluid inclusions with these halogen signatures contain less Cu (< 300 ppm). Large ranges in temperature and salinity, and evidence of multiple fluid sources, suggests mixing was important in IOCG ore formation. Detailed halogen and noble gas studies of Ernest Henry, the largest IOCG deposit in the Cloncurry district, also reveal an important magmatic (mantle) contribution, with fluid mixing identified as a key ore-forming process (Kendrick et al., 2007).

Discussion

Hydrothermal fluid studies have revealed that the Cloncurry district IOCG deposits contain distinct ultra-high salinity, high temperature fluids and CO₂-rich fluids. Halogen and noble gas studies indicate that the fluids are derived from multiple sources, but the ultrasaline fluids with the highest Cu contents have a magmatic origin (Baker et al., 2008). These ultrasaline fluids and CO₂-bearing fluids are largely absent in the Wernecke Mountain breccias, where the dominant fluid source is an evaporite-related basinal fluid. The research suggests that, in the Cloncurry district, magmas are a critical ingredient for supplying metals and for creating widespread fluid flow and regional brecciation, through mid-crustal degassing as a result of magma mixing and CO₂ overpressuring. In the Wernecke region brecciation was driven by tectonism and fluid overpressuring of saline evaporite-derived fluids rather than driven by magmatism.

Skirrow et al. (2007) and Bastrakov et al. (2007) have identified similar fluid types and sources in the Olympic Dam district of the Gawler Craton to those identified in the Cloncurry district. Both ultrasaline, high temperature brines and lower salinity fluids are recognised in

subeconomic to economic IOCG deposits. Radiogenic (Nd), stable isotope, and PIXE Br/Cl analysis suggest mixed origins for the fluid and metal sources, although the large deposits (e.g. Olympic Dam) have greater mantle-derived ore components similar to the Cloncurry district.

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BHEI 2009: Discovering the future

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Introduction

The eighth Broken Hill Exploration Initiative brings together partners from New South Wales, South Australia and the Australian Government to share ideas and understanding of the geology and mineral deposits in the Broken Hill region. Broken Hill remains iconic, and has played a pivotal role in the development of Australia. The supergiant deposit continues to draw explorers and researchers from around the globe, and the orebodies and their host sequences, are some of the most studied rocks in the world.

In 2009, the Broken Hill deposit continues to contribute great wealth and does much to support the city 125 years after commencement of mining. Like all mineral deposits, however, the Broken Hill deposit is not endless, and the Broken Hill Exploration Initiative exists to assist in further discoveries.

Since the last BHEI Conference in 2006, there has been a major minerals boom, and the global financial crisis. These have impacted on activities in and around Broken Hill and produced a different financial landscape. The importance of the region as a major minerals centre remains, however, and many exploration opportunities are yet to be tested. The scope of BHEI has expanded to reflect the changing financial and exploration landscape, now encompassing research, not just in the Curnamona Province, but throughout the economic catchment area of Broken Hill.

Geological Survey of New South Wales

The contributions of the Geological Survey of New South Wales (GSNSW) to BHEI have been funded by the NSW Government as part of statewide exploration initiatives, which include Discovery 2000, Exploration NSW and currently New Frontiers. The importance that government has placed on the Broken Hill region is reflected through contributions dating back to the discovery of Broken Hill and earlier.

The Broken Hill Exploration Initiative has continued to build on the extensive knowledge base and, importantly, encouraged the use of new technology and exploration methods in the region. These include radiometrics, high resolution magnetics, airborne gravity, hyperspectral and seismic surveys. New technology has produced compelling data and challenged many existing interpretations. Partnerships with universities, industry and research centres have produced

new approaches to understanding and exploring the regolith, and have developed 3D models and interpretations.

In the 1970's and 80's, the GSNSW undertook its ground-breaking, detailed lithological and metallogenic mapping programs. The mapping and interpretation still forms the cornerstone of regional studies in Broken Hill. The task was undertaken before computers were generally available, before satellite imagery, before high resolution airborne geophysics and before tools such as GIS and GPS were available. Today, the integration of all available data using GIS-platforms, from field geology and mapping through satellite and geophysical acquisition, permits data analysis on an unprecedented level.

Interpretation of the entire NSW Proterozoic rock succession — both exposed and under cover, has produced a major new data set which provides a complete stratigraphic framework for continued exploration in both the Willyama Supergroup (Broken Hill Domain) and in, and through, the Neoproterozoic succession. This includes compilation of existing structural interpretations into a regional digital data set for the first time.

BHEI 2009 also sees the release of major new mapping data sets and notes, products of the Koonenberry mapping project, stretching from the Queensland border to east of Broken Hill.

Value-adding to previously acquired data by improved processing and resolution is well represented at BHEI 2009. Reprocessing of the radiometric data set, first flown by GA in 1995, has produced a marked reduction in noise and enhanced the dynamic range of the data. Likewise, advances in spectrographic processing technology and the recognition of under-utilisation of airborne hyperspectral data available in NSW has led to the reprocessing of existing HyMap data. A vanguard study of the potential for high resolution spectroscopic alteration mapping demonstrates the potential of the National Virtual Core Library HyLogger project.

Improved data sets include higher resolution gravity over parts of the area, available through the GSNSW. Careful reprocessing of a range of imagery has enhanced understanding of structures and lithological variations. The release by Perilya of the regional Broken Hill 3D structural model will serve as a framework for further structural modelling throughout the block. Cooperation with industry is exemplified by the combined release (by Perilya, CBH Resources and Silver City Mining) of the expansive, high spatial resolution, field portable XRF (NITON) geochemical data covering much of the Broken Hill region. The data, and an understanding of the potential and limitations, will be of considerable value to regional explorers and academia.

In the Broken Hill region, the major future direction of the Geological Survey of New South Wales, in its continued support of exploration, will be the use of new and existing data sets and the integration of information with careful field observation to reduce exploration risk. This will include interpretation and processing of the NITON dataset, regional refinement of a 3D model for Broken Hill, increased understanding of spectral and geochemical vectors to mineralisation, and continued characterisation of mineral systems in the Broken Hill region.

Primary Industries and Resources South Australia

The major focus of Primary Industries and Resources South Australia (PIRSA) since BHEI 2006 has been the Plan for Accelerating Exploration (PACE). Between 2004 and 2009, \$22.5 million has been invested in geoscientific surveys, research and education, community engagement, next generation data delivery and collaborative drilling. The PACE program has seen a significant return on its investment, including an estimated net economic benefit in excess of \$300 million, and exploration expenditure in the state reaching \$355 million in the calendar year 2008. PACE has invested \$10 million in collaborative drilling between 2004 and 2009, with approximately 20 % of the projects focussed on the Curnamona Province and overlying

sediments of the Frome Embayment. A wide range of commodities have been targeted including copper, particularly in iron oxide-copper-gold systems, lead-zinc-silver, and uranium, in addition to geothermal energy. In particular, PACE funding was provided to Quasar Resources to explore for mineralisation in the northern Flinders Ranges-Frome Embayment and a significant new uranium discovery was made at Four Mile near the Beverley uranium mine (7.7 Mt @ 0.27 % U_3O_8) of Heathgate Resources. The Frome Embayment has been a major focus for uranium exploration in South Australia, with the Honeymoon deposit now under construction (Uranium One; 1.2 Mt @ 0.24 % U_3O_8), and Four Mile in the development stages (Quasar Resources-Alliance Resources; 3.9 Mt @ 0.37 % U_3O_8). Other major uranium projects in the region include Oban, Goulds Dam and Crocker Well.

Following on from the success of the collaborative drilling program, the Geological Survey of South Australia has initiated its own drilling campaign targeting the underexplored northern Gawler Craton. The collaborative program is supported by PACE funding, an ARC Linkage with Monash University and University of Adelaide, and also has a geothermal component through Geoscience Australia. The drilling is targeting the Proterozoic basement rocks along the Gawler-Officer-Musgrave-Amadeus seismic line (GOMA). The drilling results will provide new insights into the geology of this region and help provide new insights for exploration.

The Geological Survey of South Australia also has had a major focus in the Curnamona Province through PACE geoscience initiatives. A new Report Book, released at BHEI 2009, reviews the exploration and mineral systems of the Curnamona Province. Our geological understanding of the region also has been advanced through mapping and geoscientific studies of the southern Curnamona Province, including refinement and definition of stratigraphy in the Olary Domain, presentation of a new stratigraphic, lithological and regolith map of the Mingary 1:100 000 sheet, and geophysical definition of the boundary between the Olary and Broken Hill Domains. In addition, new Explanatory Notes will be released for the Callabonna 1:250 000 map sheet. Another important new development in South Australia is the establishment of a HyLoggerTM instrument at the Glenside Core Library in Adelaide funded through the Australian Government's National Collaborative Research Infrastructure Strategy via AuScope. This instrument has the potential to map regional- to deposit-scale alteration systems through analysis of archived and company drill core and new results will be presented on the Curnamona Province through collaboration between the Geological Surveys of NSW and SA.

Another important initiative that PACE has delivered is the Centre for Exploration Undercover at the University of Adelaide. Targeted funding by PACE, and the establishment of a critical mass of researchers, combined with extensive industry support, has now resulted in the award of the Deep Exploration Technologies Cooperative Research Centre, to be headquartered at the University of Adelaide. The ongoing collaboration between the survey and the University of Adelaide includes a wide range of important research projects, which are addressing tectonic linkages between the Curnamona Province and the Gawler Craton, the uranium cycle from Proterozoic basement to cover and analysis of the biogeochemical expression of uranium. Other collaborative activity includes work with Geoscience Australia, particularly through interpretation of the deep seismic lines in the Curnamona-Gawler regions, a new magnetotelluric survey of the Curnamona-Gawler seismic link line, and a potential airborne electromagnetic (AEM) survey of the Frome Embayment.

Two other new developments within the PACE program includes PACE Geochronology and the Geoscientist Assistant Program (GAP). PACE Geochronology is providing the opportunity for industry to date mineral systems in South Australia and, in a similar manner to the PACE drilling program, will be assessed on a merit basis through formal submissions. The GAP initiative is being coordinated by the South Australian Chamber of Mines and Energy, and is providing \$750K for short term contracts with industry and the survey, to enable geoscientists to keep employed, and maintain the skills base in South Australia, during the economic downturn.

Geoscience Australia

Work by Geoscience Australia within the region covered the Broken Hill Exploration Initiative is carried out within the Onshore Energy Security Program (OESP), which will deliver reliable, precompetitive geoscience data and scientifically-based assessments of the potential for onshore energy resources, including oil, gas, hot rocks (geothermal energy), uranium and thorium. The Program is scheduled to finish in mid 2011, and is designed to significantly boost investment in exploration for onshore energy resources, to assist in securing a sustainable energy supply for Australia's future. The Onshore Energy and Minerals Division is implementing the OESP, in consultation with the State and Northern Territory Geological Surveys and peak minerals and petroleum industry bodies. Projects under the OESP have both a national and a regional focus.

National Focus

A major output of the OESP, the Radiometric Map of Australia, was released in February 2009. The processed radiometric data from the Australian Wide Airborne Geophysical Survey (AWAGS) define the Australian Radioelement Datum and are used to adjust existing Australian, State and Territory public domain data in the National Radiometric Database, including pre-existing data from the greater Curnamona region. The survey also serves as the base for radiometric data to be acquired in future decades. The processed magnetic data will be used to improve the frequency content of the Australian Magnetic Anomaly Map and will be incorporated into continental-scale data sets. The data fill the gap between wavelengths of about 100 km from airborne surveys and wavelengths greater than 400 km from satellites. The data will assist with the assessment of uranium and thorium potential across the continent and with regional heat flow studies aimed at identifying geothermal energy resources.

The National Geochemical Survey of Australia aims to provide a nation-wide, internally-consistent and state-of-the-art dataset on the geochemical composition of surface and near-surface materials in Australia. Samples collected within the region covered by the BHEI will form part of the national dataset, which is expected to contribute precompetitive knowledge towards more effective exploration for energy and minerals resources.

Work in GA on geothermal energy aims to increase understanding of the type and location of geothermal energy resources on a national scale, and to encourage exploration for, and investment in, this type of renewable energy. The multi-faceted work program is broadly aimed at compiling a single dataset, using existing data, to identify high heat producing granites, and to acquire new data to better understand the distribution of temperature in the continent's upper crust. New heat flow data will be collected within the Curnamona Province, to further contribute to our understanding of this high-heat flow region.

Work on uranium mineral systems within the OESP aims to map the distribution of known uranium enrichment and related rocks across Australia, develop a new understanding of the processes which control where and how uranium mineral systems develop, and assess the potential for undiscovered uranium mineralisation at regional to national scales. On the regional scale, a mineral systems approach to understanding the sedimentary-hosted uranium deposits in the Frome Embayment, and its uranium prospectivity, is in progress.

A study on thorium, completed in 2008, established the extent of known thorium resources in Australia, and described the geochemical environments in which thorium occurs in Australia. In view of ongoing interest from the government, energy and minerals industry and members of the public in thorium, as a possible source of fuel for nuclear reactors, Geoscience Australia is maintaining a watching brief on overseas developments in thorium reactors.

Focus in Curnamona Region

Within the BHEI region, the main focus of the OESP work is in the development of an understanding of the geodynamic setting of the region, leading to an assessment of its energy systems potential. This work currently is in progress.

The main focus in understanding geodynamics is through the acquisition, processing, interpretation and release of new deep seismic reflection and magnetotelluric data. To this end, 262 km of deep seismic reflection and magnetotelluric data were collected in 2008 along a north-south traverse across the Benagerie Ridge in South Australia. Related studies include SHRIMP geochronology on samples from the Mount Painter Inlier to test the geodynamic evolution of this part of the Curnamona Province with the Olary and Broken Hill Domains further to the south. Drillcore from key drillholes near the seismic line have been sampled for petrological, geochemical and geochronological studies, to provide further constraints on the interpretation of the seismic traverse.

The geodynamic setting for the Curnamona Province will be reported through a time-space framework, and reports and predictive map products on the geothermal and uranium potential of the region also will be developed.

Airborne electromagnetics (AEM) data have been acquired in areas considered to have potential for uranium and thorium mineralisation, with the focus being on geological architectures indicative of unconformity-related and paleochannel-hosted uranium potential. To date, regional-scale datasets have been acquired in the Paterson Province in Western Australia (WA) and the Pine Creek Province in the Northern Territory (NT). A third dataset may be acquired in the Frome Embayment and the northwest Murray Basin region in South Australia (SA), subject to funding being available.

Acknowledgements

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The Forgotten Hawsons Iron Prospect: Is there significant magnetite iron-ore mineralisation in the Neoproterozoic at Broken Hill?

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Location and Regional Setting

The Hawsons Iron Prospect is located approximately 60 km southwest of Broken Hill (NSW) within two contiguous Exploration Licences (EL) granted to Carpentaria Exploration Limited (Carpentaria) and Perilya Resources Broken Hill Limited. EL 7208 is 100% owned by Carpentaria, whereas EL 6979 is under a joint venture agreement with Perilya. Carpentaria manages exploration at the prospect.

The prospect lies over folded Neoproterozoic sedimentary rocks of the Nackara Arc of the Adelaide Fold Belt, and is situated just outside the extent of the peerless 1:25 000 scale Broken Hill geological fact mapping by the Geological Survey of New South Wales (GSNSW). The most recent published coverage is the Menindee 1:250 000 Geological Sheet (Rose, 1967), which assigns the area to the Upper Proterozoic, possibly the Torrowangee Group.

Regional relationships convincingly demonstrate that the Neoproterozoic rocks exposed at the Hawsons Prospect are part of the Yudnamutana Subgroup (Umberatana Group) which contains diamictitic siltstone (tillite), quartz sandstone, calcareous siltstone, dolomite and magnetic ironstone units of the Braemar Iron Formation. The Braemar ironstones are examples of glaciomarine Raptian-Sturtian sedimentary iron-formation type, which has a world-wide occurrence in the Neoproterozoic (Klein and Beukes, 1993; Lottermoser and Ashley, 2000).

In regional aeromagnetic data, the Hawsons Prospect show up as a pronounced, large, curvilinear, high amplitude, magnetic anomaly, interpreted to be a regional scale fold of magnetite-rich Braemar Iron Formation. The exposed geology at the prospect is also distinctive in satellite imagery and aerial photography.

Exploration History and Target Rationale

The Hawsons Prospect area has only attracted modest prior mineral exploration activity, possibly due to its location within less interesting Neoproterozoic rocks adjacent to the famously base-metal mineralised, and heavily targeted, Willyama Supergroup.

Small pits and a shallow shaft, sunk on a prominent pisolitic ferricrete exposure, are evidence of early (probably late 19th century) prospecting activity in the Hawsons Prospect area.

Interestingly, the first significant recorded modern exploration at Hawsons Prospect was for high-grade iron ore in 1960. Enterprise Metals (the exploration arm of Consolidated Zinc, that evolved into CRAE, and is now part of Rio Tinto) completed detailed geological mapping, surface rock geochemistry and vertical component ground magnetometry to investigate the iron ore potential of the area (McManus, 1960).

Enterprise outlined a number of track-like exposures of Neoproterozoic magnetite ironstone (\pm hematite), with a maximum iron concentration result of six metres at 49.1% Fe, from a cross-strike channel sample. Associated with the magnetite ironstone exposures were broader, denuded mesas of limonite-goethite regolith. They concluded the Hawsons area had little potential for the type of iron ore they were seeking, which, in this era, was giant high-grade, direct-shipping, hematite deposits. In 1962, Enterprise ultimately discovered one of the world's major, high-grade, hematite iron-ore deposits in Western Australia at Mount Tom Price (initial resource ~900 Mt @ 64.0% Fe), which spawned development of the vast Hamersley direct-shipping, hematite iron-ore mining province – one of Australia's natural resource jewels. In this context, it is not surprising that the magnetite ironstone occurrences at Hawsons faded from the published record and the consciousness of explorers. A measure of how the Hawsons locality has been forgotten is that the magnetite ironstone exposures and prospecting pits are not recorded in the Geological Survey of New South Wales metallic mineral occurrence (METMIN) database, or in other recently published mineral occurrence compendiums (e.g. Brownlow et al., 2007).

In South Australia (SA), the Braemar Iron Formation is better known, and the SA Department of Mines and Energy (SADME) completed extensive iron ore exploration in the late 1960's at Razorback Ridge, located approximately 150 km west of Hawsons (Whitten, 1970). A near-surface resource of Braemar Iron Formation of 120 Mt @ 26% Fe was informally estimated at Razorback Ridge, but metallurgical test work was unfavourable, and under the economic standards of the time the resource was discounted as a potential source of iron ore.

Following completion of high-resolution airborne magnetic surveys in the Broken Hill district commencing in the 1980's, the fold-like, high-amplitude magnetic features at the Hawsons Prospect attracted several explorers, including CRAE (now Rio Tinto) and Placer (now Barrick), specifically seeking precious and base metal mineralisation.

CRAE completed considerable work, including drilling five holes seeking gold mineralisation in a second-order linear magnetic low, interpreted to be a concealed faulted iron formation within the hinge of the curvilinear Hawsons aeromagnetic anomaly (Rheinberger, 1989). CRAE's program failed to locate significant gold or base metal mineralisation, but drilling intersected relatively broad magnetite ironstone units, interbedded with diamictite adjacent to the then untested peak of the highest amplitude segment of the Hawsons aeromagnetic anomaly.

In the 1990's, Placer completed a cored drill-hole testing for iron oxide copper gold (IOCG) mineralisation on a separate, recent cover-buried, high-amplitude, aeromagnetic anomaly (Wonga Anomaly), located 6 km to the southeast of the peak amplitude of the Hawsons aeromagnetic anomaly. The drill-hole intersected a substantial thickness of sulfide-barren, magnetite siltstone that was not geochemically analysed, but reported magnetic susceptibilities averaging over $20,000 \times 10^{-5}$ SI units for intervals up to 10 m (Hoskins, 1993).

Carpentaria, after initially entering the Broken Hill district with an interest in base and precious metal discovery, recognised that the ironstone exposures and associated large aeromagnetic anomaly at Hawsons had potential for bulk tonnage magnetite mineralisation. Therefore, a work program directed to magnetite iron-ore exploration commenced in early 2009, which to date has consisted of aeromagnetic data modelling, detailed GPS controlled geological mapping, surface hand-held Niton XRF rock geochemical surveying, surface magnetic susceptibility measurements, petrographic analysis and reconnaissance reverse circulation (RC) drilling.

Aeromagnetic Character and Modelling

The entire Hawsons Prospect was covered by a 100 m line spacing, 60 m terrain clearance, aeromagnetic survey flown by Geoscience Australia in 1995. The Hawsons Prospect is dominated by a high-amplitude curvilinear anomaly, located within a 140 km, northeast-trending geophysical belt containing similar anomalies which characterise the Nackara Arc of the Adelaide Fold Belt (Figure 1). The curvilinear aeromagnetic anomalies in this belt are up to 400 m wide and have amplitudes of 3,000 to 7,000 nanoTeslas (nT) above background.

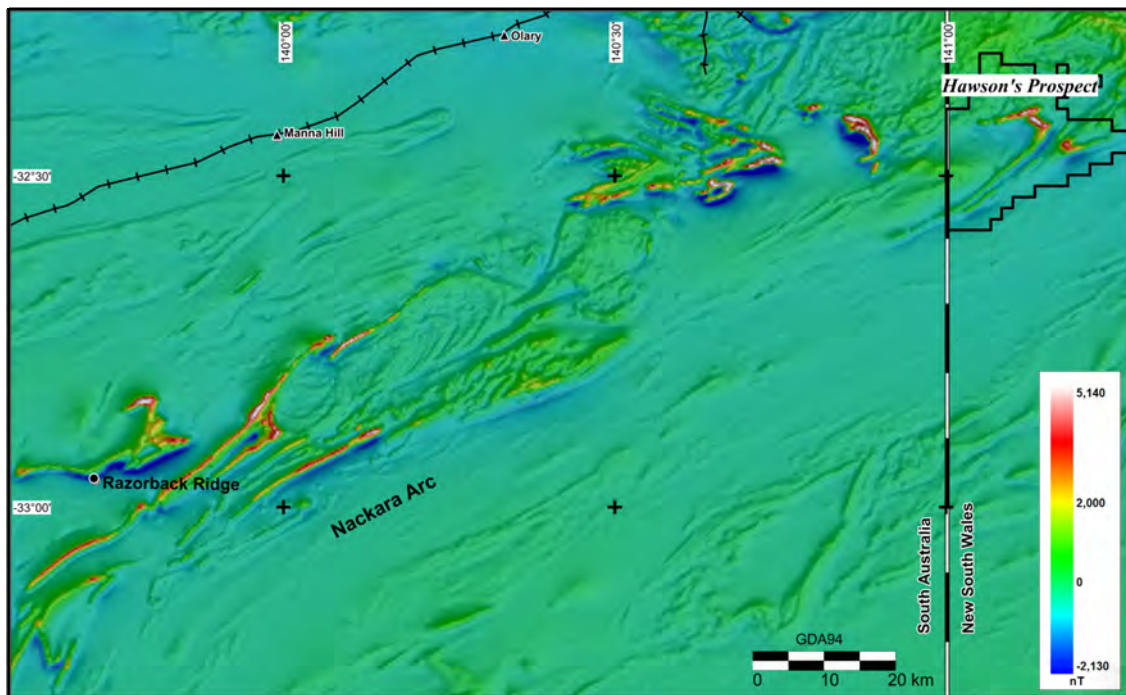


Figure 1. Regional aeromagnetic image and location of Hawsons Iron Prospect

The Hawsons aeromagnetic anomaly is a segmented, hook shaped feature with a southwest trending long axis interpreted to be a regional-scale, plunging and faulted fold (Figure 2). The Hawsons anomaly is up to 8 km across and has a southeast limb approximately 30 km long (traversing in to SA), and a northwest limb 9 km long. The northwest limb is a relatively broad magnetic ridge, with an amplitude peak of approximately 6000 nT, twice that of the southeast limb. The northwest limb is separated from the hinge zone of the Hawsons anomaly by a linear break, interpreted to be a fault or shear. The hinge or core zone of the Hawsons anomaly is a 2.5 x 1.5 km, roughly elliptical shaped feature with the highest magnetic amplitude (+6000 nT) of the entire Hawsons anomaly. This core magnetic anomaly is concealed by post-mineral cover, and is interpreted as a regional fold hinge, where thicker and higher magnetite content ironstone units than those currently known at surface could be present. The core aeromagnetic anomaly has been the priority exploration target recently investigated by Carpentaria.

Three-dimensional magnetic-susceptibility modelling of aeromagnetic data over the core anomaly, using the MAG3D software from the University of British Columbia (UBC), determined that the anomaly could be sourced by an irregular, flattened ellipsoidal body, 2400 m long by 800 m thick and more than 1000 m deep, dipping approximately 60° to the southwest, which is buried under 80 to 100 m of nonmagnetic cover. Figure 3 is a $30\,000 \times 10^{-5}$ (0.3) SI magnetic susceptibility isosurface from the 3D modelling of the Hawsons core anomaly.

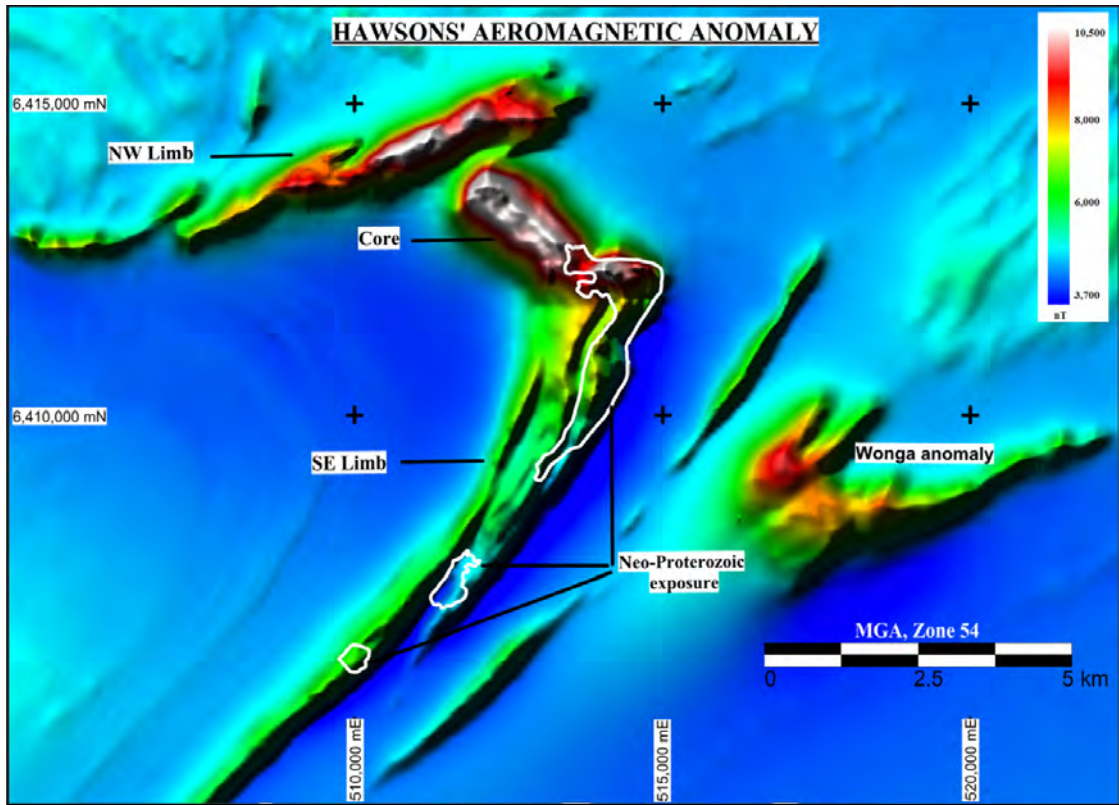


Figure 2. Hawsons total magnetic intensity (TMI) aeromagnetic image and limits of exposure

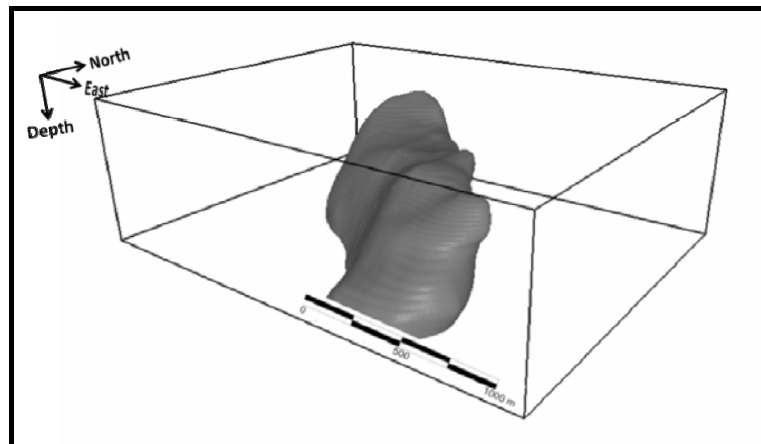


Figure 3. Schematic of 0.3 SI magnetic susceptibility isosurface of the Hawsons core anomaly.

Prospect Geology

Exposure is limited to a window of folded, greenschist-metamorphosed, Neoproterozoic strata located on the southeast limb of the Hawsons aeromagnetic anomaly (Figure 2). An irregularly exposed succession of steep, west-northwest to south-dipping strata, which kinks in strike about

a fold structure in the northern part of the exposure window, is present at the prospect (Figure 4).

From the structural base of the Neoproterozoic succession at the prospect, orthoquartzite is overlain by interbedded magnetite-hematite ironstone, siltstone-shale and rare carbonate units. Siltstone is recessive, but where exposed is a cleaved grey to green mica- or chlorite-bearing, quartz-rich rock. Regionally, this type of siltstone is often diamictite that contains granitic erratics and interbedded carbonate units. Although erratics were not noted in any of the siltstone exposures mapped at the Hawsons Prospect, core from historical CRAE drillholes, located close to the exposure window, contains siltstone matrix diamictite with angular granitic erratics. Ironstone units are numerous and form protruding, track-like exposures up to 10 m wide, many hundreds of metres long interbedded with recessive siltstone. The ironstone units are composed of generally dark grey to black; fine-grained, diffusely laminated magnetite and, less commonly, specular hematite-rich rocks. Differentiated quartz and silicate rich bands are rare within mapped ironstones. The number and thickness of ironstone units increase up section and northward along strike until obscured by younger ferruginous duricrust and recent sheet wash/aeolian sand (Figure 4).

The Neoproterozoic exposures display two penetrative fabrics and infrequent mesoscopic parasitic folds, with a later, cross-cutting, non-penetrative axial plane cleavage. The early crenulated foliation is best developed in hematitic ironstone, and is occasionally observable in magnetite ironstone. The later mesoscopic fold-related, spaced cleavage is most evident in recessive siltstone. The mesoscopic folds are tight to open and plunge to the southwest at moderate to steep angles. Mesoscopic fold geometry and stereographic analysis of bedding orientations demonstrate the regional curvilinear Hawsons magnetic anomaly is a southwest-plunging synform (Figure 4).

Several large areas of an incompletely-stripped, well-developed, ferricrete duricrust/regolith surface of probable Cenozoic age, overlain by recent unconsolidated sheet-wash and aeolian sands, are a feature of the Hawsons Prospect.

The ferricrete duricrust forms rounded mesas or mounds that display a well-cemented cap of pisolitic goethite-limonite, with an apron of less well-cemented, coarse, angular ironstone saprock fragments. There are rare small exposures of foliated, iron-rich saprock interpreted to be highly weathered in-situ Neoproterozoic ironstone remnants within the ferruginous regolith. Ferruginous regolith and recent sandy cover entirely obscure the amplitude peaks of the Hawsons aeromagnetic anomaly. It is speculated that the ferruginous regolith has been developed preferentially and preserved over thicker and potentially higher magnetite content, Neoproterozoic ironstone units responsible for the peak amplitudes within the Hawsons aeromagnetic anomaly.

Surface Rock Geochemistry and Magnetic Susceptibility

A surface rock geochemical and magnetic susceptibility survey using a handheld Niton XL3t, XRF microanalyser and Geoinstruments JH-8 meter, respectively, was completed to investigate the distribution and tenor of iron and magnetite in both Neoproterozoic ironstone and probable Cenozoic ferricrete exposed at the prospect. Analysis of a small number of control samples via conventional laboratory geochemical methods was also completed.

Magnetic susceptibility of ferricrete is low, whilst exposed Neoproterozoic ironstone has variable, but generally elevated, susceptibilities, with a maximum determination of $60,000 \times 10^{-5}$ SI units. Correlation between magnetic susceptibility and Niton XRF-determined, iron concentrations is variable, due to the combination of magnetic and nonmagnetic iron minerals present in the surface exposures. High magnetic susceptibility ironstones, however, display some of the highest Niton XRF determined iron concentrations.

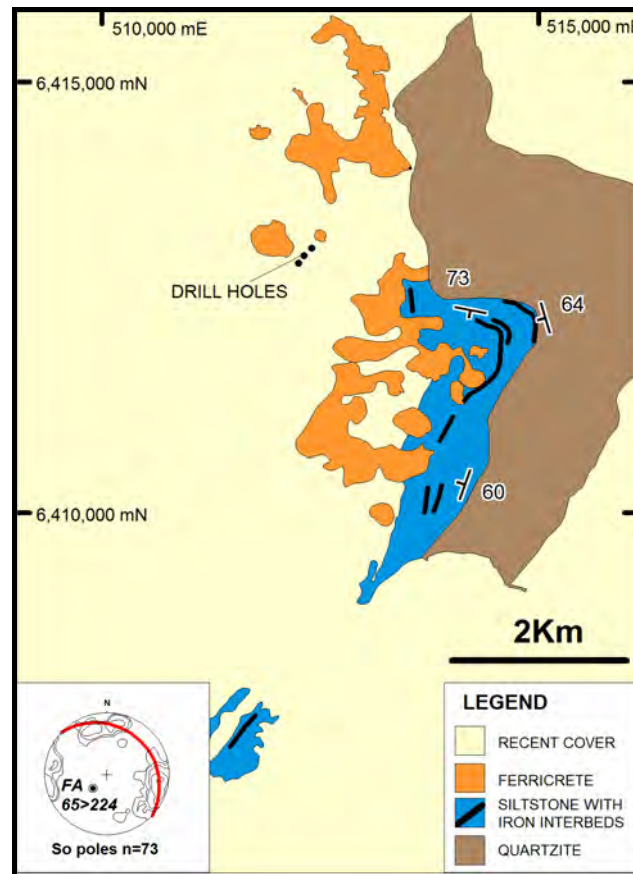


Figure 4. Hawsons Iron Prospect - simplified geology and bedding pole stereonet plot (GDA94 Zone54)

In situ Niton XRF determinations at 90 ferricrete exposure sites averaged 36.7% Fe, with a maximum value of 53.8% Fe. There is no discernable pattern of iron concentrations within ferricrete, although the most prominent ferricrete exposures are located over the amplitude peaks of the Hawsons aeromagnetic anomaly.

In situ Niton XRF determinations at 146 Neoproterozoic ironstone sites averaged 34.9% Fe with a maximum value of 51.9% Fe. The average iron concentration of Neoproterozoic ironstone is similar to ferricrete, suggesting that no large-scale surface enrichment of iron has occurred at the prospect. Unlike ferricrete, iron distribution in the Neoproterozoic ironstone exposures displays a roughly defined pattern of increasing iron concentrations northwards along strike, towards the cover-concealed peak amplitude core of the Hawsons aeromagnetic anomaly.

Conventional laboratory-analysed samples confirmed that the precision and accuracy of the Niton XRF analyses were within acceptable limits. The laboratory samples provided information on additional chemical elements not determined via the Niton, and showed that concentrations of elements deleterious to potential iron ore including Al, P, Mn, and S within the Neoproterozoic ironstone were relatively low (Table 1). In addition, preliminary orientation Davis Tube Recovery (DTR) on two ironstone samples returned magnetic concentrates with very high iron grades, essentially free of deleterious elements (Table 2).

Table 1. Example Laboratory (ICP) Analyses of Hawsons Prospect Ironstone.

Sample	MGAE-Zone 54	MGAN-Zone 54	Rock Type	Mag. Sus. SI X10 ⁻⁵	Fe%	P%	Al%	Ti%	Mn %	S%	Ca%	K%
CAP3120	512915	6415052	magnetite (martitised) ironstone	30,000	48.2	0.138	2.29	0.08	0.031	0.06	0.23	0.07
CAP3140	514539	6411658	magnetite-hematite ironstone	15,000	57.3	0.066	0.67	0.07	0.011	0.06	0.11	0.21
CAP3143	514540	6412096	magnetite-hematite ironstone	20,000	47.5	0.112	0.76	0.07	0.016	0.01	0.25	0.23

Table 2. Example of preliminary Davis Tube Recovery (DTR) Analysis of Hawsons Prospect Ironstone.

Sample	DTR - 38 micron % Weight Magnetic Fraction Recovery	DTR Con. Fe%	DTR Con. SiO ₂	DTR Con. Al ₂ O ₃	DTR Con. TiO ₂ %	DTR Con. P%	DTR Con. S%	DTR Con. As%	DTR Con. Cu%	DTR Con. Mn%
CAP3143	21.64	71.7	0.49	0.09	<0.01	0.008	0.005	<0.001	0.005	0.021

Clearly, the surface iron concentrations present at the prospect are well below those required for unbeneficiated, direct-shipping, high-grade iron ore. However, the prevalence of magnetite, moderately high bulk-rock iron concentrations, and low deleterious element content of the Neoproterozoic ironstone exposures at Hawsons, are guides to the potential of the prospect for low-grade, magnetite mineralisation suitable for ore beneficiation.

Whilst the mapped ironstone exposures at the Hawsons Prospect are modest in size, the observation that the number, thickness, and iron concentration of ironstone units increase towards the large concealed core of the Hawsons aeromagnetic anomaly, highlight this feature as a magnetite iron-ore exploration target with bulk tonnage potential.

Ironstone Petrography

A small number of samples were taken from various Neoproterozoic ironstone exposures across the prospect for polished thin-sectioning and petrographic examination.

The samples revealed that there are two basic types of quartz-biotite±chlorite ironstones present at the Hawsons Prospect: magnetite-dominant and magnetite plus primary hematite-bearing.

Magnetite-dominant ironstone contains abundant blocky subhedral to euhedral magnetite grains in the 25 to 150 micron grainsize range (Figure 5). Magnetite is generally inclusion free, and dispersed to weakly-banded within a simple quartz-biotite±chlorite silicate matrix of similar grain size. Texture is granoblastic to weakly lepidoblastic, with biotite and/or chlorite forming an irregular schistosity. Biotite predominates, and chlorite mostly replaces biotite and is therefore likely retrogressive. There are very few other minerals present. Biotite stability implies upper greenschist facies, regional metamorphic conditions, potentially slightly higher grade than the dominantly chlorite-bearing assemblages reported from similar ironstones at Razorback Ridge in South Australia (Whitten, 1970). In all samples, magnetite is extensively, but irregularly, pseudomorphed by martite (hematite), which is interpreted to be the result of surface oxidation.

Magnetite-primary hematite ironstone samples contain both blocky magnetite (martitised) and plate-like or micaceous hematite (Figure 6). Hematite is always significantly finer-grained, and

more irregular in shape, than associated magnetite. Silicates present are the same as those in the magnetite dominant ironstones, and there is a diffuse differentiation into micaceous hematite, and silicate mineral bands. In all, the magnetite-primary hematite ironstone samples, hematite forms a distinct crenulated schistosity, which both wraps around, and is truncated by, the coarser (+100 micron), porphyroblastic magnetite grains.

These petrographic observations suggest that the type of ironstone at Hawsons is potentially satisfactory for consideration as a low-grade magnetite iron-ore suitable for beneficiation, if very large tonnages of easily accessible material are available.



Figure 5. CAP3120 reflected light photomicrograph showing subhedral martitised magnetite and quartz-biotite matrix. Scale-bar 100 microns.



Figure 6. CAP3143 higher magnification reflected light photomicrograph showing crenulated micaceous hematite and martitised magnetite porphyroblasts. Scale-bar 100 microns.

Reconnaissance Drilling

A single fence of three, angled, reverse-circulation percussion (RC) drillholes, with an aggregate length of 606 m, was completed across a selected part of the core zone of the Hawsons aeromagnetic anomaly during July 2009 (Figures 7, 8). Figure 7 shows a cross section with Niton XRF percent iron determinations plotted as a line graph, and Figure 8 shows a geological section interpreted from the drill data.

The drillholes intersected thin recent 'soil' on a variable thickness of puggy clay-rich alluvial sediments incised into residual saprolite that is up to 70 m thick. The depth to base of oxidation encountered in all holes was approximately 80 m vertically below the surface.

The unoxidised, Neoproterozoic geology intersected, consisted of a monotonous succession of massive to laminated green-grey to black, foliated, magnetite rich, quartz-biotite-chlorite siltstone. Lesser schistose, specular hematite-dominant units were also intersected. The relative lithological homogeneity, and absence of markers, makes geological correlation between chip sample drillholes difficult. Preliminary Niton XRF analyses of the drill chips, however, define a distinctive pattern of downhole iron concentrations able to be correlated between the holes. The chemical correlation shows that the succession has an apparent dip of approximately 45° to the southwest, which is consistent with field structural measurements and geophysical modelling of the Hawsons magnetic data.

At the time of writing, laboratory Davis Tube Recovery (DTR) magnetite content, DTR concentrate and bulk geochemical analyses of drill chips are awaited. However, on the basis of geological logging, magnetite susceptibility measurements, and preliminary uncontrolled Niton-XRF analyses, there are a number of relatively closely-spaced, magnetite-bearing units, in the order of 10 to 40 m thick, present in the drilled section (Figure 8). These drill-intersected,

magnetite-bearing units have the potential, pending laboratory results, to be candidates for low-grade magnetite ironstone mineralisation. Furthermore, if sufficient magnetite grade can be achieved, the thickness of the drill-intersected units and modelled dimensions of the core aeromagnetic anomaly suggests a large tonnage of similar material is potentially available.

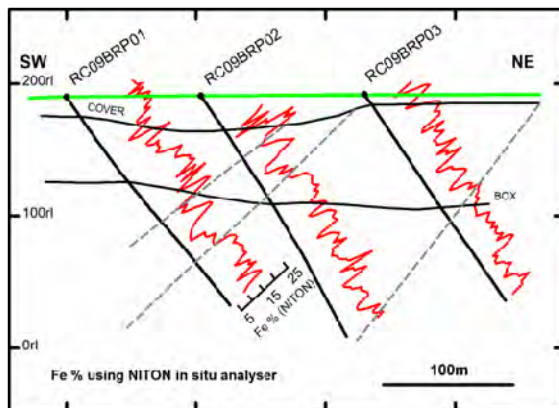


Figure 7. Drill Section with Niton Fe% line graph

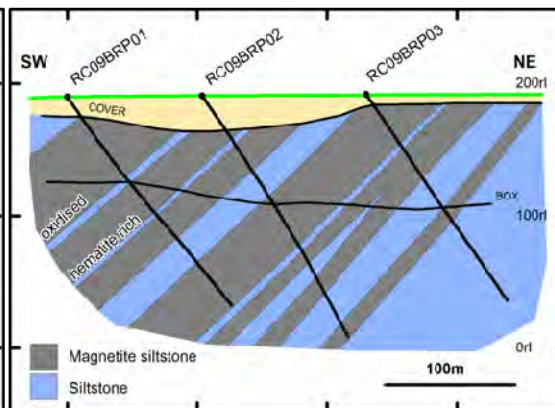


Figure 8. Interpreted Geological Section

Conclusions

The Hawsons Iron Prospect is situated within Neoproterozoic rocks of the Nackara Arc, Adelaide Fold Belt, approximately 60 km south-southwest of Broken Hill. The prospect was explored for iron ore in 1960 and then, not surprisingly, forgotten after the early 1960's resource discoveries and development of the giant, high-grade Hamersley iron-ore mining province.

The Hawsons Iron Prospect displays an outcrop window with numerous relatively narrow, strike extensive exposures of magnetite ironstone of the Braemar Iron Formation, situated on the southeast limb of a regional-scale, plunging, fold-like, high-amplitude, aeromagnetic anomaly. The highest amplitude hinge segment, or core, of the Hawsons aeromagnetic anomaly is adjacent to the outcrop window, but otherwise is completely concealed by transported ferricrete and other younger cover.

Detailed surface exploration by Carpentaria indicates that the number, thickness, and iron concentration of ironstone exposures increases towards the high amplitude core of the Hawsons magnetic anomaly. Petrographic observations show that the exposed ironstone lithology at Hawsons has potential for low-grade magnetite iron-ore mineralisation suitable for beneficiation, if very large quantities are available.

Reconnaissance drilling of the core aeromagnetic anomaly has just been completed, and laboratory grade analyses were not available at the time of writing. The drilling intersected a 45° southwest-dipping siltstone succession, containing several, relatively closely-spaced, magnetite-bearing, ironstone units, each in the order of 10 to 40 m thick. If sufficient magnetite grades are achieved in the laboratory analyses, the thickness of the drill-intersected units, and modelled dimensions of the core aeromagnetic anomaly, implies a large tonnage of similar material is potentially available.

Exploration at the Hawsons Iron Prospect is at a very early stage, and receipt of laboratory analyses from the reconnaissance drilling will assist in answering the question of whether potentially significant magnetite mineralisation is present at this locality. Regardless of these laboratory analyses, further testing of the various target components of the very large Hawsons Prospect and other adjacent aeromagnetic anomalies, coupled with metallurgical and

engineering investigations will be required to determine if this locality could become New South Wales' largest, low-grade magnetite iron occurrence, and be forgotten no longer.

Acknowledgments

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Stratigraphic, magmatic and tectonic evolution of the southern Curnamona Province

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Separated from the western Gawler Craton by the Kalinjala Shear Zone is the ~1750 Ma Wallaroo Group and, further to the east, the sedimentologically and magmatically similar, but younger, ~1720-1640 Ma Willyama Supergroup of the Curnamona Province. The easterly younging sedimentation implies basin migration to the east; thus rollback of an oceanic slab further to the east is suggested as the cause of crustal attenuation, and hence backarc basin formation.

The development of a lithostratigraphic scheme for the Willyama Supergroup of the Olary region has, since the time of Mawson (1912), been an ongoing process. Over the years there have been several contributors affiliated with the South Australian Geological Survey (e.g. Campana and King, 1953; Forbes and Pitt, 1980; Forbes, 1991; Flint and Parker, 1993; Laing, 1996a; Flint, 2001; Conor 2000a, 2000b, 2006a), as well as universities (e.g. Talbot, 1967; Clarke et al., 1986; Grady et al., 1989; Ashley et al., 1997), and mineral exploration companies (e.g. Cotton, 1980). In recent years, understanding has been greatly improved via the BHEI program, especially with the application of isotopic studies of high precision (e.g. Ashley et al., 1996; Teale, 2000), and stratigraphic correlations with the northeastern Australian Pb-Zn belt (Page et al., 2005) and central Australia (Barovich and Hand, 2008), has been demonstrated. The scheme shown here (Figure 1) has combined stratigraphic elements of previous versions with more recent field observations; geochronology has allowed the incorporation of the critical dimension of time, so that now confidence has been significantly improved in benchmarking Olary stratigraphy against the long-standing and robust scheme for the Broken Hill Domain devised by the Geological Survey of New South Wales (Stevens et al., 1988).

The present scheme (Figure 1) varies little from that published by Conor (2006a) and Conor and Preiss (2008) (for details of this variation see Appendix 1); both references show not only similarities between the Olary and Broken Hill Domains (Figure 2), but also that, whereas the oldest rocks are preserved in the Olary Domain, subsequent sedimentation in the Broken Hill Domain was more continuous. The evidence for relatively continuous deposition in the Broken Hill Domain and sporadic deposition in the Olary Domain supports the notion that the southern Curnamona Province preserves parts of a late Palaeoproterozoic rift system (Willis et al. 1983; Laing, 1996b). Integration of elements of litho- and chronostratigraphy with magmatism provides a sound basis for discussion of the tectonic evolution of the southern Curnamona Province.

The 1718-1711 Ma A-type felsic magmatism of the Basso Suite, that characterises the Curnamona Group (the oldest known rocks of the Willyama Supergroup), suggests mantle connectivity and hence crustal attenuation. Age data derived from volcanic units in the Curnamona Group are essentially within error, thus implying rapid sedimentation. This is supported by mafic volcanism in the Weekeroo Inliers, and evidence provided by the ~1718 Ma George Mine and Tommie Wattie formations for the development of second- or third-order rifted

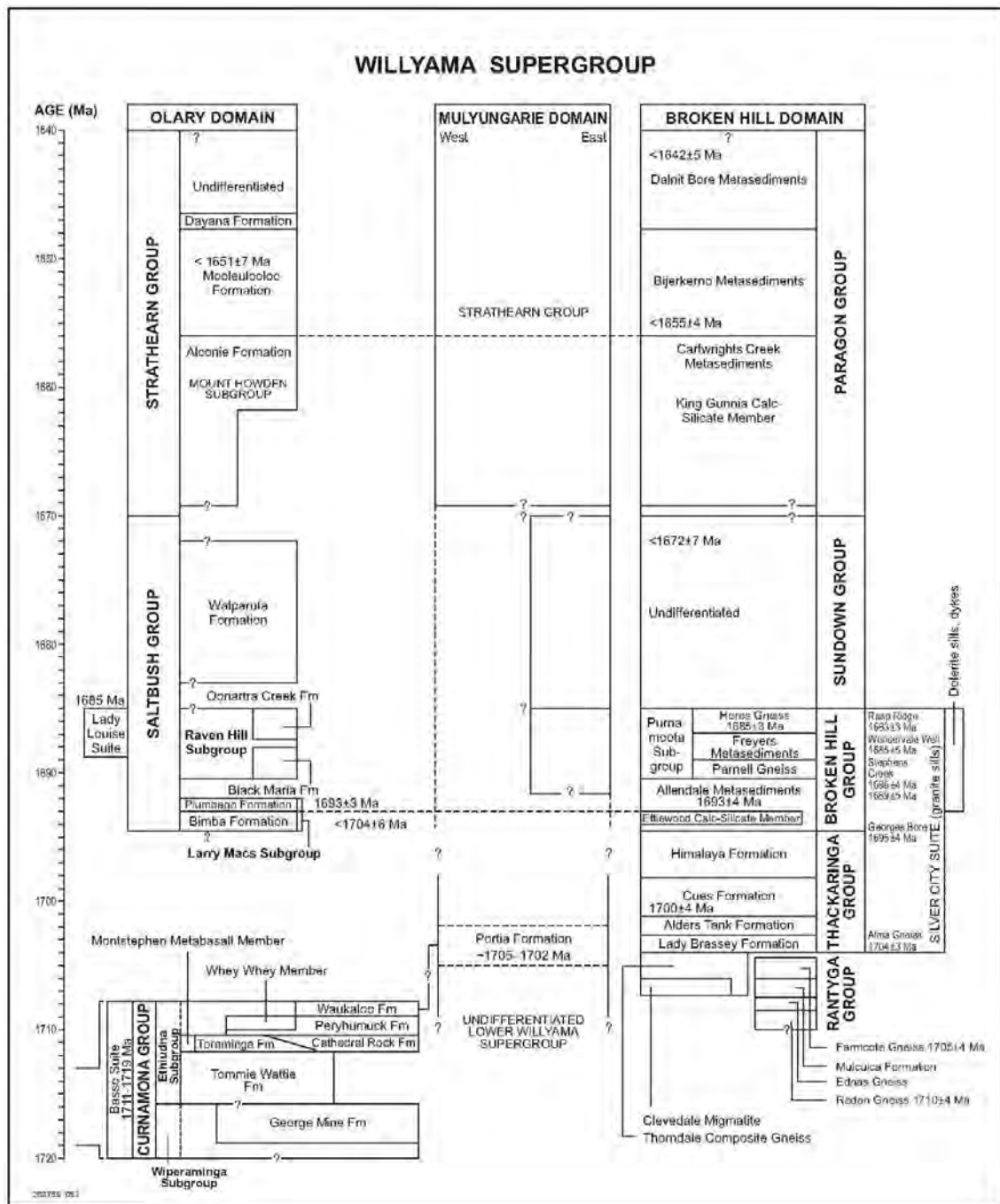


Figure 1. Lithostratigraphy of the Olary Domain, compared with the Mulyungarie and Broken Hill Domains

basins (Conor, 2006b; Conor and Preiss, 2008). Indicators of shallow water sedimentation and evaporite deposition (Cook and Ashley, 1992), in the thin, 1715 Ma Peryhumuck Formation, provides evidence of emergence in the Olary Domain, but to the east in the Broken Hill region, similar sedimentation in the Redan Domain is much thicker. Although the units are of slightly different age, the variation in thickness between the Peryhumuck Formation and the Redan Gneiss provides the first evidence for the Broken Hill region being proximal to the rift decollement, with Olary being part of the distal western shelf.

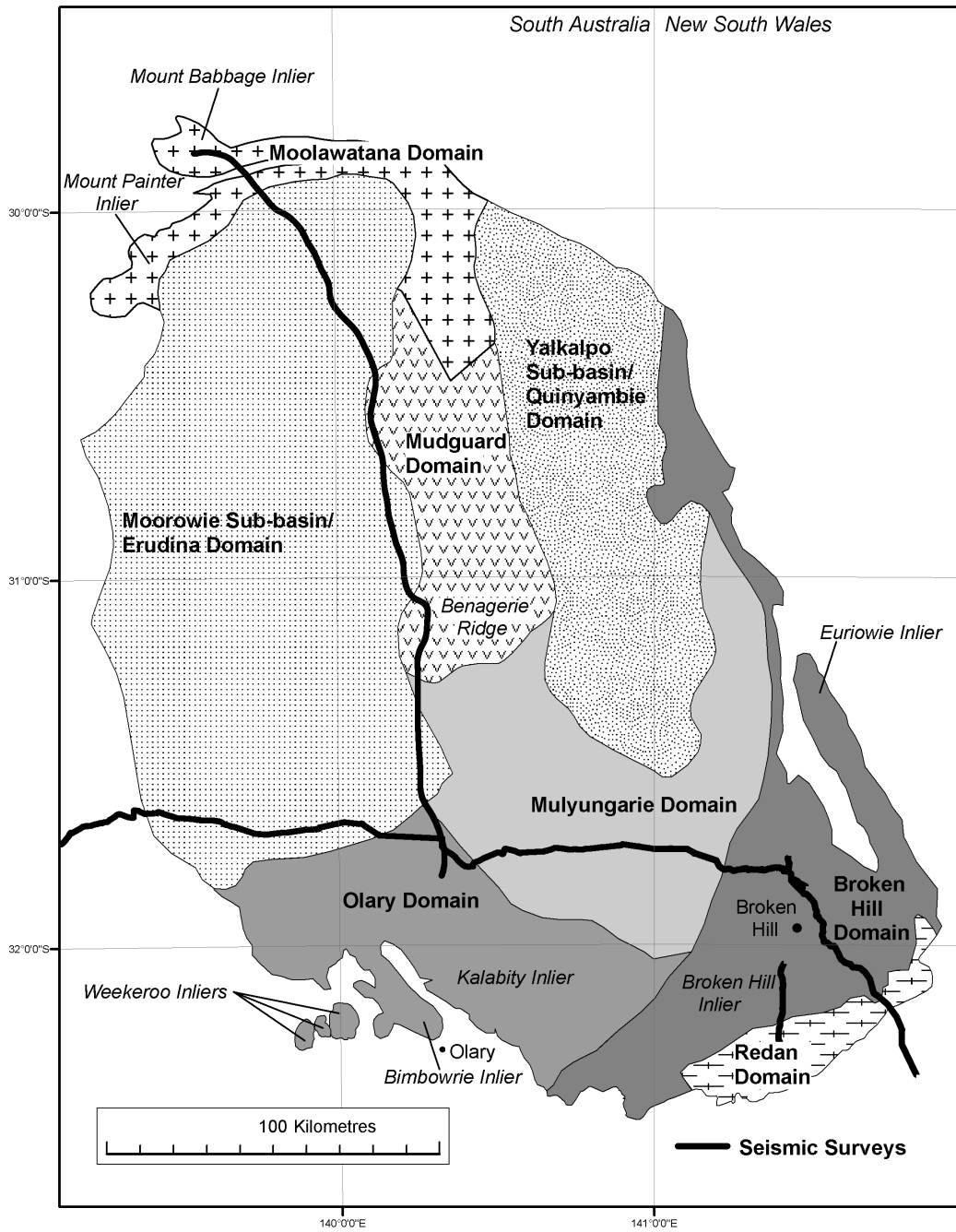


Figure 2. Geological domains of the Curnamona Province

Sound geochronological evidence (Figure 1) demonstrates that while the ~1710 Ma Rantya and ~1700 Ma Thackaringa Groups were being deposited in the Broken Hill rift system, there was little or no sedimentation on the Oлары shelf (erosion of the missing units is a possibility, but non-deposition more likely). The possible combination of mantle-derived heat being transferred through the extended lower crust, and radiogenic heating of the rift-fill, resulted in melting of the buried parts of the Willyama Supergroup to produce the early S-type components of the Silver City Suite (Stevens et al., 2008).

The rift-shelf scenario continued through the ~1695-1670 Ma period, during which the Broken Hill and Sundown Groups reached their maximum thickness in the Broken Hill Domain, but, combined as the Saltbush Group in SA, are only sporadically represented in the Olary Domain. At the base of the Saltbush Group a thin sulfidic-calcareous unit, is named the Ettlewood Calc-Silicate Member in NSW; its equivalent, the <~1701 Ma Bimba Formation, appears to be a continuous cap-like unit throughout the Olary Domain, where geochronological evidence suggests that it overlies an unconformity representing an hiatus approximating 20 million years. The combined psammitic, calcareous and sulfidic nature of the Bimba Formation is suggestive of shallow lagoonal or sabkha-type deposition, and so possibly represents the ebb and flow of local regressions and transgressions across the rift shoulder. Evidence for the Bimba Formation being part of a diachronous series comes from the similar, but much thicker, and apparently slightly older, ~1705 Ma Portia Formation in the intervening Mulyungarie Domain (Figure1).

The base of the Portia Formation is defined by the change in iron mineralogy, that is from pyrite-pyrrhotite down into magnetite or haematite. This change is observed throughout the region, and possibly represents a fluctuating variation in basinal conditions between 1710 Ma and 1705 Ma. Whatever the cause, the change in oxidation state forms a redox boundary of regional extent that is observable in magnetic imagery, with most Pb-Zn and Cu-Au (Mo) deposits being in the vicinity. Also, significantly or not, at about 1705 Ma the dominant composition of magmas also changed from A-type to S-type. Like the Bimba Formation, the Portia Formation contained not only weak syngenetic Zn-Pb mineralisation, but also provided suitable chemistry for the trapping of metals such as Cu, Au, Mo.

The Broken Hill Group was deposited mainly in the Broken Hill Domain between ~1700 Ma and 1685 Ma. Throughout this period, the S-type magmatism of the Silver City Suite continued in the Broken Hill rift system, but became bimodal towards the end with the intrusion of high Fe-tholeiite sills into both the Broken Hill and Olary Domains. In the Olary Domain, the mafic rocks, called the Lady Louise Suite, are strongly differentiated. Magmatism and the formation of Fe-Mn-Ca 'exhalites/inhalites' shut-off abruptly at ~1685 Ma, with the deposition of the aerially restricted Hores Gneiss volcanic mass-flow deposit, a unit of considerable importance because it became host to the Pb-Zn-Ag lodes. The cessation of magmatism suggests that it was probably the mantle component of heat that was removed, because radiogenic material was still being amassed by sandstone-mudstone deposition, this being the ambient form of sedimentation for both the Broken Hill and Sundown Groups. Finally, the ~1640 Ma Paragon and Strathearn Groups are the youngest preserved sedimentary units of the Willyama Supergroup and represent sag-phase deposition of sufficient thickness to form a thermal blanket that was conducive to greenschist to granulite grade metamorphism early during the succeeding ~1620-1590 Ma Olarian Orogeny.

Sedimentation, A-type, S-type and mafic magmatism were all components of the evolution of the rift basin at the now southern extremity of the Palaeoproterozoic eastern Australian Pb-Zn belt; of these four components it is the S-type activity that appears circumstantially to be the most important in relation to the Pb-Zn-Ag mineralisation, because the ~1705-1685 Ma S-type magmatism is the only component not shared with the Olary Domain. In support of this, there was significant Pb-Zn mineralisation early during the Silver City magmatic event (e.g. Pinnacles Mine), and this continued, to climax with the deposition of the Hores Gneiss, host to the Broken Hill lodes. It seems likely that partial melting, and other forms of segregation of the rift-fill forming the Willyama Supergroup, would have concentrated metals such as Fe, Mn, Pb, Zn, and Ag in solution, which could then migrate along structures to form either inhalite deposits in suitable rock hosts, or exhalites at the sediment-water interface.

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Appendix 1

Notes summarising recent changes to the Olary Domain lithostratigraphic scheme of Conor (2006b).

The former Whey Whey Formation has been down-graded to Whey Whey Member of the Peryhumuck Formation, Ethudna Subgroup.

The former Bewooloo Formation has been downgraded to Bewooloo Member of the Toraminga Formation, Ethudna Subgroup; it represents a dominantly volcanoclastic facies and Mn-Fe chemical lithologies associated with the Montstephen Metabasalt Member.

The name Mooleugore Formation has been dropped, but instead the name Mooleugore facies set is used informally in reference to a component of the Tommie Wattie Formation.

A magmatic-hydrothermal origin for the giant Broken Hill Pb-Zn deposit

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Introduction

The Broken Hill Pb-Zn-Ag deposit (300 Mt) is the largest known accumulation of Pb on Earth (28 Mt of Pb metal). It occurs in the Paleoproterozoic Willyama Supergroup in western NSW, within highly deformed metasedimentary rocks, as stacked ore lenses along a line of lode ~7km long. Metagabbroic sills are common in the district. Although some consensus exists that the deposit, and its host rocks, formed in a rift setting around 1700-1670 Ma, the origin of this giant ore system remains controversial. Importantly, S isotopic data and S/Se values for the ores are homogeneous, and totally mantle-like, with minimal evidence for seawater-derived S. We argue here that the giant Broken Hill Pb-Zn-Ag deposit formed from fluids that evolved during extended fractionation of rift tholeiitic magmas, which formed widespread sills across the Broken Hill Domain. Accumulation of these magmas along a major, synrift extensional detachment led to strong synkinematic fractionation, generating remarkably Fe-rich ferrogabbros along this structure. Fluids evolved from deeper, highly-fractionated magma batches which contained the magmatic Pb budget, and reacted with the ilmenite-rich ferrogabbros, concentrating Mn (and probably Zn), and transporting metals to sites of ore lens formation in the sub-seafloor in the synrift sediments. New Pb isotope data for the Broken Hill metagabbros support the model presented here.

Magmatic-Hydrothermal Model

Away from the line of lode, the sills are typical rift tholeiites with flat REE patterns and E-MORB compositions. As has been noted previously, however, in the vicinity of the line of lode, the sills are strikingly Fe-rich tholeiites, with well-preserved chilled margins having up to 22 % total Fe as Fe₂O₃. No similarly Fe-enriched sills were encountered elsewhere in the region. We believe that the remarkably Fe-rich compositions of sills along the line of lode reflect the operation of extensive synkinematic fractionation of structurally-focussed magma batches, during which late stage interstitial Fe-rich melts were pumped out of the crystal-mush pile and up an extensional shear zone. This process is well documented for ultra-slow spreading crust on the southwest Indian Ridge, where ODP Hole 735B revealed the presence of large volumes of often foliated oxide (ferro)gabbros. The major Thorndale gravity anomaly is centred east of, and bordered on its west by, the Broken Hill Line of Lode, and probably records the presence of these ferrogabbros on a major crustal structure that defined the Line of Lode.

Fractional crystallisation very effectively separates Cu from Pb and Zn, since Cu partitions strongly into a magmatic vapour phase from the early stages of fractionation, whereas lithophile Pb and Zn remain in the magma as fractionation proceeds. We argue that late magmatic fluid

evolution from these Fe-rich magmas transported large amounts of Pb and Zn into a robust hydrothermal system that ultimately formed the ore deposits along the trace of the extensional shear system. We ascribe the abundant Mn in the alteration halo, a characteristic of the Broken Hill deposit, to alteration of ilmenite (0.5-2 % MnO), a major phase in oxide gabbros.

New Pb isotope data (Figure 1) for the sill metagabbros, including step leaching experiments and mineral separate analyses, strongly support the proposed model, with both near Line of Lode and remote from Line of Lode sills having Pb isotopic values identical, within error, for the Broken Hill ore galenas. Samples for several sills diverge to higher ^{206}Pb and higher ^{207}Pb , and suggest some equilibration and redistribution of Pb during the well-documented, Olarian deformation at 1600 Ma.

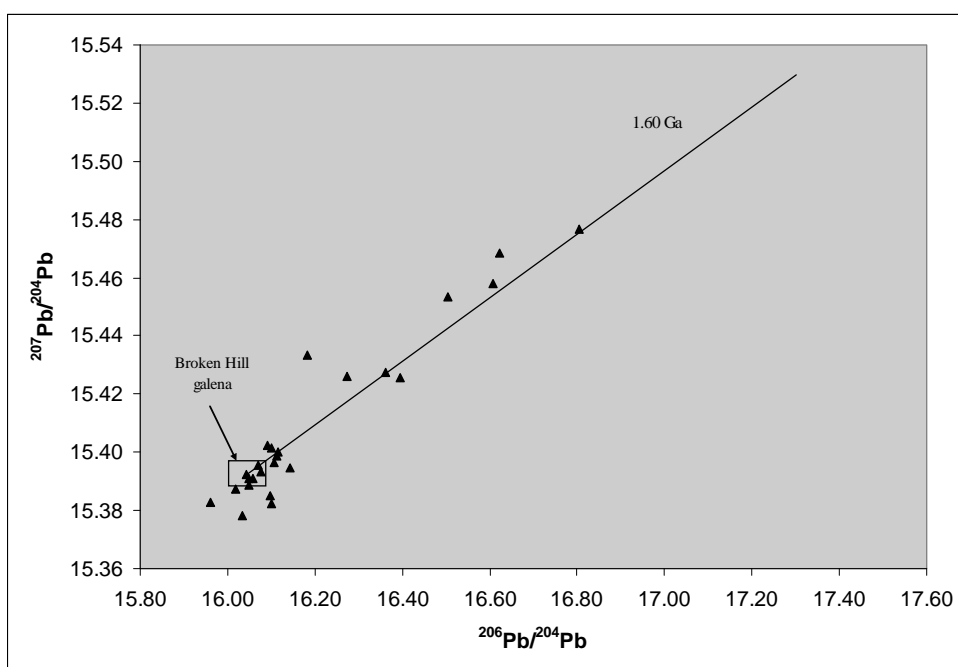


Figure 1. $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{207}\text{Pb}/^{204}\text{Pb}$ for Broken Hill metagabbros (from both Line of lode and remote from mine) – samples that diverge from the field of Broken Hill galena suggest redistribution of Pb during the ~1600 Ma Olarian deformation event

The Cu/Pb ratios of typical rift tholeiites are usually >20. Accepting a Cu/Pb value for the Broken Hill ferrogabbros of ~10 (because of a relatively high Pb mantle source for these rocks), implies that immense amounts (>200 Mt) of Cu are sequestered within the Broken Hill magmatic – hydrothermal system.

Finally, the distinctive Potosi Gneiss, which occurs closely associated with the ores along the line of lode consistently has 1-3% more total Fe than the other Broken Hill granitoids (Alma Gneiss, Rasp Ridge Gneiss) at any SiO_2 level. Recent experimental work, on unmixing of felsic magma from very Fe-rich tholeiitic magma, has noted that the felsic product of this process is 'an Fe-rich granite'. We suggest that the Potosi Gneiss may have unmixed from the remarkably Fe-rich gabbroic complex, and that the well known 'potobolites' are a frozen record of this process.

Conclusions

We argue that the Broken Hill Pb-Zn ore metals and S derived ultimately from very strongly-fractionated, rift ferrotholeiite magmas emplaced along a major detachment around 1685 Ma.

Synkinematic fractionation forced highly evolved Fe-rich melts, out of intercumulus sites in gabbros, up the detachment, to crystallise as very Fe-rich oxide gabbros. The Thornedale gravity high just east of the Broken Hill Line of Lode reflects the mass of gabbroic rocks along the east-dipping detachment. Late magmatic fluids exsolved from these evolved melts reacted with oxide gabbros above the detachment (possibly scavenging further Zn from interactions with FeTi oxides), and eventually formed massive sulfide lenses beneath the seafloor. There is no requirement for the involvement of seawater-derived fluids, nor of metal extraction from the metasedimentary pile.

Mapping retrograde metamorphism and alteration across the Broken Hill Domain using airborne HyMap imagery

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The abundance and composition (level of Tschermak cation substitution) of white mica (and other minerals) that formed during post-granulite facies retrograde alteration was measured and mapped across the Broken Hill Domain, Australia, using airborne hyperspectral visible to shortwave infrared HyMap imaging data. These mineral maps were validated through ground and laboratory analyses (ASD spectra and X-ray diffraction). The airborne and laboratory results show that muscovite (no paragonite) is pervasively developed across the region, with an overall pattern trending from Al-rich mica in the west to Al-poor mica in the east. Muscovite abundance is generally higher in the east. Shear zones do not show increased levels of abundance in muscovite, but do show relatively Al-poor composition with respect to neighbouring country rock. The most Al-poor micas are located in mapped shear zones in the northeast part of the study area, which are also associated with many of the known Thakaringa vein styles of base metals mineralisation. This specific mica information is not apparent in either the published airborne radiometric or magnetic data and is only weakly evident in processed satellite ASTER data. There is also no apparent influence of parent rock composition on the hyperspectral-mapped mica chemistry, which is interpreted to be evidence for fluid-fluid rather than fluid-rock mineral reactions. These interpreted fluids consist of a deeper-sourced alkaline/oxidised fluid (original metamorphic fluid?) that migrated (upward) from the current northeast parts of the Block along a network of shear zones (high water-rock ratios), and interacted with relatively "shallow" or downward-percolating, pervasive (low-water rock ratios) acid-neutral/reduced fluid that could have been sourced from seawater/meteoric origin.

Interestingly, the regionally and economically anomalous 20 km long corridor of Broken Hill base metal deposits is located along a major gradient change in mica composition. The significance of this is unclear, although it could reflect a major discontinuity in syngenetic/epigenetic geological architecture that could be valuable in exploring for related styles of mineralisation in other regions. The main conclusion from this study is that regional and local-scale alteration footprints can be measured and mapped with accuracy, using a new generation of hyperspectral imaging systems that deliver valuable geological information not available previously from other government precompetitive geoscience data.

A guide for mineral exploration through the regolith in the Curnamona Province

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Introduction

The Curnamona Province has a long history of exploration following on from the discovery of the world-class Broken Hill Deposit. The majority of exploration and subsequent discoveries, however, have been made in and around bedrock exposures which account for <10 % of the landscape. The major challenge facing exploration within the region is exploring effectively through transported regolith.

A guide for mineral exploration through the regolith in the Curnamona Province forms part of a series of six mineral explorer’s guides for some of Australia’s major metallogenic provinces and are one of several key legacy products of the Cooperative Research Centre for Landscape Environments and Mineral Exploration (CRC LEME). These guides are focussed towards assisting mineral explorers working in regolith-dominated regions. They provide an introduction to the regolith and landscape history of the region, together with advice on appropriate exploration strategies and techniques for exploring within or beneath the regolith.

Exploration strategies

Employing the appropriate exploration strategy in covered terrains relies on combining conventional geological exploration data layers (e.g. geophysics, drilling, geological mapping) with a sound understanding of regolith materials and the evolution of the landscape (Figure 1).

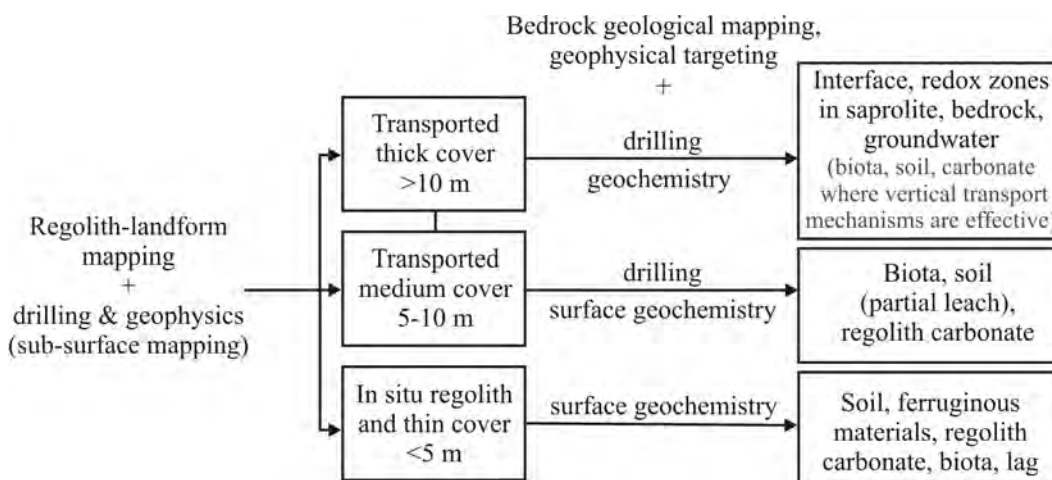


Figure 1. An approach to exploration in regolith-dominated terrains (Fabris et al., 2008)

Such an understanding is fundamental to knowing what can be sampled, and what should be avoided, as well as being an aid in designing geochemical sampling surveys and interpretation of assay results.

There are a number of strategies that can be applied in the Curnamona Province. These draw upon significant research that has been conducted in the Curnamona over the years.

Soil geochemistry

Soil can be an appropriate and convenient sampling medium where it overlies *in situ* regolith, shallow transported regolith (<5 m), or contains significant bedrock-derived components (via bioturbation or down-slope processes). In areas of moderate to thick transported cover (>5 m), caution is required as studies in the region have shown both poor (Skwarnecki et al., 2001) and potentially useful results (Hedger and Dugmore, 2001; Leyh and Corbett, 2001; Fabris et al., 2007).

Soil surveys can be meaningful at a range of scales; however, it is important that soil results are interpreted in context of their regolith-landform setting, where regolith mapping can assist with the interpretation of anomalous values (Brown and Hill, 2003). Different regolith units commonly have different geochemical thresholds.

In many situations, particularly those where the substrate being sampled is transported, the collection of as fine-grained a fraction as practical is recommended due to the greater surface area available to chemical attack during digestion (typically <75 µm).

In areas of moderate to thick transported cover, partial leach techniques are preferred. Samples for partial extraction are generally taken between at 10-25 cm depth (Mann et al., 2005). Partial leach methods are designed to target loosely bound ions on the surface of mineral grains, rather than dissolving the entire mineral grain. The effect is to increase exotic metal ion contribution that may reflect underlying mineralisation, and to limit the contribution of the transported regolith components that are not related to mineralisation. Partial leach methods, however, are also more susceptible to contamination, minor changes in analytical practice, and subtle regolith-landform variations.

Although there have been a number of reports describing equivocal results from partial leach methods, a few studies have shown the potential application of soil sampling in areas with thick transported cover including over the Polygonum and Kalkaroo prospects (Hedger and Dugmore, 2001; Leyh and Corbett, 2001; Fabris et al., 2007).

Phytoexploration

Sampling plants is not a new concept, but recent work has proven its validity as an exploration media and one which should be more routinely used (Morris, 1974; Cohen et al., 1998; Hill and Hill, 2003; Hulme and Hill, 2003; Hill et al., 2005). The basic principle of plant biogeochemistry in mineral exploration is that the roots of plants take up trace elements, including metals, from the ground and transfer these within the plant. Geochemical variations between different geological substrates can therefore provide different amounts of metals and trace elements for plants to take up. Phytoexploration can be conducted at the regional scale through to prospect scale. Specific advantages of vegetation sampling include their often widespread distribution, easy access to samples, ability of plant organs to penetrate through transported cover and provide chemical expression of buried lithology, including mineralisation, ability to selectively extract and concentrate some elements, and to homogenise a potentially heterogeneous substrate (Fabris et al., 2008).

Species to sample often rely on the particular regolith-landform settings within the area of interest. Results of case studies within the Curnamona Province and sampling protocols are summarised in Fabris et al. (2008).

Regolith carbonate

Calcrete sampling has been widely used in exploration in the Gawler Craton (Lintern, 1997, 2004; Chen et al., 2002) but has not been as readily applied in the Curnamona Province. More recent studies, however, have shown that there is widespread distribution of regolith carbonate in the region and that it can be a useful sampling media over different styles of mineralisation and through transported cover (McQueen et al., 1999; Wittwer, 2004; Dart et al., 2007; Fabris et al., 2007).

Sampling regolith carbonate from a similar position within the carbonate horizon and of similar calcrete morphology (e.g. powdery, nodular, platy) are the key to consistent sampling. An investigation into the distribution of Au within the soil profile was conducted at the White Dam Deposit (Dart et al., 2006). Two detailed profiles were sampled from the surface to ~3m depth and the results suggested that the top of the carbonate profile is the best place to sample, with the silt-sized fraction generally the preferred fraction.

Groundwater

Hydrogeochemistry may be useful in exploration at a range of scales and cover depths. A major project investigating the use of groundwater as a possible sampling media was conducted within the southern Curnamona Province and involved sampling of more than 350 boreholes (de Caritat and Kirste, 2005; de Caritat et al., 2005). de Caritat and Kirste (2005) showed that an index of 'sulfur excess' can be used to identify samples that contain more sulfur than can be accounted for by evaporation or mixing. These samples can be further sorted using the stable isotopes of S and O in sulphate and categorised into either a meteoric or sulfide mineral source. Multi-element analyses can then be used to determine those samples of economic significance and used to infer proximity to potential mineralisation.

Although direct comparison of groundwater data is complicated by variations in groundwater chemistry, with the appropriate approach, hydrogeochemistry is a viable exploration technique with the potential to record groundwater-mineralisation interaction and assist exploration programs in areas of thick cover.

Acknowledgements

The information presented in this abstract is a summary of research conducted through CRC LEME by various participating parties and collaborative partners. For a more detailed account of exploration strategies in regolith-dominated terrains of the Curnamona region, see Fabris et al. (2008).

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Industrial Mineral Opportunities in the Broken Hill Area

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The Curnamona Province, which includes the town of Broken Hill, is recognised as a world-class mineral province for a wide range of metallic minerals. There are also many areas that contain industrial minerals that potentially could be economic. These industrial minerals include barite, beryl, dolomite, feldspar, fluorite, garnet, kyanite, lithium, magnetite, mica, silica, sillimanite, staurolite, topaz and rare earth elements that could be extracted on their own or together with metallic minerals.

The main current and historic producer of industrial minerals is the Triple Chance feldspar deposit. A processing plant on site is currently used to process feldspar from South Australia (Olary deposit) for use in South Australian glass making plants.

There are several rock types that host industrial minerals in the Broken Hill area. Pegmatites represent a major target for such industrial minerals, offering opportunities for a range of industrial minerals, although many occur in relatively small quantities. There has been little recent prospecting of pegmatites for industrial minerals using modern exploration methods.

Lishmund (1982) described in detail four types of rocks (Types 1, 2, 3 and 4) in the Curnamona Province that are loosely termed “pegmatites”. “Type 1” and “Type 2” pegmatites are the only types prospective for industrial minerals.

Zoned pegmatites (Type 1a; Lishmund, 1982) offer underexplored potential for industrial minerals and host the most significant source of industrial minerals, the Triple Chance deposit. They are:

- scattered widely throughout the region,
- do not correlate with regional-scale variations of metamorphic grade, and,
- probably formed in response to fractional crystallisation of magmas (London, 2008).

Their composition and predominantly coarse grainsize provide enhanced potential for feldspar, beryl, mica and possibly fluorite.

Some variably-zoned pegmatites host significant cassiterite-rich zones (Type 1b) including those hosted by restricted stratigraphic intervals within the Paragon and Sundown Groups (Barnes, 1988). At the local scale, however, they are elongate or podiform and cross-cut stratigraphy (e.g. Waukeroo and Euriowie districts; Barnes, 1980; Maiden, 1981). Although mainly prospective for cassiterite, they could also host rare earth elements and possibly fluorite and beryl (Burton, 2000), although feldspar is commonly altered and therefore less suited for glassmaking.

Albite “pegmatites” (Type 2; Lishmund, 1982) consist mainly of variably deformed albite, quartz, with lesser apatite, muscovite and biotite, with accessory rutile, zircon and sphene (Vernon, 1961). They broadly occur in areas of high metamorphic grade, are mapped as plagioclase–quartz rocks on maps by the Geological Survey of New South Wales, and probably are not true pegmatites that formed as a result of fractional crystallisation of hydrous melts (Stevens, 1986; London, 2008). Some contain up to 90% feldspar, with low iron contents (suitable for glassmaking), and are up to hundreds of metres wide near Thackaringa and within the Stirling Vale Syncline. The Reatos deposit also produced significant beryl and mica.

Tailings at Broken Hill base metal mines contain several million tonnes at ~2 % fluorite providing considerable opportunities for extraction (MacNevin and Dawood, 1973). Furthermore, the potential of these tailings for rare earth elements and siderite is yet to be systematically tested.

Pelitic metamorphic rocks of the Willyama Supergroup contain up to 5 % or more garnet, with almandine (which is generally preferred for sand blasting) the most abundant type. Cenozoic fluvial sediments that drain garnet-bearing rocks are yet to be systematically tested for their potential for industrial garnet. Also, some base metal deposits locally contain metamorphic rock units consisting of up to 80 % garnet, with spessartine the most common type.

Quartz–magnetite rich rocks such as in the Sisters–Razorback areas and quartz–pyrite rich rocks (e.g. Great Eastern, Iron Blow; Barnes, 1988) are yet to be systematically tested for their potential for iron.

Conclusions

Apart from being a world-class province for base metals, the Broken Hill area hosts opportunities for such industrial minerals as feldspar, beryl, garnet, rare earth elements, and possibly sillimanite group minerals and magnetite. The main targets are pegmatites, but some industrial minerals could also be extracted from base metal deposits and from metamorphic rocks.

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1590 Ma magmatism in the Curnamona Province: Mineral potential of the Ninnerie Supersuite

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Introduction

During the early Mesoproterozoic (ca 1610–1550 Ma) a continental-scale, thermal event, characterised by regional high-temperature metamorphism and bimodal magmatism, was recorded in the Proterozoic of eastern Australia. This orogenesis and high-grade metamorphism is interpreted to be related to contractional phases in a long-lived accretionary orogen (Rutherford et al. 2007). In the Gawler Craton, this event included the extrusion of the bimodal Gawler Range Volcanics (ca 1592 Ma) followed by the intrusion of the Hiltaba Granite Suite (ca 1590–1580 Ma) (Creaser et al., 1991; Creaser and Cooper, 1993; Allen et al., 2003), which was responsible for the formation of the Olympic Dam and other Cu-Au-U deposits. Contemporaneous magmatism also occurred in the Curnamona Province, where vast quantities of A-, I- and S-type magma were also generated. A-type magmas of the bimodal Benagerie Volcanics were extruded ca 1585–1581 Ma (Fanning et al., 1998; Wingate, pers. comm. 2007) and emplacement of the I- and S-type granites of the Ninnerie Supersuite occurred ca 1590–1570 Ma (Ludwig and Cooper, 1984; Cook et al., 1994; Page et al., in prep.). The emplacement of the Gawler Range Volcanics and Hiltaba Granite Suite is considered to have been formed by the interaction of a mantle plume with the continental lithosphere, which resulted in intracratonic extension, partial melting of the lower crust and shallow pluton emplacement (Giles, 1988; Creaser and White, 1991). The mantle plume has been traced from the Gawler Craton through the Curnamona Province and to the Mt Isa Inlier (Betts et al., 2007), essentially linking these provinces.

Ninnerie Supersuite

The Ninnerie Supersuite consists of several suites which span several domains in the Curnamona Province. The most widespread and most studied granites are found in the Olary Domain, where at least three individual granite suites have been identified. The granite suites in the Olary Domain include:

- 2-mica, S-type granites of the Bimbowrie Suite
- Sodic to biotite-only S- and I-type granites of the Crocker Well Suite
- Hornblende-biotite I-type granodiorites to diorites coeval with the Crocker Well Suite.

Several other types of mafic and felsic intrusives and volcanics have been identified in the Mulyungarie Domain and Mudguard Domain, including:

- Buried magnetic gabbros to granodiorites and non-magnetic granodiorites to monzogranites
- Buried non-magnetic granites (so called Honeymoon Type)
- Magnetic, anatectic granites (so called Mundaerno Type).

The Mudguard Domain is dominated by the bimodal, A-type Benagerie Volcanics. Mafic volcanics are of two types. In the drillhole Bumbarlow 1, mafic volcanics are mainly fine-grained, amygdaloidal basalts interlayered with coarse sandstones and siltstones and peperite basalts, most likely representing several lava flows, some with vesiculated and brecciated flow tops (Youngs, 1978). In drillhole LNM10, basalts are green chloritised, altered amygdaloidal basalts (Curtis, 1990) and hyaloclastite basalt with pillow lavas. The felsic volcanics have been intersected in three drillholes: Mudguard 1, Culberta 1 and WK1. Volcanics from Mudguard 1 are porphyritic, homogeneous and medium- to coarse-grained, with phenocrysts of embayed quartz, sericitised plagioclase and turbid corroded K-feldspar in a recrystallised matrix (Youngs and Callen, 1977; Giles and Teale, 1979). The volcanics from drillhole Culberta 1 are massive, quartz-feldspar porphyritic rhyolites, with haematite alteration and calcite veining (Youles, 1981; Barovich et al., 2006). Volcanics intersected in the WK1 drillhole are amygdaloidal, porphyritic trachytes, which are fairly extensively altered and consist of a series of flows with scoriaceous tops (Youles, 1982).

Origin

Seismic interpretations and Nd isotope geochemistry indicate that there is a possible boundary between the western and eastern Curnamona Province (Korsch et al., 2006), where two differing crustal blocks are juxtaposed against each other (Barovich et al., 2006). These crustal blocks host granites of the Bimbowrie Suite in the east and the Crocker Well Suite in the west. ϵNd values for the Bimbowrie Suite and Crocker Well Suite indicate they were derived from anatexis of metasedimentary rocks of the Willyama Supergroup (Barovich and Foden, 2002); whereas ϵNd values obtained for diorites in the western Olary Domain indicate significant mantle input in their genesis, which is not seen in granites of the Bimbowrie Suite to the east (Barovich and Foden, 2002). Geochemical and geophysical similarities between the Benagerie Volcanics, the Crocker Well Suite and the coeval diorites have been highlighted by Barovich et al. (2006), which suggests these magmas were part of the same crustal block, and are more similar to the Gawler Range Volcanics and Hiltaba Granite Suite.

Mineralisation

Similarities between the Benagerie Volcanics and the Gawler Range Volcanics have been long recognised (Giles and Teale, 1979) highlighting the IOCG potential of the Benagerie Ridge (Teale, 2000; Burt et al., 2004). Barovich et al. (2006) highlighted geochemical similarities between the diorites from Crocker Well and the Benagerie Volcanics, enhancing mineral exploration for IOCG-type deposits in the western Olary Domain.

The Southern Curnamona Province is host to numerous, small uranium prospects. The Crocker Well region contains the most significant hard rock uranium mineralisation in the Curnamona Province, with deposits in the Crocker Well uranium fields and the Mount Victoria deposit. The source of the uranium mineralisation is largely related to melting of originally uranium-enriched metasedimentary rocks of the Willyama Supergroup and granites during the late stages of the Olarian Orogeny (Fabris, 2004). Uranium and thorium mineralisation at the Crocker Well prospect is hosted in sodic granitic rocks associated with sodic felsic gneisses and occurs in sheared zones, veins, stockworks, disseminations and breccias (Campana and King, 1958; Ashley, 1984). Most of the U-Th mineralisation is similar to porphyry Cu and stockwork Mo deposits, with the deposits forming by mechanically-induced fracturing and local breccia bodies during the sub-solidus cooling of the granite body (Ashley, 1984).

Erosion of the uranium-enriched terrane in the southern Curnamona Province has produced significant sedimentary uranium accumulations (e.g. Honeymoon Deposit and Goulds Dam Prospect) (Fabris, 2004). These sandstone-hosted uranium deposits are hosted by medium- to coarse-grained fluvial, marginal marine or alluvial sands in the Cenozoic Callabonna sub-basin.

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A model for the formation of granite plutons in the Olary Domain: A ring dyke model

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Introduction

Zonation in granitic plutons is a common and widespread phenomenon in the geological record. Two types of zoned granitic plutons exist; these are normal- or reverse-zoned. Normal-zoned plutons are the more common and possess mafic rims and felsic cores (Mustard, 2004). Reverse-zoned plutons are rare, and possess felsic rims and mafic cores (Janoušek et al., 1997). Granite plutons may also form as cone sheets or ring dykes, which also display these types of compositional zoning.

Cone Sheets and Ring Dykes

Cone sheets or ring dykes are discordant intrusive bodies which are often circular, elliptical, polygonal or arcuate in plan (Johnson et al., 1999). Cone sheets usually have inward-dipping contacts; whereas ring dykes have steep, often outward-dipping contacts. Cone sheets are suggested to have formed by over pressurising of a magma chamber, which causes doming or upward expansion, and magmatic pressures create a fracture system in the overlying country rocks (Phillips, 1972; Johnson et al., 1999; McDonnell et al., 2004). Cone sheets are formed by magma intruding along these conical fractures. As the magma subsides, relaxation in pressure allows cauldron subsidence into the magma body and causes magma to intrude along vertical to steeply outward dipping faults to form ring dykes (McDonnell et al., 2004).

In order to understand the above processes responsible for the formation of granitic plutons, spatially, well-constrained lithological identification and mapping in conjunction with detailed petrological and geochemical studies are essential.

Zoned Granite Plutons in the Olary Domain

Transects across three granite intrusions in the Olary Domain, Curnamona Province, indicate geochemical and lithological zonation. The Ninnerie Hill pluton and the Crocker Well pluton have been dated at ~1579 Ma (Ludwig and Cooper, 1984). A molybdenite-bearing granite dyke in the Triangle Hill intrusion has a reported magmatic crystallisation age of 1580 ± 3 Ma (Page et al., in prep.).

Ninnerie Hill Pluton

The Ninnerie Hill pluton, located in the western Olary Domain, is a lithologically- and geochemically-zoned pluton, and measures approximately 9 km x 8 km, occupying ~66 km².

The pluton is characterised by its distinctive radiometric response which highlights three broad zones:

- Th-K-dominant outer rim;
- Th-dominant middle zone; and
- U-dominant core.

Mapped lithological boundaries broadly correspond with these radiometric zones and zonation displays characteristics of a normal-zoned pluton. The rim is predominantly biotite granodiorite to microdiorite, followed inwards by leucoadamellite to biotite adamellite and sodic-rich zones, then a second biotite granodiorite to microdiorite zone in the middle and finally a biotite adamellite and sodic granite core.

Crocker Well Pluton

The Crocker Well pluton is located adjacent to the Ninnerie Hill pluton, measuring approximately 8 km x 11 km and occupying ~55 km². This pluton is also distinguished by its radiometric response, which is similar to the Ninnerie Hill pluton. The rim is dominated by a Th-K radiometric response, whereas the core is a mixture of Th-dominant and U-dominant radiometric zones. U-rich parts appear as discrete zones within the Th-dominant zone.

The Crocker Well pluton contains a porphyritic, biotite adamellite to biotite granite and leucoadamellite rim, with zones of biotite granodiorite, biotite tonalite to diorite, biotite adamellite and sodic granite in the core. The zones of biotite granodiorite, biotite tonalite to diorite, biotite adamellite and sodic granite in the core may represent several individual intrusions, and give the Crocker Well pluton characteristics of a reverse-zoned pluton.

The Crocker Well pluton is well known for the uranium and thorium mineralisation at the Crocker Well prospect, which is hosted in sodic granitic rocks (Ashley, 1984). The mineralisation occurs in sheared zones, veins, stockworks, disseminations and breccias (Conor et al., 2006). Thorian brannerite is the main uranium phase at Crocker Well, but only represents a small proportion of the U-Th mineralisation (Ashley 1984). Most of the U-Th mineralisation is similar to porphyry Cu and stockwork Mo deposits, with the deposits forming by mechanically-induced fracturing and local breccia bodies during the sub-solidus cooling of the granite body (Ashley, 1984). Proximal to the U-Th lodes at Crocker Well is a circular zone that is depleted with respect of the radiogenic elements (U, Th, K); therefore it is possible that this zone represents the source of the mineralisation.

Triangle Hill Intrusion

The Triangle Hill intrusion is located in the eastern Olary Domain and measures approximately 9 km x 6 km. The Triangle Hill intrusion is essentially a ring of porphyritic biotite-muscovite K-feldspar-phyrlic adamellite granite that surrounds a 7 km x 5 km core consisting of Paleoproterozoic metagranite of the Ameroo Subsuite (~1710 Ma) and metasedimentary rocks of the Tommie Wattie Formation (lower Willyama Supergroup). The rim is ~2 km at its thickest measured part in the northwest and ~0.3 km at its thinnest measured part in the northeast.

Proposed Ring Dyke-Cone Sheet Intrusion Model

From field observations, the morphology of the Triangle Hill intrusion is consistent with characteristics of a ring dyke or cone sheet in that the intrusion is essentially an annulus of K-feldspar-rich granite enclosing Paleoproterozoic host material. The dip of the outer rim is not known, and the present knowledge does not allow understanding as to whether the central core of older Paleoproterozoic granitic gneisses and metasedimentary rocks has been raised or

lowered. Therefore, it is not known, at this point in time, as to whether the intrusion has the geometry of a ring dyke or cone sheet.

Extending the observations from Triangle Hill, because the Ninnerie Hill pluton shows a similar discrete outer rim, it too might have been initiated as a cone sheet or ring dyke, but, in this case, with the core zone being in-filled later by both felsic and mafic material, as per the Ossipee ring complex (Kennedy and Stix, 2007). Triangle Hill, and perhaps the Ninnerie Hill and Crocker Well plutons, are unusual ring complexes in that they were formed deeper than subvolcanic depths, the usual for such complexes elsewhere.

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Minerals systems approach to geothermal exploration

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Introduction

The Australian geothermal industry has emerged from being almost nonexistent just ten years ago to now consisting of more than 48 individual exploration companies (ten publicly listed) and at least two new geothermal-specific consulting companies. State and Federal geoscience agencies now have targeted geothermal work programs, and a number of peak research institutions are involved through three Centres of Excellence and various other research departments and programs. There is currently an area of over 300 000 km² under geothermal exploration leases, with work programs in the order of \$1.5B. The geothermal industry has attracted the attention of large energy companies such as AGL, Origin and TRUenergy, all of which have committed significant funds to joint venture projects or buy-in options.

The absence of active volcanism on the Australian continent limits the opportunity for the use of conventional geothermal systems, as found in other countries such as New Zealand, Indonesia or Iceland. This has led to the development of two models used to describe geothermal systems in this country; the Hot Rock (HR) model and the Hot Sedimentary Aquifer (HSA) model (Figure 1).

Established exploration industries are able to utilise a wealth of available precompetitive data at both the state and federal levels. The continental coverage of the primary geothermal specific dataset, heat flow, however, is at best very limited. There are only ~ 150 reliable, publicly-available, heat flow data points for the whole of the continent.

There have been various attempts to integrate broader geoscientific data for the purposes of geothermal exploration (Budd, 2007) and at least one high profile lease area was selected based on acquired geological knowledge (C. Matthews, pers. comm., 2008). To date however, geothermal exploration in Australia has largely been targeted using interpretations of crustal temperature.

Various images of crustal temperature at 5 km depth (Somerville et al., 1994; Chopra and Holgate, 2005) have been constructed from bottom-hole temperature data collated primarily from petroleum well-completion reports. The provenance of the data has resulted in an heterogeneous spatial distribution that, with a few exceptions, is restricted to known petroleum provinces (Figure 2). While the interpolated temperature images have provided an easily understood portrayal of Australian geothermal potential, and have been influential in shaping geothermal exploration in Australia, by nature they can only provide a limited and, at times, biased indication of prospective areas.

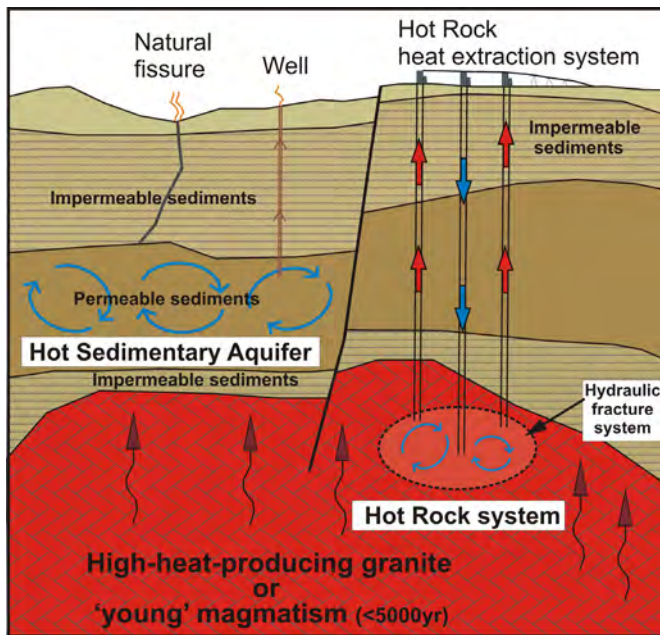


Figure 1. Diagrammatic representation of the two styles of geothermal play models in Australia.

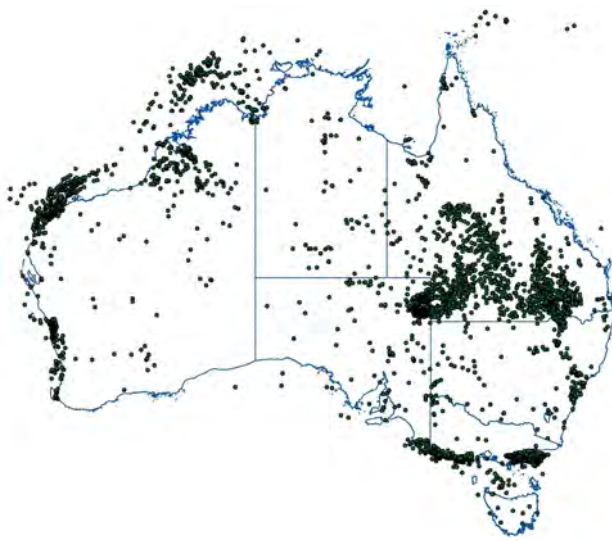


Figure 2. Locations of bottom-hole temperature measurements showing the heterogeneous spatial distribution across Australia.

In order to broaden the targeting of geothermal exploration, Geoscience Australia and others are looking at the development of practical proxies to define exploration criteria. This is being done to develop a Geothermal Plays System approach; which will be based on the mineral systems '5 Questions' approach (Barnicoat, 2008).

Exploration Data for Geothermal Plays

When exploring for a geothermal play, temperature is the fundamental property. The expected nature of the play, and the intended end use, will prescribe the required temperature. This holds regardless of whether the highest possible temperature is being targeted or a certain temperature at a given depth is required.

Temperature in a geothermal system is dependant on two fundamental components; a heat source and an insulating layer (Budd et al., 2009). The relationship can be expressed with equation 1.

$$T = \int \frac{Q_z + Q_m}{\lambda} dz \quad (1)$$

where: $Q_z = \int A(z) dz$

where the determinants are; thermal conductivity λ , heat generation A, mantle or basal heat flow Q_m , and the crustal thickness under consideration z.

Although for much of Australia, data does not exist to directly solve this equation, the above mentioned geothermal system components are quantifiable, and proxy data can be applied to help predict the thermal conditions of the upper crust.

Insulation

Thermal conductivity is dependent on mineralogy, grainsize, porosity, temperature and pressure. Lithological knowledge developed from basic exploration activities can be used to estimate grainsize, mineralogy and porosity. Porosity data can also be derived from well logs and other density measurements. Pressure can be considered to be depth dependent. As temperature is considered here to be the unknown of interest, and its influence is less than that of grainsize and composition, it can be ignored in a simplistic first-pass assessment.

Heat source

Radiogenic heat generation is primarily dependent on the abundance of the radioactive elements uranium, thorium and potassium. The density of a rock must also be taken into consideration, as shown in equation (2) (Rybach, 1988).

$$A = 10^{-5} \rho(9.52U + 2.56Th + 3.48K) \quad (2)$$

where, A = Heat Generation in $\mu W.m^{-3}$, ρ = density in $kg.m^{-3}$ and U, Th and K are the concentrations of uranium and thorium in parts per million and potassium in weight percent.

Concentrations of radioactive elements (U, Th and K) are frequently collected as part of whole rock geochemical analysis, or can be measured directly with a spectral gamma well log. The measurement of density is less common in mineral exploration, although the process is relatively simple, and again can be measured with well logging. The time dependent nature of radioactive decay means that the relative age of a rock also impacts on the heat production.

High-heat-producing (HHP) granites are the most viable geothermal source rock. Some consideration can be given to immature sediments derived from HHP granites, and also to accumulations of heavy mineral sands, but both of these rock-types would require unusually thick accumulations in order to generate anomalous heat flows. Given the related geochemistry within granite suites, it is potentially feasible to use geochemical data from exposed parts of suites to provide some indication of the heat production in unsampled plutons. Geophysical data may be used to identify trends of granites beneath cover, which may enable assumptions to be made regarding the compositions of buried plutons.

The nature of granites in various geological provinces and time periods in Australia has been studied in varying detail over recent years, yielding a knowledge base that can be applied to

geothermal exploration. For example, the concentrations of U, Th and K in most Proterozoic granites in Australia are higher than in granites from older or younger periods (Budd et al., 2001; McLaren et al., 2003) and, indeed, the Australian Proterozoic granites are anomalously high-heat producing compared with the world average (Neumann et al., 2000).

Interpretations of regional scale geophysical data such as gravity, magnetics, seismic surveys and the recently released Radiometric Map of Australia (Minty et al., 2008), provide additional practical mappable proxies. These data can aid in identifying and mapping trends of granites from outcrop to beneath basin cover, or provide pointers to areas of high U, Th and K which may indicate exposed HHP granites.

One of the strengths for Australia is that much of these data are publicly available in formats easily incorporated into 2D and 3D mapping and modelling packages.

Basal heat input

The basal or mantle heat flow is the parameter which is hardest to constrain in Australia. For much of the northern hemisphere, there is a more detailed understanding of the thermal structure of the crust than exists in this country. The available data in Australia is poorly distributed and does not provide full coverage of the continent (Figure 3). The majority of the data have come from early studies of heat flow (Sass and Lachenbruch, 1979; Cull and Conley, 1983; Cull, 1991). Even with such sparse data, these studies were able to recognise several areas of Proterozoic crust with anomalously high heat flow. There have been subsequent studies of the occurrences of high heat flow, examining the possible explanations and implications, including, but not limited to, Neumann et al. (2000); Sandiford et al. (2001) and McLaren et al. (2006), although these studies mainly approach the topic from the perspective of tectonic evolution, rather than geothermal prospectivity.



Figure 3. Locations of the ~150 publicly available heat flow measurements in Australia.

The growth of the geothermal exploration industry has seen renewed interest in heat flow data in Australia. Work continues to improve knowledge of the heat flow regimes, through both government programs and commercial work in the geothermal industry. Improved data and further work may lead to a better understanding of the application of heat flow provinces as outlined by Roy et al. (1968). The abovementioned studies, in particular Sass and Lachenbruch (1979), made some progress toward delineating heat flow provinces with the limited data available. Improvements in the data coverage will allow refinement of the heat flow provinces.

An understanding of the crustal structure is obviously integral to an understanding of the thermal structure and mantle heat flow. Interpretations of deep seismic reflection surveys can

be used to understand the crustal structure, through interpretations of lithologies and crustal architecture. Seismic velocities have implications for the interpretation of temperature and thermal conductivity. In addition, seismic velocity can be used as a proxy for density which, when incorporated into gravity inversions, can be used to delineate potential buried granites (Meixner and Holgate, 2009). The delineation of previously unknown granites has implications for heat production and the identification of potential geothermal plays (Budd et al.; in press; Meixner and Holgate, 2009).

Conclusion

Through linking of the fundamental components of a geothermal system to their geological expressions, it is possible to use existing exploration knowledge and datasets to explore for geothermal plays in Australia.

By utilising regional and national scale datasets to build Geographic Information Systems or 3D maps, an assessment of geothermal potential can be made at the large scale. With its full history of mineral exploration and geoscience research, the Broken Hill area has a wealth of available data to serve geothermal exploration decision-making.

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Tectonics, magmas and mineralisation: Keys to exploring for BHT mineralisation

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Introduction

Here, we will attempt to distil 10 years of research (1996-2006) into Broken Hill-type systems, undertaken at Monash University, in collaboration with BHPBilliton. We will present this in the form of a series of conclusions, briefly argued below, with implications for exploration. Our work was conducted in the Broken Hill Block, eastern Mount Isa Inlier and the Georgetown Inlier and involved three PhD theses (Giles, 2000; Hills, 2003; Raveggi, 2008), two MSc theses (Forbes, 2001; Hansen, 2002) and two Australian Research Council Linkage grants (2000-2002; 2003-2005). The key participants in these grants were Maarten Krabbendam, Mike Raetz, Massimo Raveggi, David Giles and Gordon Lister (Monash University) and Jeremy Reid, Mark Dugmore, Tony O'Sullivan, Darren Stephens, Sudipta Nag and Jean de Rivieres (BHPBilliton).

Our work, clearly, was not conducted in a vacuum, and we have attempted to give due consideration to the considerable volume of research that has been contributed to the BHT puzzle during the period of our own study. For reasons of brevity, not all of that work is referenced here, and we apologise for the many notable omissions.

Tectonic Setting of BHT Mineralisation

Our work supports the long-held conclusion that BHT deposits formed in failed continental rifts (e.g. Willis et al., 1983; Stevens et al., 1988). Furthermore, our continent-scale analysis of Paleoproterozoic Australia suggests that BHTs formed in rifts of a specific type – in the overriding plate of a convergent continental margin (Giles et al., 2002, 2004; Betts and Giles, 2006). These rifts have a number of characteristics that distinguish them from other styles of basin (e.g. East Africa style rifts, passive margins, foreland basins) and make them more likely to host BHT mineralisation, namely:

- They have prolonged (100s of millions of years), episodic histories of basin formation, often with successive periods of magmatic and sedimentary enrichment of metals (as opposed to East Africa style rifts that can be expected to have a monocyclic evolution).
- They have consistently high geothermal gradients, multiple periods of (typically) bimodal magmatism, and multiple periods of active normal faulting (as opposed to foreland basins that are essentially cold and non-magmatic, with relatively little faulting).
- They have a high potential for basin inversion, exhumation and preservation (as opposed to rifts that developed into passive margins, see below).
- They are characteristically filled by turbidites derived from neighbouring magmatic arcs or mountain ranges.

Mineralisation occurred at a specific time within the evolution of the rift, coinciding with the propagation of deep rift structures, rapid subsidence, and high geothermal gradients, leading to melting of the crust (and indeed of the lower parts of the basin), and the initial tapping of MORB-like melts from the underlying asthenosphere. The association of high-Fe-Ti tholeiitic mafic magmas with Broken Hill and Cannington provides compelling evidence for a propagating rift setting (Williams, 1998; Raveggi et al., 2007). The evolution of MORB-type melts, toward extreme Fe-Ti enrichment, requires isolation within restricted magma chambers at low oxygen fugacity. On the modern Earth, this occurs in regions of rifts, including segments of mid-ocean ridges, where there is some throttling of the magmatic system, restricting magma migration, and allowing relatively small, isolated magma chambers to develop. This can occur in local regions of transpression, or in the propagating tip of a rift system. Conversely, successful rifting leads to flooding of the magmatic system, with large volumes of relatively homogeneous MORB-type melts of average Fe-Ti composition.

In the Broken Hill Domain, despite profound effects of deformation and high-grade metamorphism, the axial zone of the rift, corresponding to the most prospective parts of the block, is still preserved. This northeast-trending belt represents the depocentre of the Broken Hill Group, which is thin or absent in the adjacent Olary Domain (Conor and Preiss, 2008), has the highest concentration of rift-stage bimodal magmatism, and has high Fe-Ti tholeiitic mafic chemistry consistent with a propagating rift setting (Raveggi et al., 2007).

How did (do) BHt Deposits form?

We did not set out to answer this question in our research but, nevertheless, our work has led us to some conclusions that are worth presenting here, a number of which are given more substance below. To summarise:

- As above, BHt deposits formed within a basin environment during the sedimentary phase, and specifically during a period of rapid subsidence and magmatism, corresponding to a significant episode of rifting in the basin (Parr and Plimer, 1993; Parr et al., 2004). This subsidence is recorded as a transition, from relatively oxidised, terrestrial to shallow marine, episodically evaporitic depositional environments, to deep marine, turbiditic sedimentary environments. The sedimentary succession at Broken Hill is now relatively well-constrained by U-Pb zircon dating, with the mineralising episode occurring at ca 1685 Ma (Raetz et al., 2002; Page et al., 2005a, 2005b).
- Bimodal magmatic rocks, including felsic end-members derived from partial melting of the sedimentary pile and mafic end-members derived from partial melting of asthenospheric (MORB) sources, were important components of the rift system. Mineralisation appears to be associated with magmatic centres, which we interpret as important thermal engines driving the hydrothermal system (cf. Parr and Plimer, 1993).
- A plume of hot, saline, sulfur-bearing and metal-charged fluids was driven toward the surface, by buoyancy and seismic pumping, along active faults in the hangingwall of major normal fault systems (commonly reactivated as thrusts or strike-slip faults during later tectonic reworking).
- Salt, metals and sulfur were derived most likely from the sedimentary and magmatic rocks within the basin at the time of mineralisation (e.g. at Broken Hill, the lower Broken Hill Group, Thakaringa Group and Redan Gneiss; in the Eastern Fold Belt, Mount Isa Province, the lower Maronan Supergroup and the Corella/Doherty Formation). These successions include relatively oxidised (sulfate stable) metasedimentary rocks as a source of sulfur, evidence of evaporitic rocks as a source of salt, and large volumes of metal-depleted rocks as a source of Pb, Zn and Ag.
- Thermal reduction of sulfate within the hydrothermal fluid (i.e. the fluid drives local reduction and carries reduced sulfur to the trap site) provides the simplest explanation for the relatively oxidised and low-sulfide nature of the host-rocks, in comparison to SEDEX systems.

- Metal zoning and metal ratios in the deposits are consistent with deposition of the base-metal sulfides due to mixing of hot, relatively saline ore fluids with cool, lower salinity basin waters, at or near the ocean floor.
- Structural, metamorphic and metasomatic reworking of the deposits are important processes in terms of: (a) redistribution of sulfides and formation of high-grade shoots (b) metamorphic differentiation and coarsening of the ore and, (c) exhumation of the deep basin architecture to recoverable mining depths.
- The last of these points (7c) provides an explanation for the empirical observation that BHT deposits are invariably deformed and metamorphosed at amphibolite facies or greater. Namely, the formation of the BHTs during rapid subsidence and their burial by a thick (probably >10km) pile of turbiditic sediments means that they would not have been exposed at or near the surface, unless they were exhumed during subsequent deformation, most likely by thrusting and erosion of the overlying sedimentary pile. Hot, deep basins are likely to be zones of lithospheric weakness (potentially for 100s of millions of years after active extension) and will tend to focus subsequent shortening – manifest as ‘hot-mode’ basin inversion and high T-low P metamorphism. Further, the hangingwalls of prior normal faults, and the most likely location of BHT deposits, are the most likely regions of crust to be exhumed as the normal faults are reactivated as thrusts.

Source of Fluid

There is some support for a significant mantle input of fluids and metals in BHT systems, either by direct plumbing of mantle fluids (e.g. Plimer, 1985) or by fluids exsolved from mantle-derived mafic magmas (e.g. Crawford and Stevens, 2006).

In our view, there is no need to call on fluids or metal sources external to the basin in which the BHT deposits formed. Metal ratios at Broken Hill and Cannington (Pb>Zn>Cu) are the reverse of what might be expected from a mantle-derived fluid, and are most consistent with an upper crustal source. Lead isotope ratios at Broken Hill and Cannington, often cited as evidence of mantle input, are entirely consistent with crustal Pb reservoirs (Zartman and Doe, 1981), albeit not as isotopically evolved as the north Australian SEDEX deposits. The small isotopic difference between the two systems could be explained easily by a minor contribution of Pb via leaching of syndepositional mafic rocks in BHT systems. Neodymium isotopes from the Broken Hill orebody and related metasedimentary units, have a crustal signature (~ -4 to -6 ‰) identical to metasedimentary rocks of the Willyama Supergroup, and considerably more negative than contemporaneous mantle (~ +4 ‰) (Raveggi, 2008).

Source of Metal

The likely source of metals for the Broken Hill system is the lower parts of the Willyama Supergroup, specifically the Na-rich quartzofeldspathic rocks often referred to as albitites. These rocks have similar rare earth element patterns and concentrations to Proterozoic sedimentary rocks throughout Australia, implying a similar provenance and sedimentary processes. They are remarkably depleted, however, in a range of elements that are coincidentally enriched in the Broken Hill deposit (Pb, Zn, Ag, Fe, Mn, Ca, K) (Forbes, 2001).

In our view, the dissolution of salt, and albitisation and leaching of metals, from these sediments were synchronous and related processes, which are predictable in a thermodynamic sense, and have analogues in modern hydrothermal systems (e.g. the Salton Sea). An interesting aspect of this is that albitisation and metal leaching should be volume-reducing processes, that can be expected to increase permeability and facilitate further fluid flow through the altered rocks. This provides an explanation for the restricted and largely stratabound nature of albitisation in the Broken Hill Domain, that is, there was a feedback mechanism that focussed fluid flow and alteration within certain aquifers.

The charging of subsurface aquifers with saline and metal-rich fluids may have been a relatively long-lived process, beginning soon after deposition of the lower Willyama Supergroup

sediments (Forbes, 2001). Tapping of this fluid, due to faulting and thermal convection during deepening of the rift provided the necessary link between the source and trap site, close to the sediment-water interface. This view of the mineralising system has similarities to hydrocarbon systems and has implications for BHT exploration. Namely, understanding and locating potential source rocks within the basin is an important, but often overlooked, exploration strategy that may help to build confidence in a terrane and possibly(?) to vector toward mineralisation.

Source of Sulfur

The tight cluster of Broken Hill $\delta^{35}\text{S}$ measurements, at approximately zero, has been proposed as evidence of a primordial mantle signature (Plimer, 1985). The $\delta^{35}\text{S}$ data from Broken Hill, however, is not centred on zero but is slightly positive, and is shifted approximately -15‰ compared to seawater sulfate, of the same age, deposited in the same basin (Parr and Plimer, 1993; Lottermoser and Ashley, 1996). This isotopic shift, and tight clustering of data, are consistent with thermal sulfate reduction in modern sub-seafloor hydrothermal systems. Thus, the data are entirely consistent with an intra-basin source of sulfur. Further, the sulfur isotopes provide some constraint on the nature of the ore system. Namely, a thermal plume that entrained sulfate from the surrounding sedimentary pile, reduced it to sulfide and transported it to the site of deposition. This, in turn, helps to explain the conundrum of a massive sulfide deposit hosted within a sulfide-poor environment.

Role of Evaporites

The (prior) existence of evaporites in the lower Willyama Supergroup (Broken Hill) and the Corella/Doherty Formation (Eastern Fold Belt, Mount Isa) can be inferred from widespread albitisation, scapolitisation, tourmaline chemistry, high Cl-contents in common hydrous minerals, and highly-saline fluid inclusions (e.g. Cook and Ashley, 1992).

The importance of these rocks is threefold:

- They provide the most likely source for the salt within the voluminous, highly-saline hydrothermal fluids, thought to be associated with BHT systems. The solubility of most metals increases markedly with increasing salinity, such that hot, highly-saline brines (~ 30 wt% NaCl) are efficient scavengers of metals from the rocks through which they pass. Lower salinity meteoric or ocean waters are not nearly as efficient. Magmatic fluids can be highly saline, but in the context of Broken Hill or the Eastern Fold Belt, would be volumetrically minor – magmatic rocks of appropriate age being of low volume. It can be argued, therefore, that: no evaporites = no voluminous, highly saline hydrothermal fluids = no BHT.
- They are a potential source of sulfur, originally as evaporitic sulfates.
- They provide a link between tectonics, climate and metallogenesis, which is potentially mappable. Evaporites form in specific geographic environments of high evaporation, low precipitation typically between ~ 15 and 45° latitude. Australia occupied such a location at around 1.7 Ga (Idnurm, 2004). High volume evaporites of wide geographic distribution (as might be comparable to the ca 1.7 Ga Australian basins) have analogues in the Phanerozoic record, where they have three broad settings: (a) continental interior sag basins, (b) post orogenic foreland basins and, (c) late-stage rifts with partial connection to the ocean (Warren, 1999). The latter is the most appropriate analogue for the Australian BHT terranes. The high volume evaporite deposits of the Phanerozoic are further associated with periods of global oceanic lowstands, and widespread marine regression from continental margins.

Global sea level variations are a function of tectonic, eustatic and climatic controls, which are difficult to infer from the analysis of individual basins. It is interesting to note, however, that one important first order control appears to be the distribution and growth of the continents. Continents of large area (specifically supercontinents such as Pangaea, Gondwanaland,

Rodinia or Columbia) can be expected to be high-standing, with broad continental margins potentially exposed to evaporitic conditions. This may provide some explanation for the temporal distribution of sediment-hosted, base metal deposits (BHT, SEDEX, MVt and Sed Cu) during periods of inferred supercontinent stability.

Thus, paleogeography, in terms of the supercontinent cycle, and paleolatitude, can be added to specific basin processes as first order controls on the distribution of BHTs, and other sediment hosted base metal deposits, in space and time.

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Mineral systems of the Koonenberry Belt

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Introduction

The Koonenberry Belt in northwestern New South Wales (Figure 1) is an underexplored terrane which has been a focus of activity for the Geological Survey of NSW through the Discovery 2000, Exploration NSW and the current New Frontiers initiatives. Analysis of new geological mapping, geophysical, geochemical and isotope data, along with 3D mapping of geophysically-modelled cross sections, have resulted in revised interpretations of the tectonic evolution of the Koonenberry Belt, with direct implications for the mineral systems and exploration potential of the belt.

Forming part of the Delamerian Orogen on the eastern margin of the Curnamona Province (Figure 1), the Koonenberry Belt has undergone a complex tectonic history from the Neoproterozoic to the present. This has included multiple cycles of sedimentation, volcanism and deformation (Figure 2). The Koonenberry Fault, the dominant structural feature of the belt, is a long-lived, deep crustal structure that has provided a conduit for fluid flow, in association with other structures.

Since mining in the Koonenberry Belt commenced in the 1880s, a diverse range of mineral occurrences have been recorded. The belt is prospective for orthomagmatic Ni, volcanic-associated, massive sulfide (VMS; Besshi-style) Cu–Zn–Ag–Au, turbidite-hosted orogenic gold, and epithermal polymetallic mineralisation (Figure 1). Furthermore, conceptual base metal mineralisation such as sediment-hosted base metals, ultramafic-hosted Ni–Co, and Late Delamerian half-graben-hosted Au, remain untested. Some Late Permian to Early Triassic diatremes have been targeted for diamond and base metal mineralisation, although the majority remain untested. A complex post-Permian landscape evolution has resulted in fossil and recent placer gold deposits in Mesozoic and Quaternary units respectively. Opal deposits are hosted by Mesozoic units in the White Cliffs area. Industrial minerals are an underexplored commodity group, primarily due to the isolation of the area.

In addition to primary mineralisation, the belt has undergone multiple deformation events, which provide structural complexity and the potential for upgrading mineralisation. The Koonenberry Fault, and related splays, the Grasmere Knee Zone and Cobham Kink Zone (Figure 1), are all major structural features that have undergone a complex history of reactivation and fluid infiltration.

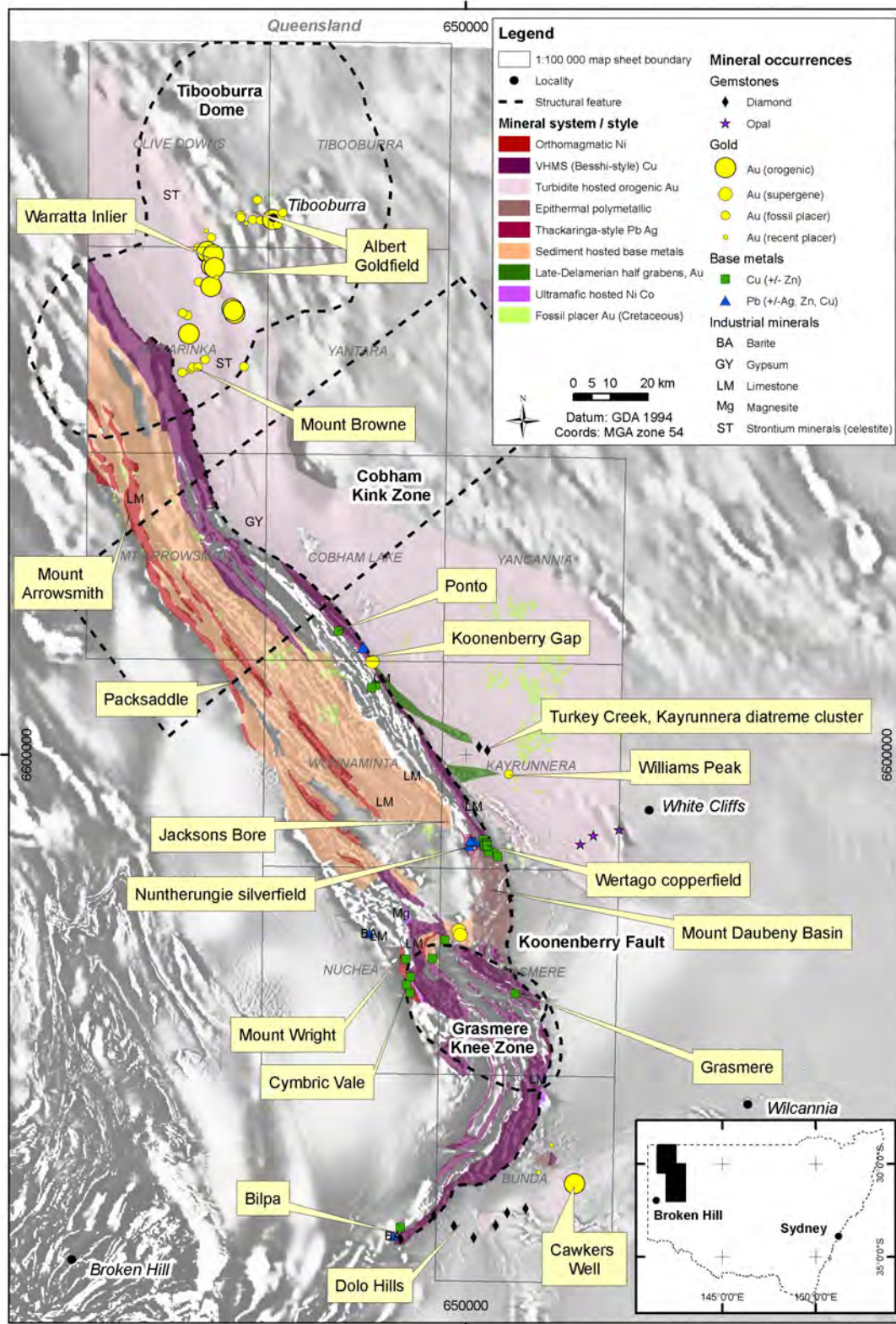


Figure 1. Known mineral occurrences and potential mineral systems of the Koonenberry Belt, over an image of the first vertical derivative of total magnetic intensity.

This abstract aims to relate mineral systems of the Koonenberry Belt to tectonic setting, geological history and landform evolution through time. A more detailed synthesis of mineral systems of the Koonenberry Belt (Gilmore, 2009) is available in Greenfield et al. (2009).

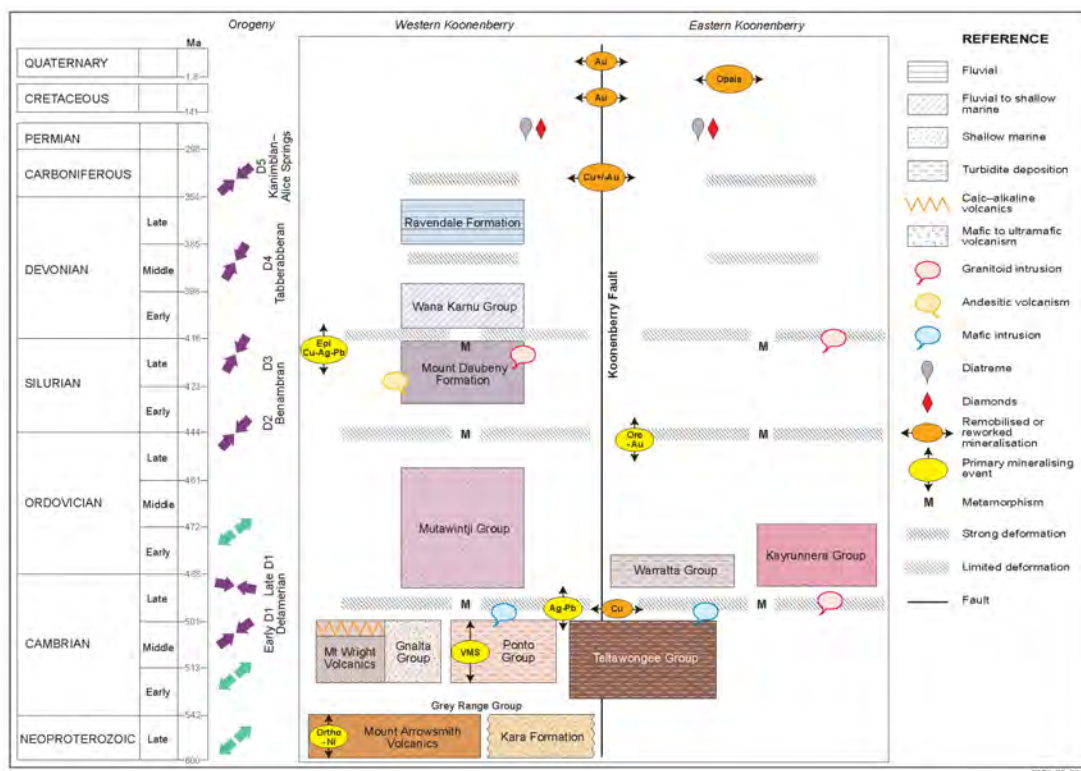


Figure 2. Simplified time–space plot, illustrating geological history and mineralising events in the Koonenberry Belt. Note: Arrows show approximate extension and contraction vector directions. Ortho-Ni = orthomagmatic Ni; VMS = volcanic-associated massive sulfide base metals; Ag–Pb = Thackaringa-type veins; Epi-Cu–Ag–Pb = epithermal base metal mineralisation; and Oro-Au = turbidite-hosted orogenic Au. Not to scale. After Greenfield and Reid (2006), Greenfield (2009) and Gilmore (2009).

Mineral Systems

Orthomagmatic Nickel

The Neoproterozoic Mount Arrowsmith Volcanics, of the Grey Range Group, consist of transitional alkaline suite from basalt through to alkali rhyolite, with associated ultramafic and mafic intrusions. They are interpreted to be related to intracontinental rifting, with volcanic centres identified at Mount Arrowsmith, Packsaddle and near Mount Wright (Figure 1). Further units have been interpreted from regional airborne magnetic surveys, buried under sedimentary and/or Quaternary cover.

The Mount Arrowsmith Volcanics are host to orthomagmatic Ni (\pm Cu) mineralisation. Primary sulfides (pyrite–chalcopyrite–pyrrhotite) and violarite (ex-pentlandite) have been intersected in exploration drilling (Sharp, 2006), with intersections up to 0.5% Ni and 0.45% Cu occurring. This mineralised interval is hosted within a peridotite intrusion with gabbroic margins to the east of Mount Arrowsmith (Sharp, 2006). Controls on mineralisation, such as flow or intrusion dynamics, location of feeder conduits and stratigraphic relationships, however, are unknown at this stage.

Stratiform Sediment-hosted Zn–Pb–Ag or Mississippi Valley Type Mineralisation

The Neoproterozoic Kara Formation, of the Grey Range Group, is a package of shelf to slope sedimentary rocks. Outcrops of the Kara Formation typically consist of bleached interbedded sandstone and siltstone, although manganese-rich exhalative and dolomitic units are common (particularly near Mount Arrowsmith), while samples from drilling include carbonaceous slates (\pm pyrite \pm pyrrhotite). These units are interpreted to have been deposited in an intracontinental rift setting, and are synchronous with the alkali basalts of the Mount Arrowsmith Volcanics.

This geodynamic setting is known to contain stratiform, sediment-hosted Zn–Pb–Ag mineralisation (McGoldrick and Large, 1998) and Mississippi Valley Type mineralisation (Dörling et al., 1998). Little modern exploration, however, has been undertaken for base metals in the Kara Formation. This is despite historic stream sediment geochemistry, indicating an elevated copper and zinc background in the Kara Formation (Needham, 2002).

In the Jacksons Bore area (Figure 1), anomalous base metal assays (90 m @ 8 g/t Ag, including 3 m @ 89 g/t Ag, 1.5 % Pb, 0.14 % Zn) were intersected in drilling associated with sulfide–goethite–rich veining at a black shale–siltstone contact (Madden, 1998). This intercept was never followed up, and remains one of the few holes drilled into the Kara Formation targeting base metal mineralisation. Furthermore, the Kara Formation is equivalent to the Adelaidean Farnell Group to the west of the Bancannia Trough, which has been a focus for Mississippi Valley Type exploration on the Mundi Mundi Plain (Richardson, 2007).

Volcanic-associated Massive Sulfide (VMS) Besshi-style Cu–Zn–Ag–Au

The Ponto Group is a mid to late Cambrian package of ocean floor phyllites with sandstone lenses, exhalative horizons (including quartz–magnetite units) and felsic tuffs, with MORB-affinity extrusive basalts and mafic intrusives of the Bittles Tank Volcanics. This package is consistent with deposition in an ocean-floor setting proximal to a spreading ridge.

Besshi-style, volcanic-associated, massive sulfide (VMS) mineralisation results from massive sulfide deposition on the seafloor or sub-seafloor, due to the combination of basinal brines and the mixing of continental- and volcanic-derived sediment, with heat input provided from the injection of spreading ridge basalts (Höy, 1995). This syngenetic mineralisation is typically Cu-rich, with various grades of Zn \pm Pb \pm Ag \pm Au (Höy, 1995).

Besshi-style VHMS mineralisation is hosted by the Ponto Group, such as thrust repeats, folding, and remobilisation of fluids in the Delamerian Orogeny, and later events, may have upgraded the deposits. Pb-isotope analysis supports a model of two mineralising events at the Grasmere deposit – a primary syngenetic event, and a later remobilisation event, that is, the Delamerian Orogeny (Zhou et al. 1992; Gilmore 2009). The Ponto Group is strike-persistent, with over 200 km of prospective ground, including areas under shallow Quaternary cover, remaining untested, with only limited historical drilling.

Turbidite-hosted Orogenic Gold

Orogenic gold has been recorded on the eastern margin of the Koonenberry Belt, where turbidite successions have been deformed by a Late Ordovician to early Silurian regional D2 deformational event (correlated with the Benambran Orogeny; Greenfield, 2009). This event resulted in cleavage-parallel, crack-seal quartz veins, and thrust faults producing hangingwall anticlines. In the Warratta Inlier, orogenic gold is hosted by the Late Cambrian Jeffreys Flat Formation of the Warratta Group (Figure 1). In the Williams Peak and Cawkers Well areas, orogenic gold is hosted by the Bunker Creek Formation of the Teltawongee Group (Figure 1).

Greenfield and Reid (2006) favourably compared the style and structural controls of gold mineralisation in the Warratta Inlier with the turbidite-hosted orogenic gold systems, as defined by Bierlein et al. (1998), and to the world-class deposits of the Bendigo Zone of the Victorian Goldfields. Historic mining of the Pioneer–Phoenix reef system in the Warratta Inlier in the late 1880s averaged ~25 g/t Au. Gold is associated with pyrite and arsenopyrite. Strike-extensive, carbonate–sericite bleached zones correlate with magnetic lows (zones of magnetite destruction) and narrow halos of phengite–chlorite–pyrite–carbonate alteration. Drilling in 2006 confirmed the continuation of gold mineralisation at depth, including 4m @ 4.39 g/t Au from 88 m depth (Mortimer, 2007). Transpression in the regional D3 event (following, or late in the Benambran Orogeny) in the latest Silurian, folded the early Benambran foliation and reactivated major faults (e.g. Warratta and New Bendigo faults) in the inlier (Greenfield, 2009).

Epithermal Polymetallic Mineralisation

The Mount Daubeny Basin (Figure 1) is a pull-apart basin that is interpreted to have opened through dextral transpression, related to a dilational jog in the Koonenberry Fault during the regional D3 deformational event (either following or late in the Benambran Orogeny; Greenfield, 2009). Sediment fill of the basin resulted in the Mount Daubeny Formation, with the sediment being sourced from the nearby Delamerian Highlands. Clasts in the basal conglomerates of the Mount Daubeny Formation are recognisable as being sourced from the nearby Cambrian basement Ponto and Teltawongee Groups. Volcanism of the Wertago Volcanics was synchronous with early deposition in the basin, with andesitic lavas and volcanoclastic rocks intercalated with basal conglomerates in the northeast corner of the basin. Late-stage, quartz–feldspar porphyry dykes of the Wertago Volcanics are oriented north-northeast across the basin, in a tensional array (Greenfield, 2009). These dykes intrude both the Mount Daubeny Basin and the Cambrian basement units.

In the north of the Mount Daubeny Basin, two historic mining fields are of note, the Nuntherungie Silverfield (including the Great Nuntherungie, Central and Nil Desperandum mines) and the Wertago Copperfield (including the Eclipse, Big (or Great) Wertago, Bunker Hill, Copper Well mines) (Figure 1).

Three styles of mineralisation are interpreted for the northern Mount Daubeny Basin.

Argentiferous galena-bearing quartz–siderite veins, mined on the Nuntherungie Silverfield, have been described as Thackaringa-style veins, as seen in the Curnamona Province (Barnes, 1975). Pb-isotope ratios of samples from the Nil Desperandum indicate a mixed mantle and crustal source, with a Cambrian lead model age.

Epithermal textures (e.g. botryoidal quartz and malachite, comb textures and quartz cavity-fill textures) have been observed in deposits, in both the Nuntherungie Silverfield and Wertago Copperfield, hosted by Cambrian Ponto and Teltawongee Groups and by the Siluro-Devonian Mount Daubeny Formation and Wertago Volcanics. Copper-rich mines are clustered around the andesitic volcanism in the north of the basin. We interpret the andesitic volcanism to be the driver for epithermal mineralisation. Cu-rich breccias (e.g. Eclipse, Bunker Hill) are controlled by north-northeast trending structures, reflecting a tensional orientation. Porphyritic felsic dykes of the Wertago Volcanics are in a parallel orientation, and are intimately related to mineralisation.

We interpret the remobilisation of copperiferous fluids around the Wertago area (e.g. Bradys Open Cut) to have occurred during the Kanimblan–Alice Springs Orogeny, exploiting reactivated faults. For example, the lode at the Big (or Great) Wertago Mine is a Cu-rich crush zone along the Koonenberry Fault.

The distribution of primary mineralisation may be a reflection of thermal zonation, with Cu-rich deposits of the Wertago Copperfield proximal to the volcanic pile, and the Ag–Pb rich deposits of the Nuntherungie Silverfield being distal.

Further work is required to map the structures and volcanic facies variation to define zones of alteration and mineralisation, and to ascertain the chemistry and the source of mineralising fluids. Limited drilling in the area has not targeted epithermal style mineralisation, or sufficiently tested Ag–Pb mineralisation at Nuntherungie.

Placer Gold

Fossil placer gold deposits are hosted by the Namur Sandstone, the basal Mesozoic unit, throughout the Koonenberry Belt, but especially around the margins of the Tibooburra Inlier, and the southeastern margin of the Mount Browne Inlier (known as the Albert Goldfield, Figure 1). There has been much speculation on the source of gold in these areas, given the lack of primary mineralisation in these inliers, and the lack of fossil placer gold around the Warratta Inlier, which is known to host orogenic gold. Hill et al. (2008) proposed a gold source to the northwest of the Tibooburra Inlier, and that both the Tibooburra and Mount Browne inliers were emergent during the Mesozoic, causing interruptions to fluvial and marine currents, resulting in sediment (and alluvial gold) deposition. In contrast, the Warratta, Mount Poole and the Gorge Inliers were probably submerged at that time, thus explaining the lack of basal Mesozoic deposition and associated gold around those inliers (Hill et al., 2008).

Reworking of the Cretaceous units has resulted in recent placer gold deposition within Quaternary and modern day alluvial systems. Quaternary alluvial leads were mined around all inliers in the northern Koonenberry Belt (McQueen, 2007).

Gemstones

Over 200 bullseye anomalies have been identified in the Koonenberry Belt, some of which may be potentially diamondiferous. The Koonenberry Fault system, a major crustal feature, with multiple episodes of movement and possible oceanic crust at depth, may represent a potential pathway for mantle-derived pipes (Temby, 2004). The Turkey Creek (or K1) diatreme breccia pipe, and associated diatremes, in the Kayrunnera diatreme cluster (Figure 1) contain high-pressure kimberlitic indicator minerals, suggesting the area has major potential for diamonds (Temby, 2004). No diamonds, however, have yet been discovered in this area. Emplacement ages of 260 ± 67 Ma (Rb–Sr dating; Stracke et al., 1977) and 264 ± 18 Ma (sphene fission track dating; Gleadow and Edwards, 1978) have been determined. In the south of the Koonenberry Belt, in the Dolo Hills area (Figure 1), recovery of one macrodiamond and six microdiamonds in the 1990s, and nearby shedding of kimberlitic chromite from basaltic intrusives, suggest a local source of diamond (Temby, 2004).

Drilling of diatremes, spatially associated with the Cobham Kink Zone, intersected Late Permian to Early Triassic mafic breccias of alkalic-basaltic affinity (Nelson, 1990). These diatremes, however, were targeted for gold and base metal mineralisation, and there was no investigation of diamond potential.

Opals were discovered in the White Cliffs area in 1889, where they occur as thin veins hosted by the sedimentary rocks of the Early Cretaceous Doncaster Member of the Wallumbilla Formation of the Rolling Downs Group (Burton and Mason, 1998). Two opal prospects occur on the Kayrunnera 1:100 000 map sheet area.

Industrial and Heavy Minerals

Due to the remoteness of the area, and the small size/low quality of known resources, little investigation of industrial minerals has been undertaken throughout the Koonenberry Belt. Several occurrences are of interest, however, including magnesite, strontium minerals, gypsum, maghemite pisolite-rich units and potential for heavy mineral placers/strandlines and rare earth elements (Gilmore, 2009).

Mining and Exploration History

The Koonenberry Belt has a rich mining history dating from the discovery of gold near Mount Poole in 1880 (McQueen, 2008). This includes the 1880's gold rush on the Albert Goldfield, mining of copper from 1870 from the Wertago Copperfield, Ag–Pb mining at Nuntherungie from 1890, and copper mining at Grasmere from 1898 (Gilmore, 2009). The remoteness and aridity of the area, variations in metal prices and the relative richness of commodities in adjacent areas (e.g. Broken Hill, White Cliffs), rather than a lack of ore, however, eventually led to cessation of mining operations with the last mining in the early 1900s.

In terms of modern exploration, the Koonenberry Belt remains an underexplored region, despite significant mineral occurrences and high potential for discovery of further resources and additional styles.

Acknowledgments

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DHEM and DHMMR at the North Mine, Broken Hill

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Introduction

The use of borehole geophysics in Broken Hill has waxed and waned with the success of the various tenement holders. Companies such as Pasminco and Perilya applied borehole geophysics routinely on deeper (~>150m) drill holes, whereas other companies used it very rarely, if at all. This abstract reviews the benefits and drawbacks of some of the borehole geophysical techniques, and presents results of the recent, innovative application of downhole magnetometric resistivity (DHMMR) on the North Mine Zinc Lodes mineralisation.

Background

Drilling aims to directly sample geology in order to detect and define economic deposits. The main limitation of this method is that each drillhole only samples a tiny proportion of the target and may not be representative. At best the target area will be under-sampled, and speculative conclusions drawn about any ore resource. At worst, a world-class deposit might be missed. Borehole geophysics provides a way to minimise the risk of misinterpreting the drilling data, reduce the need for closely-spaced, costly drilling, and maximise the value of each drill hole.

The cost-benefit analysis is simple. Taken on a per hole basis, for a cost typically between 1 % and 10 % of the drilling costs, borehole geophysics massively can reduce the requirement for further holes, or even eliminate it entirely. Firstly, resources in the vicinity of the boreholes can be detected and characterised, better targeting future drilling and minimising cost. Secondly, and equally importantly, the surveys can sterilise areas to be precluded from further resource delineation.

The value of a particular geophysical technique depends primarily on the petrophysical properties, ore geometry, and immediate commercial objectives. Table 1 summarises some of the techniques available, and recent advancements. Not all of these techniques have been applied on Broken Hill mineralisation, or are even applicable in this setting, but they are listed here as a useful reference for explorers.

Downhole Electromagnetics (DHEM)

DHEM is, by far, the borehole geophysical technique that is most frequently applied in Broken Hill. A rough estimate suggests that over 40 km have been logged by the various CML 4, 5 and 6 license holders in the period 1990 to 2008. The technique is best suited to detecting highly conductive material with plate-like or block-like geometry, for example, the Lead Lodes. Historically, the technique was only hampered the lack of surface drill holes at the northern and southern end of the Broken Hill orebody (very deep), with relatively few in-mine holes available

for surveying. New EM probes, however, have smaller diameters and have been used very successfully for in-mine surveys.

Table 1. List of common borehole geophysics (Wedepohl et al., 2008)

Technique	Description	Application and Advancements
Geophysical Logging	Detailed physical property classification of the core or immediate vicinity of the borehole. Key advantage is data density and speed relative to conventional geophysical logging.	Correlation of ore and lithological zones and rock quality, with routine application to coal and iron ore mining. Advancements towards routine classification of mineralogy downhole envisaged, leading to more pervasive application.
Downhole electromagnetic (DHEM)	Locates zones of well-connected, electrically-conductive material away from the borehole. Key advantage is ability to detect significant blocks of high grade mineralisation away from the borehole.	Most applicable to mapping highly conductive and well-connected base metal mineralisation blocks, such as nickel. Recent advancement has been the use of three component magnetic sensors, which extend search radius under some conditions.
Downhole induced polarisation (IP)	Locates zones of poorly connected electrically conductive material away from the borehole. Key advantage is ability to detect disseminated mineralisation.	Used for mapping disseminated mineralisation where DHEM is not applicable (e.g. copper, lead, zinc). Can be difficult to interpret. Advancements in data modelling and inversion will improve diagnostic ability in spatially locating ore occurrences.
Downhole magnetometric resistivity (DHMMR)	Locates linear occurrences of moderately conductive electrically conductive material away from the borehole. Key advantage is the ability to map such features which cannot be well detected by DHEM.	Used for mapping linear stringers of moderately conductive base metal mineralisation, or hosting shear zones, where DHEM is not applicable. Has been particularly effective for Broken Hill type deposits. Further enhancements will improve ability to spatially locate ore occurrences.
Radio wave tomography (RWT) and electrical resistivity tomography (ERT)	Provide tomographic images of electrical conductivity or resistivity between borehole pairs. A key advantage is providing information further away from the borehole than provided by single hole techniques.	Typically applied over ranges of fifty metres to few hundred metres, so mostly applicable during second phase or infill drilling. Ability to map out base metal occurrences beyond the search radius of DHEM. Performance is dependent significantly on rock electrical characteristics and borehole geometry. Has been used to date for establishing coal seam geometry, and in mapping out base metal deposits.
Seismic Tomography	Provide tomographic images of seismic velocity between borehole pairs.	Typically applied over ranges of fifty metres to few hundred metres but with the potential to be applied over longer ranges. Key application is characterising rockmass quality where this is critical to mining operation.
Borehole Radar (BHR)	Very high resolution, which maps radar reflectors within tens of metres of the borehole. Thus, mostly applicable to tactical application during mining operations.	Has been applied successfully to mapping gold and platinum reefs in South Africa, and in mapping nickel deposits around the Kambalda Dome and Leinster in Western Australia.

DHEM at Broken Hill: 2K Mineralisation

One of the most notable examples of a clever, and highly useful, application of DHEM at Broken Hill is the 1991 DHEM survey of the 2K-mineralisation, North Mine (Bishop, 1996). Exploratory underground drilling from the Fitzpatrick Lode, which is about 1.5 km below surface, detected another separate, down-faulted block at a depth of about 2 km below surface.

Limited access and poor ground conditions meant investigation of the 2K area was difficult. It was decided to try DHEM to see if this could help determine the geometry and size of the body. If EM suggested a large source, then this would be a good argument to continue drilling. The survey and data interpretation were very challenging, but the final results indicated that the drilling hit near the centre of the 2K mineralisation. No other significant conductors were interpreted in the vicinity (Bishop, 1996). This information was highly valuable for making strategic decisions about the future of the North Mine.

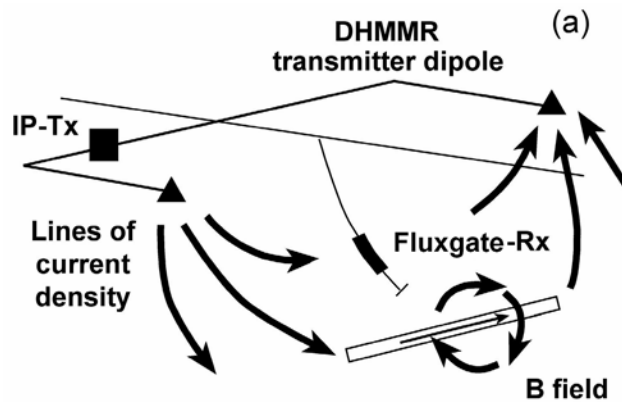


Figure 1. Survey layout for a standard DHMMR survey.

Downhole Magnetometrics (DHMMR)

DHMMR is the little-known relation of DHEM, in terms of prominence to the geological world. In the appropriate setting, however, DHMMR can give much better results. DHMMR is a pseudo-DC grounded, dipole geophysical survey method (Nabighian et al., 1984; Asten, 1988; Bishop et al., 1997), which allows absolute direction to a conductor from a borehole to be established. The grounded dipole channels the current through more conductive units (i.e., the mineralisation), and the downhole survey records the magnetic field generated by these galvanic currents (Figure 1). These are modelled in a similar way to gravity anomalies, with the current density being the prime variable, alongside anomaly location and size.

DHMMR is ideally suited for detecting narrow, ribbon-shaped and/or poorly conducting mineralisation, a target which is generally nearly invisible to EM methods. Until recently, the downhole receiver was a standard downhole, single (axial) component coil (TEM) probe measuring dB/dt . Advances in technology presented the opportunity to use 3-component B-field probes in a survey at the North Mine, Broken Hill. This proved very successful at delineating mineralisation, which DHEM failed to detect. This mineralisation was directly below the North Mine infrastructure, and therefore a real challenge to isolate and energise for geophysical surveys.

DHMMR at the Broken Hill: DHMMR versus DHEM

The main style of Pb-Zn mineralisation in Broken Hill is invariably conductive enough (10-1000 S/m; Bishop and Emerson, 1999) to give good electromagnetic (EM) responses (Bishop, 1991). Potosi and other lode horizons north and south of Broken Hill, however, contain a number of sphalerite-rich and galena-poor zones, which are much less responsive to EM. The reported conductivity for the Zinc Lodes and Potosi mineralisation is a few S/m or less (D.W. Emerson, J.R. Bishop and Y.P. Yang, unpub. data). DHMMR was so effective at delineating Potosi style mineralisation that over 55 km were logged in the period 1990 to 2008.

The prime reason for using DHMMR versus DHEM is the ability to detect narrow, elongated targets, and/or relatively low conductivity (<10 S/m) targets. This is because DHMMR requires only a conductivity contrast between the host rock and the target. Research indicates that a

conductivity contrast of 3 between host and target is sufficient to channel the current usefully and create a good DHMMR signal (Lewis, 1998).

Another reason is that DHMMR potentially can detect extremely conductive targets, such as effectively perfect conductors (nickel deposits), where pulse type TEM establishes essentially no changing currents within the body, and no response can therefore be observed. A third reason is the increased target detection range – the magnetic field due to current channelling decays as r^{-1} to r^{-2} (depending on source geometry), whereas most TEM methods involve r^{-2} to r^{-3} factors. Detection distance of >150 m have been recorded in Broken Hill surveys (Godber, 2006; Bishop et al., 1997).

Disadvantages of DHMMR are considered to be as follows:

- Lower signal to noise ratio
- Lack of readily available modelling software, and
- Poorer resolution of target dip/distance from hole

Whereas target resolution essentially is a limitation of using galvanic versus induced fields, the other perceived disadvantages of DHMMR are probably a result of inertia in the development of this technique. Simply put, the equipment and technology were available, but awareness and impetus were lacking. This survey provided the opportunity to bring together the equipment, software, and people to realise finally the potential of 3-component B-field probe DHMMR.

DHMMR at the North Mine: Geological Setting and Exploration Target

The North mine ore-body is hosted in a distinctive mine succession consisting of elements of the Broken Hill Group (Hores Gneiss and Freyers Metasediments) and the Thackaringa Group (Rasp Ridge Gneiss) of the Willyama Supergroup. There are at least six stratiform economic mineral horizons, or Lodes, (Figure 2).

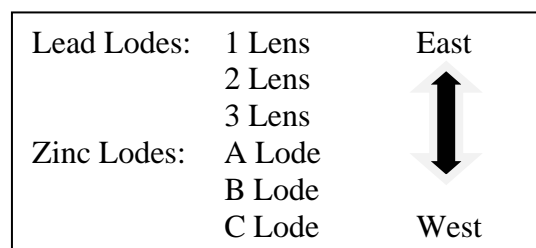


Figure 2. Horizontal position of the main North Mine mineralisation lodes.

The main 2- and 3- lens ore bodies are isoclinally folded and plunge to the northeast at about 40-60°. The Zinc Lodes locally dip ~70° north-northwest, and lie about 20-50 m northwest above the main ore bodies, with a parallel plunge. The steep plunge makes it difficult for surface electrodes to energise the mineralisation at depth in the northeast. This problem was solved by using an old drillhole, with a Zinc Lodes intersection, as the plug-in point for the northeastern electrode.

The North Mine mostly mined the 2- and 3-Lens Pb-Zn lodes, with a small portion of the Zinc Lodes. The Zinc Lodes are considered stratigraphic correlates of the Potosi mineralisation and, as such, difficult targets to define both geologically and geophysically. Zinc Lodes is probably a misleading name for this mineralisation, which is rarely >2 m thick @ 5-10 % sphalerite ± 1-2 % galena, discontinuous, and, rather, seems to be a series of narrow ribbons than continuous sheets. In addition, the mineralisation is poorly conductive, positioned only 20-50m above

massive highly conductive Pb-Zn mineralisation, and lies directly below a working mine and railway track. DHEM has been tried on the Zinc Lodes but with little success (Bishop, 1991).

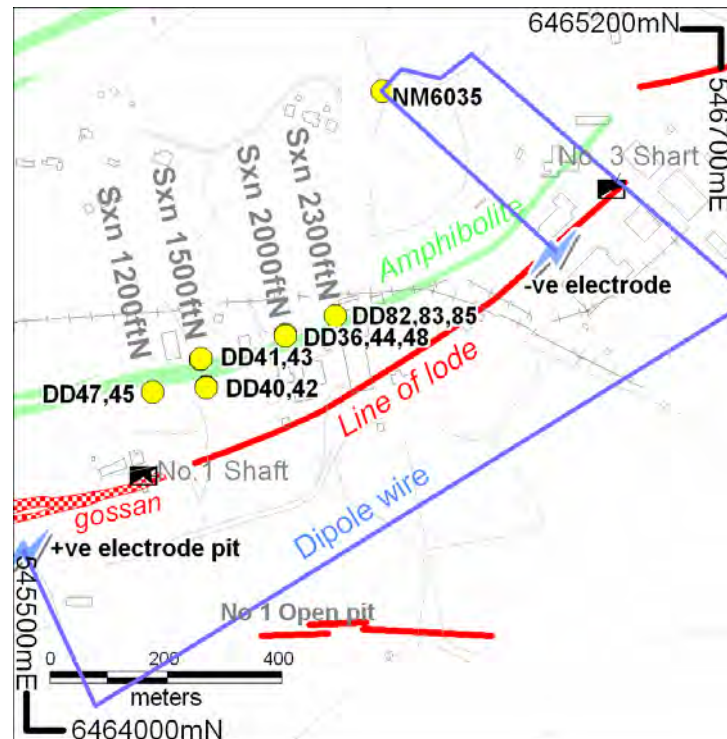


Figure 3. Location and survey set up for the DHMMR program at the North Mine.

DHMMR at the North Mine: Method

The target zone was energised with a 1 Hz square wave impressed into the earth via a grounded dipole which was laid out in a U shape, with the holes to be surveyed within the U (to reduce the effect of the magnetic field in the wire). The dipole length was 1000 m along strike, with the southwestern (positive) electrode in the surface expression of the Zinc Lodes (Figures 3 and 4). The positive electrode was a 2x2 m pit pierced by several star pickets, lined with aluminium foil, and filled with water. The dipole wire was run east, out and around the North Mine waste rock dumps, and back west to drillhole NM6035 (on section 2900ftN). The negative electrode was lowered down NM6035 to ~550 m in a weak (5 % Zn+Pb) Zinc Lodes mineralisation intersection. In this way, the current electrodes isolated and targeted the correct mineralisation, which may otherwise have been too deep for a surface electrode to energise. A standard IP transmitter was used to produce a 7-8 amp current between the electrodes.

DHMMR at the North Mine: Results

The DHMMR data were modelled on a section-by-section basis. The 2D-polygons from this modelling were extended 50 m up- and down-plunge to create 100 m strike-length polygons. These were incorporated into the mine resource modelling software as the best way to visualise the relationship between the model results and the known mineralisation (Figure 4). The primary concern was that the current had short-circuited through the nearby highly conductive North Mine main lode; however, the plotting of the model results soon proved that the models were consistently in the correct stratigraphic position.

The modelling indicated to two types of mineralisation, defined by different current densities. This variation was interpreted as primarily a function of the pyrrhotite composition of the two units, manifesting as current densities of 1 mA/m^2 (saturated) for pyrrhotite rich to 0.1 mA/m^2 pyrrhotite-poor mineralisation. This is supported by previous experience that pyrrhotite is generally very well electrically connected and highly conductive.

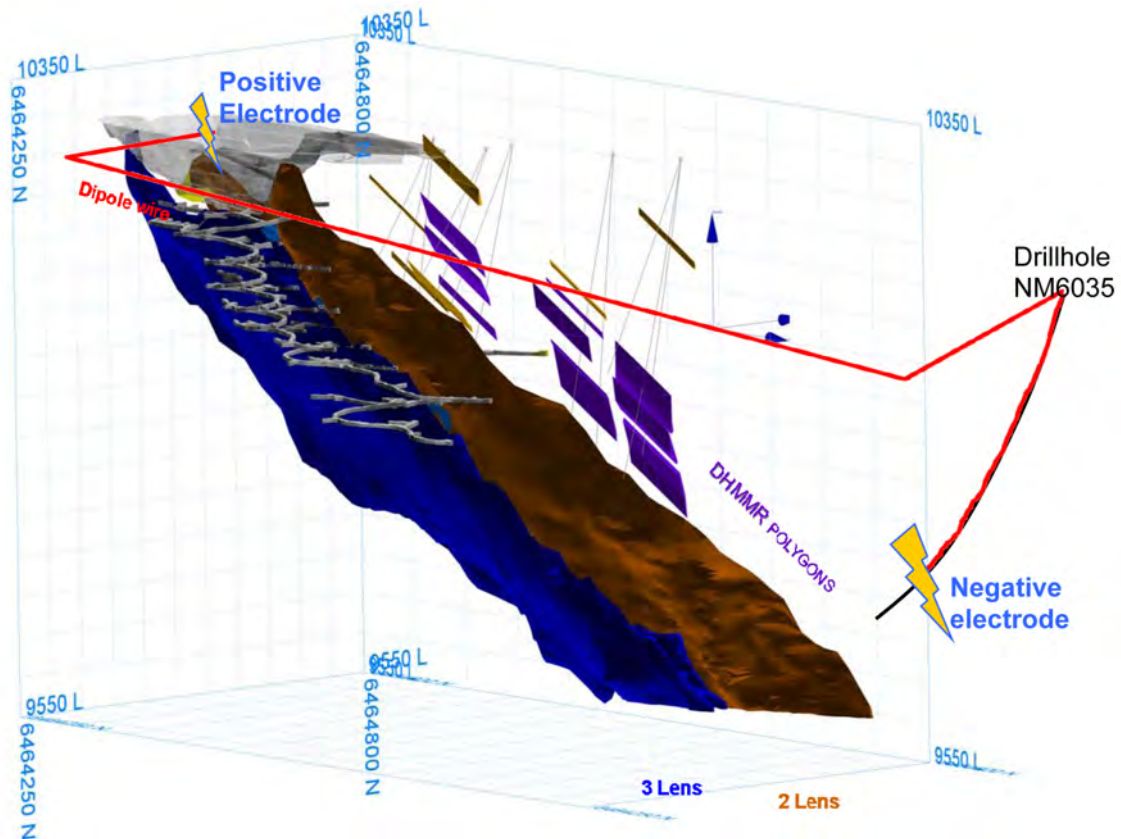


Figure 4. Perspective view looking northwest of 3D DHMMR polygons and drill hole traces with 3-Lens and 2-Lens orebodies.

DHMMR at the North Mine: Discussion

This survey represents the first use of a 3-component fluxgate probe in a DHMMR survey at Broken Hill, and one of the first examples Australia-wide. The survey was considered an excellent success, given the challenging target, location and environment (described below). The data were very low noise, with excellent repeatability, despite proximity to the underground mine workings, railway, and the North Mine infrastructure (Figure 3), which are normally significant sources of EM noise and logistical challenges. The model DHMMR polygons correlated very well with the known geology and expected mineralisation, as well as indicating several new untested zones. The modelled polygons define nearly continuous ribbons west and above the main lode (Figure 4), with different current densities associated with different types of mineralisation.

The comparison between the modelling and the interpreted geology of the North Mine provides a very strong case for the use of DHMMR to delineate low conductivity (100 S/m to $<1 \text{ S/m}$) ore in this challenging setting. In addition, the depth of investigation of DHMMR (when a downhole source electrode is used) does not seem to be limited by any physical constraint, other than

drillhole depth. The success and accuracy of this survey using new equipment is expected to lead to a better appreciation of DHMMR's potential.

Conclusion

Clever and, most importantly, suitable applications of borehole geophysics at the North Mine, Broken Hill, have significantly improved exploration success on this project. For the 2K mineralisation, the real advantage was in the prevention of drilling effort on the 2K target. For the Zinc Lodes, the main reward was information on location and size of mineralisation that was otherwise highly difficult to drill target.

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Cambrian arc–continent collision during the Delamerian Orogeny: evidence from the Koonenberry Belt, northwest New South Wales

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Geological mapping and geological-geophysical modelling of the upper crust in the Koonenberry Belt has provided new insights into the history of a Cambrian volcanic arc system termed the Mount Wright Arc (Scheibner, 1972; Sharp and Buckley, 2003).

The Koonenberry fold-thrust belt is a linear package of Neoproterozoic to Palaeozoic rocks now positioned against the northeastern edge of the Mesoproterozoic Curnamona Province. The geological history of the belt involves Neoproterozoic breakup of the Rodinian supercontinent followed by the development of the Mount Wright Arc outboard of the eastern margin of the newly formed Gondwana landmass (locally Curnamona Province). Subsequent strong deformation during the Late Cambrian Delamerian Orogeny culminated in the cessation of major arc volcanism and the thrusting of volcanic arc elements against/onto the Curnamona Province.

The Neoproterozoic Grey Range Group, which underlies the Cambrian arc elements, consists of shallow shelf marine sedimentary rocks (Kara Formation) and intercalated alkaline volcanic rocks and related intrusives (Mount Arrowsmith Volcanics). This succession is interpreted to be related to intracratonic rifting during the breakup of the Rodinian supercontinent (Crawford et al., 1997). This rifting event led to the strongly extended oceanic crustal setting that would culminate in Cambrian subduction and volcanism along the Mount Wright Arc.

The Mount Wright Arc is associated with three Early to mid Cambrian lithostratigraphic groups:

- Marine turbidites of the Teltawongee Group, which have a conformable base on the Neoproterozoic Grey Range Group, and thicken to the east, outboard of the Mount Wright Arc.
- The Gnalta Group includes calcalkaline, bimodal volcanic rocks of the Mount Wright Volcanics (extrusives dated at ~510 Ma; Black, 2007), interpreted to represent the volcanic component of the arc (Mills, 1992). Only a small area of these volcanics is exposed, however, and the majority of the volcanic pile is interpreted to lie under the Bancannia Trough, a rift-sag basin immediately west of the Koonenberry Belt.
- To the east of the exposed Gnalta Group is the Ponto Group, a marine sedimentary package that includes E-MORB tholeiitic lavas (Bittles Tank Suite) and felsic tuffs. The distal airfall tuffs give a mean age of 511.1 ± 1.7 Ma (Black, 2005). The chemistry of the Bittles Tank Suite and pelagic depositional environment of the host sedimentary rocks are consistent with a forearc setting within the Cambrian arc system.

The Delamerian Orogeny (~504-497 Ma) deformed these Early to mid Cambrian arc elements. Structural interpretation suggests there was initial coaxial shortening followed by sinistral transpression and oroclinal folding of the Ponto Group around the Grasmere Knee Zone.

Scheibner and Basden (1998) interpreted the Delamerian Orogeny in the Koonenberry Belt to be a result of eastward-dipping subduction of oceanic crust inboard of the Mount Wright Arc, causing westward overthrusting of the Middle Cambrian rocks onto the Gondwanaland margin, forming the Delamerian Highlands. In their scenario, the Koonenberry Belt was interpreted as a collection of exotic Neoproterozoic microcontinents (terranes). Geophysical image reconstruction, however, reveals a jigsaw fit across the Bancannia Trough, as well as a coincident structural fabric that has been rotated ~ 20° about a possible Euler pole to the northwest of the Koonenberry Belt. It is interpreted that this rotation was a result of rifting in the early Cambrian, causally related to westward-dipping subduction and the development of the Mount Wright Volcanic Arc in a transitional intracratonic to oceanic setting.

Acknowledgements

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Exploring through and within the cover from Mount Painter to Broken Hill to Tibooburra

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Introduction

The Lake Frome hinterland, extending between the northern Flinders Ranges-Olary Ridge-Barrier Ranges-Grey Range, hosts some of the most prospective geology in Australia for a wide range of mineral resources. The regolith provides cover across most of the prospective bedrock, as well as hosting its own mineralisation. An understanding of the regolith, its association with the landscape history, and relationship with mineralisation, is crucial therefore for mineral exploration programs in this region.

The regolith expression of mineralisation is largely dependent upon the relationships between the mineralised geochemical source and the geochemical dispersion and accumulation within the contemporary and paleolandscape. One way to help account and constrain this, is to consider regolith geochemistry within the context of the landscape, ranging from the sedimentary basin to component drainage basin scales. This is a refinement of previous transect or gridded sampling arrays that have poorly constrained the source-dispersion-accumulation of trace elements within the landscape, and have typically been biased (by being centred on the retrospective knowledge of previous drilling programs) towards buried mineralisation sources, and not necessarily beyond.

Results presented here highlight the value of the landscape geochemistry approach, at both the catchment and sedimentary basin scale, with a particular emphasis on the Lake Frome drainage basin and Cenozoic Callabonna Sub-basin of the Lake Eyre Basin and the Frome Embayment of the Mesozoic Eromanga Basin. This includes results from:

- the Mount Painter Inlier and Lake Frome Plains;
- Olary and Broken Hill areas within the Curnamona Province;
- the southwestern Thomson Orogen in NSW; and,
- parts of the Delamerian Orogen in NSW.

Regional Focus Regolith Studies and Exploration Frameworks

Mount Painter Inlier and Lake Frome Plains, SA

Recent regolith research here, largely has been in collaboration between University of Adelaide and PIRSA (Hill and Hore, in press). The main focus has been on a low order stream catchment crossing the Four Mile West mineralisation, as well as some smaller case studies within the ranges near Mount Painter - Mount Gee and the Gunsight prospect. The Four Mile West study has been able to characterise the nature of U- and Th-rich dispersion from the Mount Painter

Inlier rocks within the Flinders Ranges, across the adjacent Lake Frome Plains and distinguish this from geochemical signatures derived from underlying sandstone-hosted U mineralisation. Most significant here has been the use of regolith carbonate (calcrete) and plant biogeochemistry (especially river red gums and eremophilas) to express buried sandstone-hosted U mineralisation as well as shallow buried primary mineralisation in the ranges (Hill et al., 2008b).

Curnamona Province, SA and NSW

Some of the earliest regolith research in this region was undertaken in the Broken Hill and Olary areas. Small-scale, catchment geochemical studies were undertaken within Honours projects as part of the Pinnacles and Triple Chance 1:25k regolith mapping program (e.g. Debenham et al., 2001; Senior and Hill, 2002), and within the Stephens Creek catchment (Dann, 2001). A low-order stream tributary catchment overlying the Flying Doctor mineralisation was the subject of regolith-landform mapping, regolith geochemistry (soils and calcrete) and plant biogeochemical (prickly wattle, black bluebush, mulga and rock sida, river red gum) studies (Thomas et al., 2002; Hulme and Hill, 2003, 2004; Hill et al., 2005b; Earl et al., 2008). The most successful of the catchment regolith geochemistry and biogeochemistry studies was conducted near the Pinnacles, within the Pine Creek catchment. This study characterised biogeochemically river red gums along Pine Creek near the Pinnacles Mine and contributed to the discovery of the Perseverance Lode underlying Pine Creek (Hill, 2004; Hulme, 2009). A following study of soils and black bluebush biogeochemistry, across the Pine Creek alluvial plains, found strong geochemical and biogeochemical expressions of the Perseverance and Monarch lodes by elevated base metal contents, as well as elevated levels of In overlying mineralisation.

A detailed landscape geochemical study of the White Dam (Cu-Au) prospect examined soil and bladder saltbush biogeochemistry, and showed how >1 m of transported regolith was able to obscure the soil geochemical expression of underlying mineralisation, however biogeochemical expressions could be consistently achieved through 5-10 m of transported cover (Brown and Hill, 2003, 2005, 2007; Lau et al., 2004).

Thomson Orogen, NSW

Following detailed regolith-landform mapping of the Tibooburra Inlier (Chamberlain and Hill, 2002; Hill et al., 2005a, 2005b, 2008a; Hill, 2008; Hulme and Hill, 2008), initial catchment geochemical and biogeochemical studies were conducted in the Dee Dee Creek catchment east of Tibooburra as part of a PhD study by L. Hill (2004). Results from this work showed a strong biogeochemical expression, in bastard mulga phyllodes and twigs, of buried placer Au beneath an aeolian sandsheet. A following river red gum and stream sediment comparative study, along Racecourse and Dee Dee creeks southeast of Tibooburra, found further detrital Au expressions, particularly associated with drainage constrictions and the basal Mesozoic gravels (Hulme and Hill, 2004, 2005; Hill et al., 2008a; Hulme, 2009). A later catchment geochemical and biogeochemical study, flanking the New Bendigo Inlier south of Tibooburra, compared the expression of subcrop and buried (below ~10 m of Mesozoic sediments) primary Au alteration zones (Tucker and Hill, 2006, 2008a, 2008b; Hill et al., 2008a). This study showed that >1 m of transported regolith was enough to geochemically conceal buried mineralisation, although black bluebush twigs provided an expression of buried mineralisation through greater depths of transported cover.

Delamerian Orogen, NSW

Ongoing landscape geochemical studies are being conducted within the Fowlers Creek catchment at Fowlers Gap Arid Zone Research Station, north of Broken Hill. This includes detailed regolith-landform mapping (Hill and Roach, 2003, 2005, 2006, 2008a, 2008b; Hill et al., 2004; Roach and Hill, 2007), soil geochemistry, and river red gum and curly mallee

biogeochemistry. These components are an integral part of second year undergraduate fieldtrip and coursework at the University of Adelaide. Results so far have shown some important geochemical and biogeochemical expressions of major Adelaidean rock units, as well as strong geochemical and detrital expressions of dispersion from high-grade and igneous Willyama Supergroup lithologies to the south and west, since the Mesozoic.

Future Studies

Further landscape geochemical and biogeochemical studies are proposed within a larger Lake Frome hinterland regional study. This would include the integration of water bore hydrogeochemical (much of which has been previously completed), regolith geochemical, and biogeochemical, samples from across the Lake Frome hinterland. The results from this will provide important evidence for linkages and associations between these sampling media, as well as building on existing regional geochemical baseline characterisation. This study would also incorporate further catchment-scale landscape geochemical studies, with possible catchment settings and associated commodities including, Yandama Creek (Au), Umberumberka Creek (base metals), and Paralana Creek (U) (Figure 1). Research extensions to include paleolandscapes (e.g. basal unconformities) and associated interfaces (e.g. paleo- and contemporary redox fronts and indurated zones) also are being considered for this area.

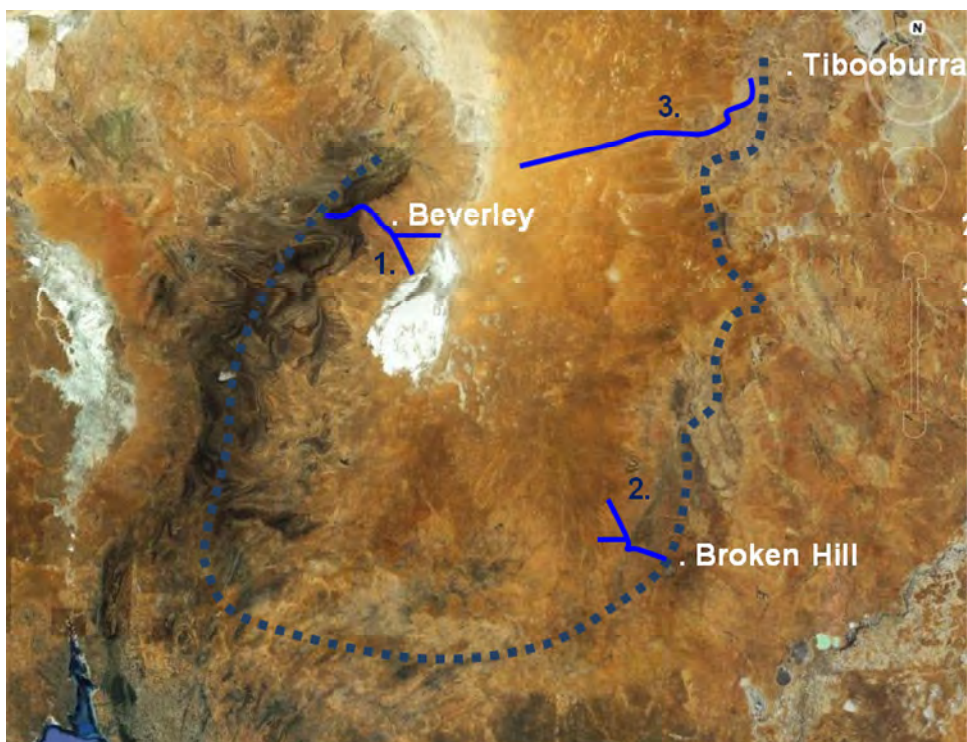


Figure 1. Lake Frome hinterland and potential detailed study catchments, 1. Paralana Creek, 2. Umberumberka Creek, and 3. Yandama Creek

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Four Mile Creek uranium: basement to cover

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Introduction

The region of the northern Flinders Ranges-Lake Frome plains is one of the most prospective areas for mineral exploration and for geothermal energy in Australia. It is well known for its uranium deposits, including the operating Beverley mine. Nevertheless, there are still major parts of the geological framework that are unresolved, including the regolith and associated landscape history. This is surprising given the exposures of a wide range of regolith materials and landforms as well as the importance of landscape evolution for the dispersion, expression and secondary concentration of uranium mineralisation.

Recent collaborative research by PIRSA and the University of Adelaide has made some major contributions to this geological framework, as well as developing this region for field-based geoscience education under the MTEC (Mineral Tertiary Education Council) scheme.

Previous Exploration and Research

In April 2005, reconnaissance drilling by Quasar Resources intercepted uranium-equivalent mineralisation in the Four Mile Creek area, to the west of the Beverley mine. Subsequent drilling over the next few years delineated what is now known as the Four Mile West and Four Mile East uranium prospects.

This uranium discovery led to the collaborative research program that primarily focussed on the Four Mile West uranium deposit. Due to its setting, within a few kilometres of the Mount Painter Inlier, and buried mineralisation around 100 m below the surface of the Paralana High Plains, it provided an ideal opportunity to undertake a controlled program to firstly characterise, and then try to constrain the surficial expression of the underlying uranium resources. The major focus of the geochemical study is on uranium mineralisation, although other elements, such as Au and base metals, are also considered both as pathfinders for U-mineralisation and associated with other types of mineral deposits.

The program commenced in 2006, with a PhD student investigating the riparian plant biogeochemical expression of buried mineralisation (Neimanis and Hill, 2006; Neimanis et al. 2007). This was followed in 2007 by five Honours student projects, centred on a small stream catchment that included the Four Mile West drilling project. Here, the regolith-landforms have been mapped at 1:20 000 (Dubieniecki and Hill, 2007), and some key sedimentary sections have been logged lithologically and interpreted stratigraphically, including previously

undescribed exposures of Mesozoic sediments underlying the early Cenozoic Eyre Formation and Namba Formation along the range-front (Hector and Hill, 2007). Within the immediate ranges and along the flanking plains, geochemical sampling of various media was undertaken to determine the comparative geochemical characteristics, including: soils, stream sediments, kangaroo-poo, vegetation and ants (McMahon and Hill, 2007; Jennings et al., 2007). Regolith carbonates, which may host geochemical characteristics related to groundwater discharge along fracture systems near mineralisation, were also sampled (Gallasch and Hill, 2007). In conjunction with the student projects, whose work were principally on the plains, the various lithologies of the crystalline basement of the Mount Painter Inlier were sampled and analysed for whole-rock geochemistry by PIRSA. In 2009, an additional Honours student examined the study site for further biogeochemical sampling of eremophila shrubs near the Four Mile West prospect, with a second student compiling and interpreting some of the large and emerging data sets.

New Research and Results

In 2008, the authors studied a tectonically-tilted exposure of Mesozoic and Cenozoic sediments on the northern bank of Four Mile Creek adjacent to the ranges - referred to as the Dead Tree section. Here, the Mesozoic sediments are overlain by the Eyre Formation, which clearly shows the basal quartzose gravels, overlain by quartzose and kaolinitic sediments, with a now-oxidised, Fe-rich central section of sediments that are laterally equivalent to some of the redox interfaces hosting the Four Mile mineralisation. The upper parts of the Eyre Formation include coarse-grained quartzose sand, and the upper 2 m is overprinted by a pedogenic silcrete. Proximal, coarse-grained sandy and gravel facies of the Namba Formation is preserved overlying the Eyre Formation in this section.

Concentrated sampling of the exposed section, and subsequent geochemical analysis, reveals up to 32 ppm U and 346 ppm Th in parts of the more Fe-rich middle section of the Eyre Formation. The Th:U ratio is ~10 for both the lower and upper Eyre Formation sections. The ratios between U and the rare earth elements (Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho), as well as Y, Zr and Hf, generally increases in the oxidised middle section, as compared to the lower section of the Eyre Formation (Figure 1).

The redox boundaries, located in the middle part of the Eyre Formation, are interpreted to have been redox interfaces in what were once reduced sediments, which have subsequently been oxidised as a result of tectonic tilting and uplift of the section.

Analysis of plant, animal and mineral samples from the Four Mile West catchment area, during the collaborative research program, have provided results offering explorers a geochemical expression of mineralisation in areas concealed under transported cover by investigating proximal exposed rock exposures and the interpretation of regolith and landscape features.

Acknowledgements

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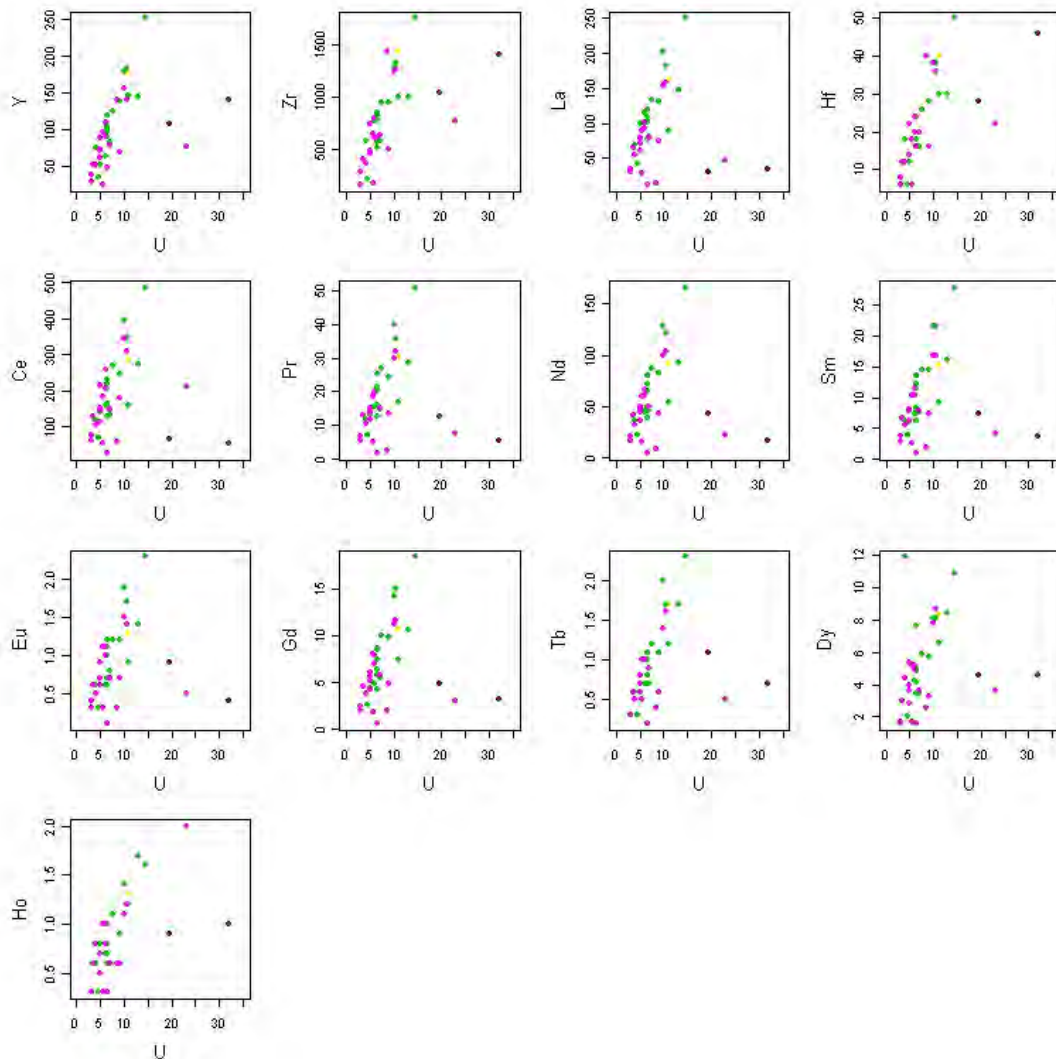


Figure 1. X-Y scatter-plots of a range of elements relative to U-content in the Dead Tree section, Four Mile West. Colour key: Lower Eyre Formation (green), Upper Eyre Formation (purple), Fe-rich middle Eyre Formation (brown)

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Discovery of Mississippi Valley Type (MVT) mineralisation at Dome Five and its regional significance

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Introduction

The Dome Five prospect is located in the northern segment of Exploration Licence 6404, 35km northwest of Broken Hill (Figure 1). EL6404 is also known as the Mundi Plains project and is the subject of an option/joint venture agreement between PlatSearch NL and Teck Australia Pty Ltd (Teck), with Teck the manager. Previous exploration companies that have completed work at the Dome Five prospect include Plutonic Resources, BHP Minerals and PlatSearch NL. Earlier work completed by these companies, from 1996 to 2005, consisted of a few gravity lines, down-hole EM, ground magnetics and three deep diamond drill holes (P2, P4 and P5). All three drill holes intersected successions of the Broken Hill Group, including garnet quartzite, BIF horizons and weak sulfide zones, with a best intercept of 7.2 m @ 0.76 % Pb, 0.2 % Zn and 14 ppm Ag, in P2. Drilling has confirmed the presence of magnetic stratigraphy, with a classic Broken Hill Lode sequence intersected at significant depths (400-1000m), but extensively intruded by undeformed Mesoproterozoic(?) leucogranite sills. The earlier explorers primarily focussed on Broken Hill Type (BHT) mineralisation, with the prospect defined by a bulls-eye magnetic anomaly originating from the above mentioned magnetic stratigraphy, buried below Neoproterozoic (presumed Adelaidean) sedimentary rocks and younger Cenozoic-to-present unconsolidated sediments.

In 2007, a drilling program by Teck discovered two narrow intervals of medium- to high-grade, zinc-lead-silver mineralisation within Neoproterozoic carbonates, situated immediately above the unconformity with the Willyama Supergroup. Drill hole DF02 intersected two sulfide intervals, consisting 1 m @ 13.9 % Zn, 8 % Pb and 75 ppm Ag from 327.3m, and 3 m @ 7 % Zn, 0.2 % Pb and 4 ppm Ag from 337.6m. The discovery of carbonate-hosted, Zn-Pb-Ag (suspected Mississippi Valley Type (MVT) mineralisation) represented a new target at significantly shallower depths than the BHT horizons, with very significant grades in flat-lying stratigraphy, and warranted further exploration.

Teck returned in 2008, completing five drillholes, totalling 3159.4 m. Four drillholes (DF04-DF07) were drilled in a wide-spaced, diamond pattern around the discovery hole DF02. Three drillholes were each completed to a depth of ~400 m and one, DF05, was extended to 1000 m, to further test the BHT potential at depth. All five holes targeted the lateral extent of the MVT horizon from 310 to 380 m. Significant intersections from the MVT horizons intersected by drilling in 2008 are shown in Table 1.

Geophysics

The prospective host units at the Dome Five prospect lie under several hundred metres of cover, and so the use of geophysics, namely magnetics and gravity, has been critical for drill targeting (Figures 2 and 3). In 2007, Teck completed a ground gravity survey, on a grid spacing of 200 m x 200 m, which covered the northern segment of EL6404, where the Dome Five bulls-eye magnetic anomaly occurs. The dominant feature is a gravity low, which is coincident with a discrete high in the magnetic data (Figure 3). Based on drilling, this is interpreted to be caused by the felsic intrusive body in the centre of a dome (paleotopographic high), intruding magnetite-bearing, metasedimentary rocks of the m Willyama Supergroup. Additional gravity ridges to the east and southwest of the dome appear to be related to better-preserved Willyama Supergroup, and also may be due to locally thicker carbonate beds in the basal Neoproterozoic succession surrounding the paleohigh, accentuated by faulting.

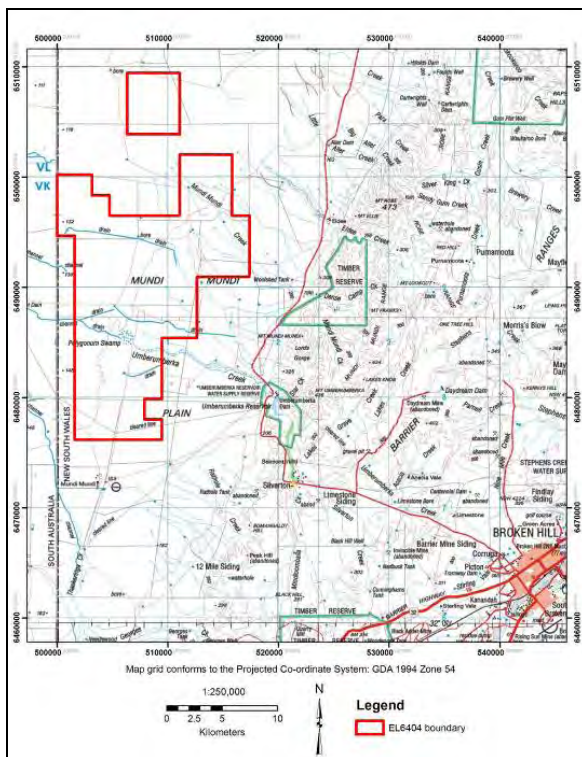


Figure 1. Map showing EL6404 (red boxed area) in relation to Broken Hill and the surrounding district.

Table 1. Significant MVT mineralisation from diamond drilling in 2008.

Hole ID	From (m)	To (m)	Interval (m)	Zn (%)	Pb (%)	Ag (ppm)
DF04	328.2	329.1	0.9	2.54	0.03	7.3
DF05	337.1	337.4	0.3	8.62	0.41	8.3
DF06	317.2	318	0.85	19.15	4.9	83
DF07	340.3	341.3	1	0.05	1.05	8.2

Geology

In the northern portion of EL6404, Neoproterozoic sedimentary rocks unconformably overlie Paleoproterozoic metasedimentary rocks, leucogranite and pegmatitic intrusives, forming the aeromagnetically-subdued Mulyungarie Domain. The Neoproterozoic sedimentary rocks are undeformed and have an apparent dip of $<5^\circ$ to the north. Immediately above the unconformity, the sedimentary rocks are composed of interbedded and intercalating dolomitic sandstone, dolostone, oolitic limestone, gravel and conglomerate. Coincident with the centre of the magnetic feature, the unconformity occurs at ~260 m depth. Moving away from the magnetic feature, the unconformity rapidly deepens to ~360 m, identifying the presence of a paleotopographic high (Figure 3). This high is composed of a one-mica quartz-granite, variable k-spar-rich granite and graphic pegmatites (Figure 4). Closely flanking this paleotopographic high, the Neoproterozoic sedimentary rocks are dominated by conglomerate, dolomitic gravel and dolomitic sandstone (Figure 4).

Moving southwest from the topographic feature, there is a change from thick successions of conglomerate and gravel to pinkish dolostone, and blue-grey oolitic and stromatolitic limestone and crinkly algal carbonate (Figure 4). Above this carbonate succession, a distinctive five metre-thick green siltstone horizon marks a transition into quiescent sedimentation of alternating and rhythmically banded brown and green siltstone.

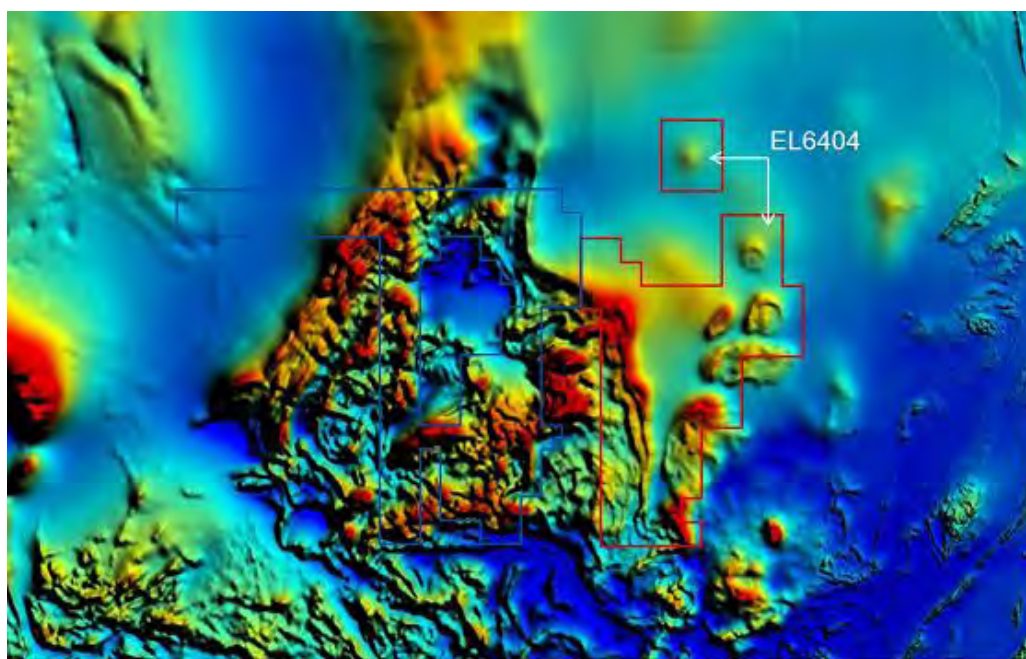


Figure 2. Total Magnetic Intensity image showing EL6404 (on the right hand side) in far western NSW.

At the top of this succession, there is a rapid transition into red-bed or chocolate-brown, fine-grained, well-sorted, massively-bedded sandstone. Within this unit are narrow intervals of matrix-supported diamictite, the clasts of which can be chloritised or hematized and of unknown origin. Over most of the prospect, this unit terminates at an erosional unconformity with Cenozoic sediments. On the northeast side of the dome, in drillhole DF08, this unit shows another rapid transition, of disconformable to finely-laminated, dark green to grey, pyritic mudstone-siltstone.

Since the discovery of the Dome Five epigenetic to stratabound carbonate-hosted Zn-Pb-Ag mineralisation in 2007, knowledge of the Adelaidean sequence stratigraphy is emerging as an important element in exploration on the Mundi Plains Project. Mineralisation is hosted within the conglomerate and carbonates at the base of the Adelaidean metasedimentary rocks. On the local scale, the Adelaidean sedimentary rocks *may* correlate with, or be equivalent to, the Adelaidean sedimentary rocks on the Benagerie Ridge in South Australia. On the Benagerie Ridge, sedimentary rocks of the Upalina Subgroup have an onlapping relationship to the Paleoproterozoic basement (Preiss, 2000; Preiss et al., 1998). This relationship is also observed over the Dome Five prospect. Regionally, the sedimentary rocks are almost certainly part of the Heysen Supergroup, consisting of glacial tillite, cap-carbonate, diamictite and post-glacial sedimentary rocks of the Umberatana Group (Preiss, 2000; Preiss et al., 1998).

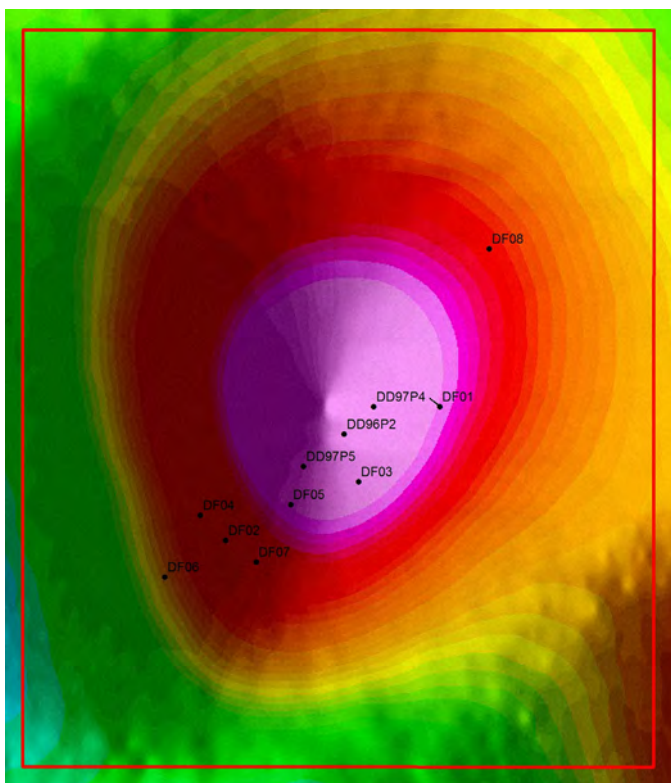


Figure 3. Image shows drilling sites with respect to the Total Magnetic Intensity image.

Characteristics of the Dome Five MVT mineralisation

A representative geological cross section of the Dome Five prospect is shown in Figure 4. The MVT mineralisation discovered at Dome Five is developed in the Adelaidean sedimentary rocks within the basal conglomeritic horizon and cap-carbonate succession above the Adelaidean-Willyama Supergroup unconformity. The detailed shapes of the domal-high and the lithology of the basement succession between DD-97 P02 and DF08 are purely interpretive. The cross section is constructed along a southwest-northeast trend from DF06 to DF08 (Figure 3).

The construction of the cross section shown in Figure 4 has been an important tool in identifying the geological environment at Dome Five. It is recognised that MVTs can form in a number of positions within carbonate units (Rhodes, 1997). The MVT mineralisation at Dome Five has formed in a classic talus or pinch-out position against the paleotopographic high, which extends into the aquatard (laminated siltstone) of the Adelaidean stratigraphy. The basal conglomeritic

successions may be important conduits for basinal connate fluids being driven out of sediments during compaction and diagenesis.

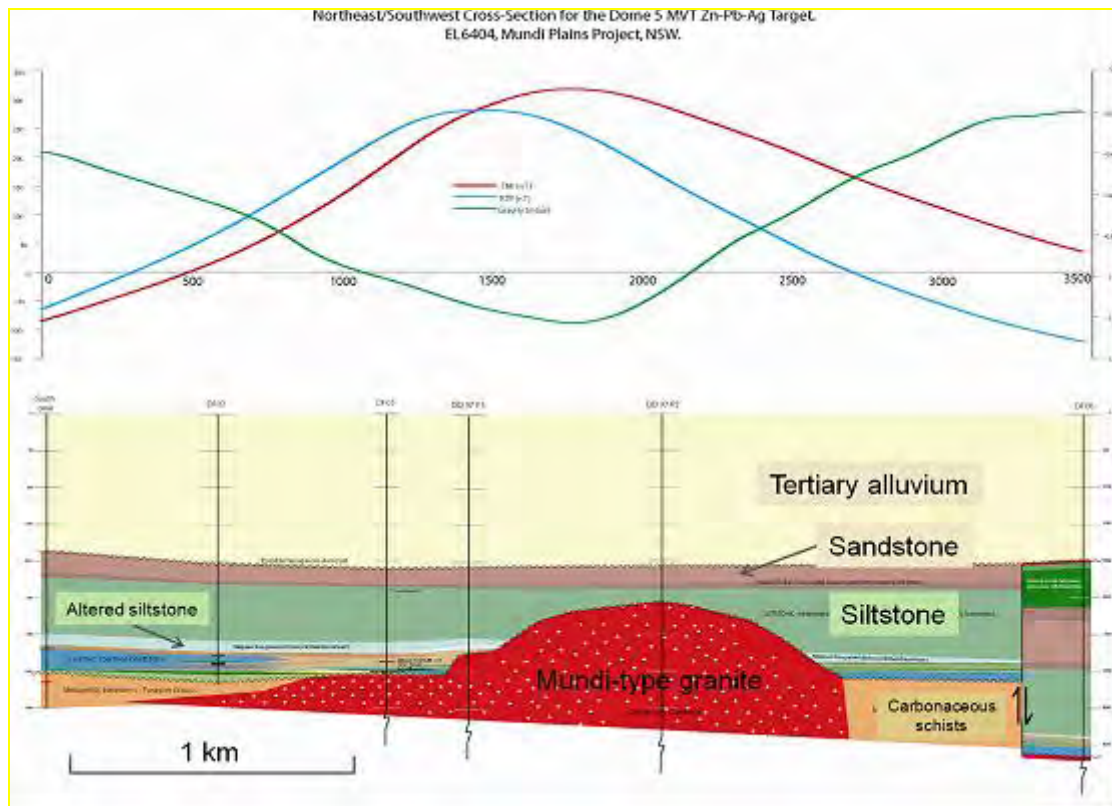


Figure 4. Cross section (focussing on the top 500 m) constructed from exploration drilling. The geophysical signature is constructed from profiling NSW state aeromagnetic data and the detailed gravity survey by Teck along the same geological transect. Note the influence of the leucogranite in producing a gravity low signature, whereas BIF horizons deeper down are causing a near-coincident increase in magnetics over the prospect.

Sulfide mineralisation at Dome Five is hosted in a carbonate succession. Chemical sedimentation is interpreted to have occurred in a very shallow, possibly occasionally sub-areal, basin (or at least within the photic zone), or, otherwise, is a shallow marine setting in an oxidised environment. There are clear stromatolitic and crinkly algal laminations within the carbonate profile. A summary of the interpreted environment and mineralising processes at Dome Five, which have been interpreted from detailed petrography, carbonate and ore textures and alteration, detailed logging and regional synthesis, is provided in the following main points:

- The carbonate succession unconformably on-laps Paleoproterozoic metasedimentary rocks and Mesoproterozoic granite, with interbedded gravel and conglomerate shedding off a local topographic high (coinciding with a granite dome). These sediments appear to have some control on fluid flow during mineralisation, with some alteration and late replacive pyrite forming between clasts in porous bands.
- The most likely source of metals is from the basement metasedimentary rocks of the Willyama Supergroup and granites, within which growth faults developed during extensional tectonism in the Neoproterozoic. Metals are also likely to be recycled from the BHT sedimentary-exhalative, highly metal-endowed horizons within the Broken Hill Group, deposited during the late Paleoproterozoic.
- The thick overlying siltstones and fine-grained siliciclastic sedimentary rocks formed an aquatard over the lower carbonate units, with the underlying, porous basal gravels and

sandstones, focussing the metal-bearing fluids into the carbonate horizons, where the basal clastic rocks pinch-out against the basement high.

- The Adelaidean sedimentary rocks are generally oxidised and low in sulfur and base metal content. It is clear that only a very minor growth of pyrite occurred during diagenesis. There is no indication of syndepositional metal deposition in the carbonate or siliclastic sedimentary rocks anywhere in the stratigraphic profile.
- Strong silicification and fluoridation of the dolostone layers extends well beyond known mineralisation. These may be good indicators for mineralisation across the basin, not just near Dome Five.
- Strong brecciation is observed with drusy and cockscomb-textured calcite, fluorite and silica vein fill. Disseminated base metal mineralisation also occurs within thin veins, and is seen to be closely associated with these minerals.
- Fluid inclusion studies indicate that moderately low temperature H₂O-CO₂-bearing hydrothermal fluids suffered boiling. They contained significant SiO₂, Ca, F, S, Zn, Pb, and minor Ba, Fe and Cu. These fluids deposited the MVT mineralisation by chemical reaction with the carbonate-rich package (Leyh, 2008).
- The geochemical signature for this style of mineralisation, as seen from analyses to date, include: Zn, Pb, Cu, Ag, As, Ca, Mn, S, F, Ba, Cd, Bi and Sb, possibly with a wider Ag, Ca, Mn, Ba and F geochemical halo (Leyh, 2008).
- Basin inversion, in addition to diagenesis, may be important to the mineralising process. The 514-490 Ma Delamerian Orogeny is at least the first tectonic event to influence these sediments after deposition and burial diagenesis.

Based on this summary of mineralising processes and timing relationships, host lithologies and knowledge from known MVT deposits, it may be possible to surmise that the timing of mineralisation may be related to the onset of subduction and slab rollback, associated with the amalgamation of Australia with Gondwanaland and the inversion of the Adelaidean rift system during the late Neoproterozoic-early Cambrian. Some of the defining characteristics of MVT mineralisation are listed in Table 2.

Table 2. Characteristics described as essential for MVT mineralisation (after Rhodes, 1997).

Favourable carbonate host rocks, generally showing widespread dolomitisation and silicification	<input checked="" type="checkbox"/>
Indications of ground preparation, that is, vuggy porosity and breccias	<input checked="" type="checkbox"/>
Coarse, wide dolospar open space fill and replacement of internal sediments	<input checked="" type="checkbox"/>
Presence of basinal high	<input checked="" type="checkbox"/>
Localised structural highs	(?) yet to be tested
Presence of unconformity	<input checked="" type="checkbox"/>
Presence of underlying aquifer (porous sandstones and conglomerates)	<input checked="" type="checkbox"/>
Presence of impermeable shale sequence capping favourable host rocks	<input checked="" type="checkbox"/>

Conclusions

The detailed gravity survey over the Dome Five prospect was successful in distinguishing dominantly metasedimentary and overlying carbonate lithologies (rock units having average to above average densities) and regions of crust dominated by lower density leucogranite.

The locally, very high-grade, MVT Zn-Pb-Ag mineralisation intersected in DF02, DF04, 05, 06 and 07, at moderate depths of ~310-380 m, is a viable new target horizon over the Dome Five prospect, and also regionally for similar settings elsewhere in the basal Adelaidean succession.

Given the known characteristics of MVT mineralisation, it is possible that Dome Five is a regionally significant occurrence. It may be possible, over the coming years, to complete more detailed geophysical surveys to delineate major bounding structures, and other significant faults, which may be important in episodic extension and contraction, and basement high pinch-out settings, suitable for trapping MVT-style ore fluids.

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The 2008 north-south oriented, deep seismic reflection transect across the Curnamona Province, South Australia

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Introduction

Deep seismic reflection surveys in the Paleoproterozoic to Mesoproterozoic Curnamona Province, acquired in 1996-97 (seismic lines 96AGS-BH1A and 96AGS-BH1B; Gibson et al., 1998) and 2003-04 (seismic line 03GA-CU1; Goleby et al., 2006) were combined to provide a single, 400 km long transect across the entire Curnamona Province from the Darling Basin in the east to the Flinders Ranges in the west (Korsch et al., 2006a). In 2008, as part of its Onshore Energy Security Program, Geoscience Australia, in conjunction with Primary Industries and Resources South Australia (PIRSA), acquired 262 km of vibroseis-source deep seismic reflection data as a single traverse in the Curnamona Province in South Australia. This line, 08GA-C1, was oriented approximately north-south (Figures 1 to 3); it tied to seismic line 03GA-CU1 in the south, ran to the east of Lake Frome along the Benagerie Ridge, and ended to the northeast of the Mount Painter and Mount Babbage Inliers. Crustal-scale, magnetotelluric data were also collected along the seismic route. Here, we report the results of a preliminary geological interpretation of this seismic line.

Aims of the Seismic Survey

The main aim of the current seismic survey was to determine the crustal architecture of this part of the Curnamona Province, which has high potential for uranium and geothermal exploration. The seismic line traversed the eastern part of the South Australian Heat Flow Anomaly, with the aim of providing insights into the large-scale character and composition of this crustal-scale, geochemical and thermal anomaly. In particular, the Mount Painter Inlier contains the most radiogenic granites known in Australia (Neumann et al., 2000).

Within the Curnamona Province, the seismic line crossed areas which have a high potential for a range of U and Th mineral systems. This includes the Benagerie Ridge, which does not crop out, but does contain igneous rocks of equivalent age to the ~1590 Ma Hiltaba Suite-Gawler Range Volcanics event of the Gawler Craton, suggesting the potential for IOCGU-type mineralisation within this area. Further south, in the Willyama Inlier, Paleoproterozoic basement hosts the granite-related U-Th Crocker Well deposit and the Radium Hill U deposit. Young cover rocks overlying the basement host three significant palaeochannel/sandstone-hosted U

deposits, Honeymoon near Kalkaroo, and Beverly and Four Mile, east of Mount Painter. The seismic lines will provide the regional-scale architecture of these different mineral systems.

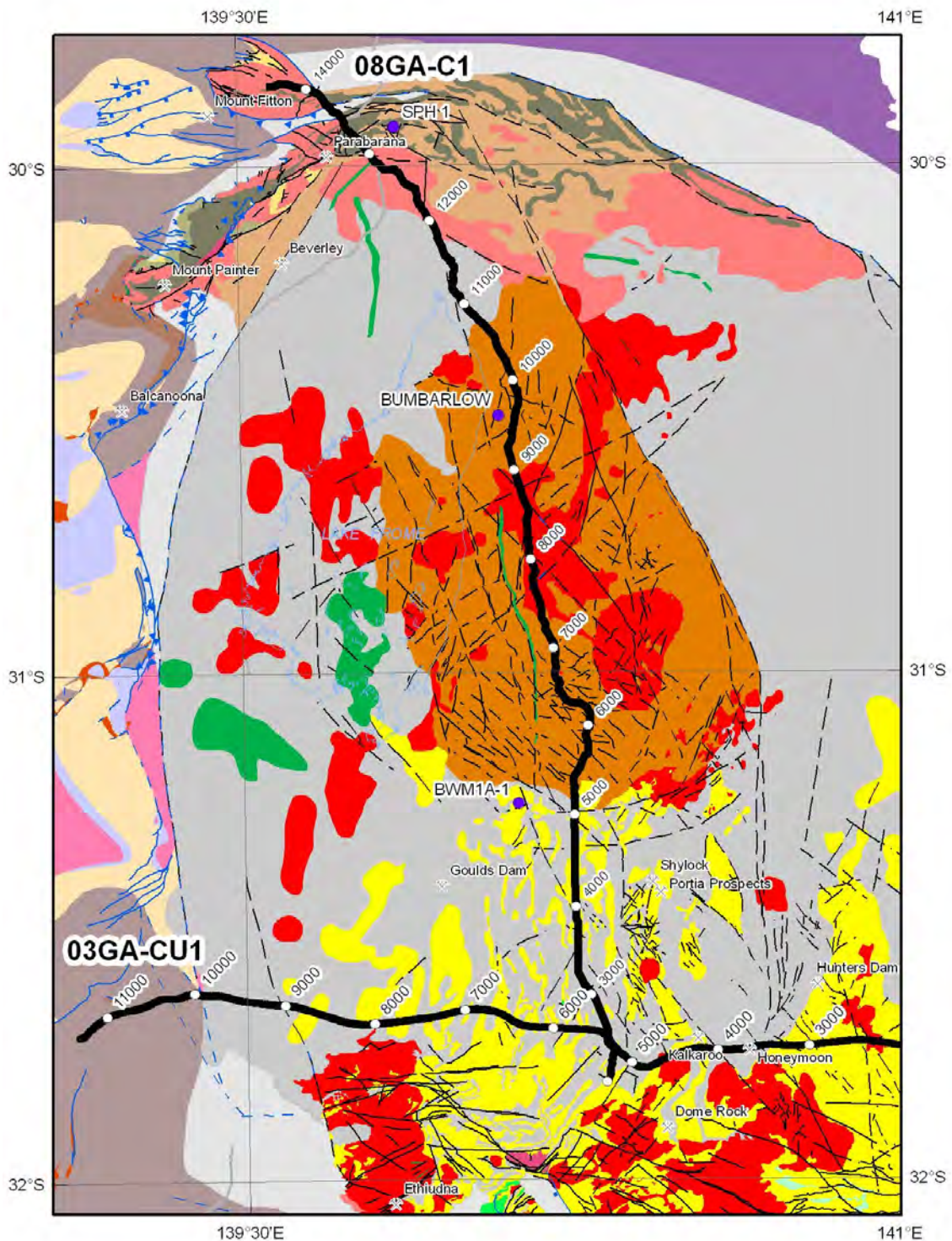


Figure 1. Map showing the solid geology of the Curnamona Province in South Australia, including the Mount Painter region, (after Cowley, 2006). Also shown are the locations of the deep seismic reflection transects 03GA-CU1 and 08GA-C1, with CDP stations labelled, and the locations of drillholes referred to in the text are also shown.

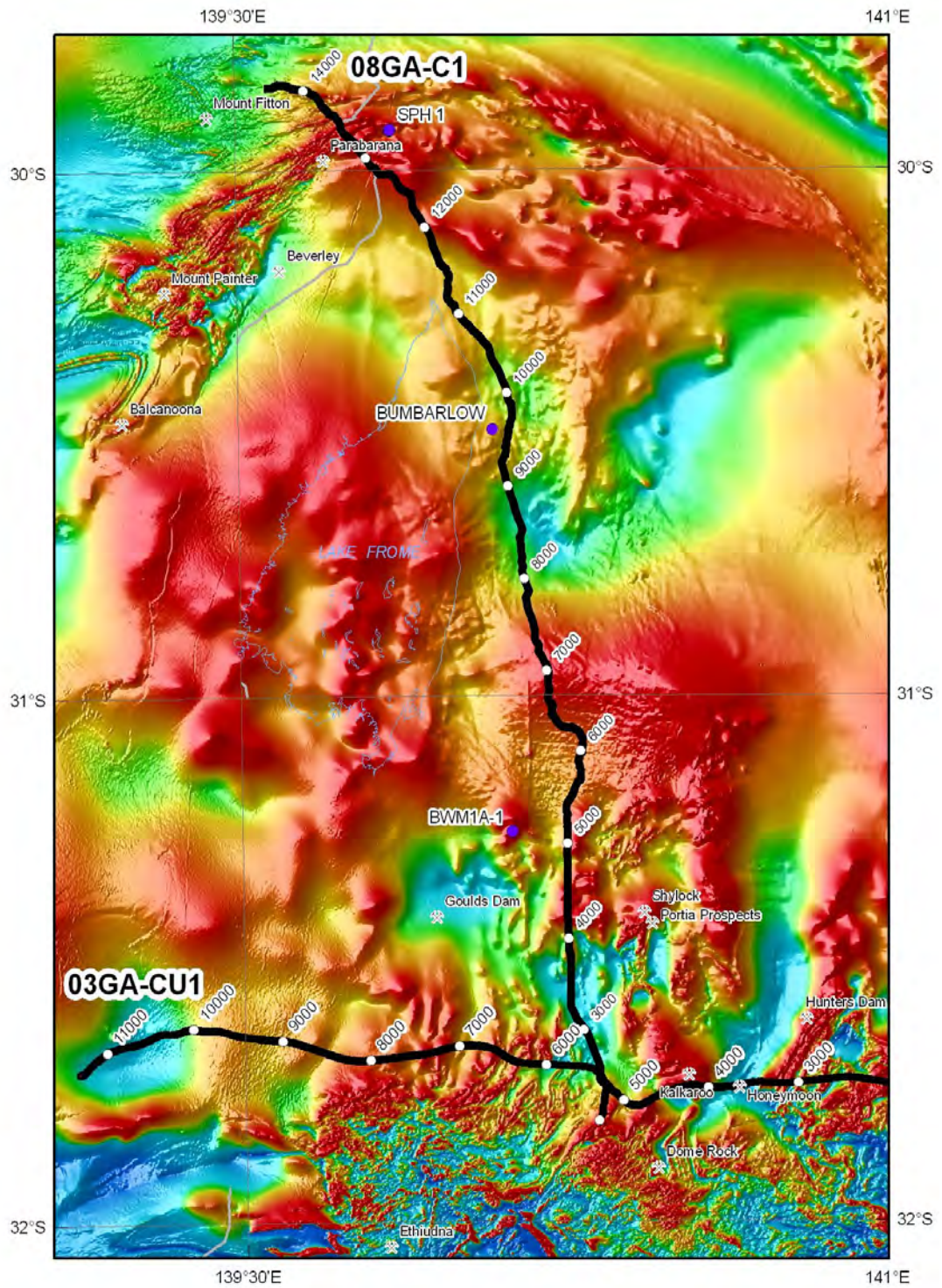


Figure 2. Map showing regional aeromagnetic data for the Curnamona Province in South Australia, including the Mount Painter region. Also shown are the locations of the deep seismic reflection transects 03GA-CU1 and 08GA-C1, with CDP stations labelled, and the locations of drillholes referred to in the text are also shown.

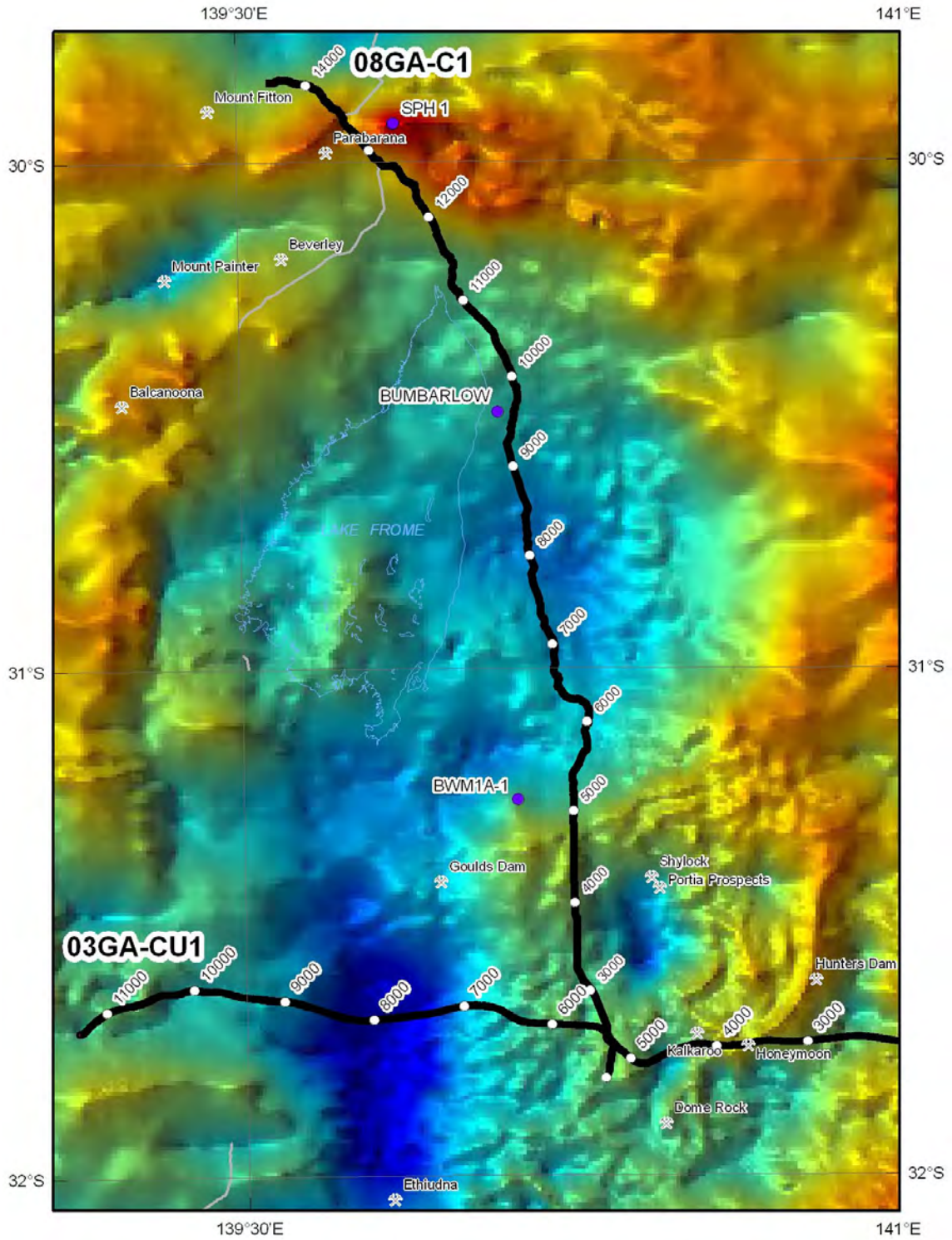


Figure 3. Map showing a regional gravity image for the Curnamona Province in South Australia, including the Mount Painter region. Also shown are the locations of the deep seismic reflection transects 03GA-CU1 and 08GA-C1, with CDP stations labelled, and the locations of drillholes referred to in the text are also shown.

The Mount Painter Inlier hosts the Paleozoic Mount Gee U system, a poorly understood hematite-rich breccia system, with some similarities to the Mesoproterozoic Olympic Dam system. The seismic line across and between the Mount Painter and Mount Babbage inliers will aim to elucidate the regional structure that may have controlled Proterozoic to Paleozoic U mineral systems in the inliers.

Seismic Acquisition and Processing

Seismic line 08GA-C1 was acquired in June and July 2008, with project management undertaken by the Seismic Acquisition and Processing Project from Geoscience Australia. A summary of acquisition parameters is given in Table 1.

Table 1. Comparison of acquisition parameters for the two deep seismic surveys undertaken in the Curnamona Province in South Australia.

Line	03GA-CU1	08GA-C1
Direction	East to West	South to North
Length	197.6 km	262.2 km
Stations	1000 - 5940	1000 - 7554
CDP range	2001 - 11385	2002 - 14446
Source type	3 IVI Hemi-60 vibrators	3 IVI Hemi-60 vibrators
Source array	15 m pad-pad, 15 m moveup	15 m pad-pad, 15 m moveup
Sweep length	3 x 12 s	3 x 12 s
Sweep frequency	7-56 Hz, 12-80 Hz, 8-72 Hz	6-64 Hz, 12-96 Hz, 8-72 Hz
Vibration point (VP) interval	80 m	80 m
Receiver group	12 geophones @ 3.3 m spacing	12 geophones @ 3.3 m spacing
Group interval	40 m	40 m
Number channels	240	300
Fold (nominal)	60	75
Record length	18 s @ 2ms	20 s @ 2ms
Recording format	SEGY	SEGD

Table 2. Seismic reflection processing sequence for seismic line 08GA-C1

<p>Line geometry and crooked line definition (CDP interval 20 m) Field SEG-D to SEG-Y to "Disco" format, resampled at 4 ms Quality control displays, selected trace edits Common mid-point sort Gain recovery (spherical divergence) Spectral equalisation over 8 to 92 Hz (1000 ms AGC gate) Application floating datum residual refraction statics Velocity analysis Application of automatic residual statics Normal moveout (NMO) correction with 10% stretch mute, using 6000 m/s Band pass filter (0-2 s, 14-90 Hz; 2-10 s, 10-90 Hz) Offset regularisation and dip moveout (DMO) correction Common mid-point stack Omega-x migration using 85% stacking velocity Signal enhancement (digistack 0.5 and fkpover) Application of mean datum statics, datum 150 m (AHD), replacement velocity 5000 m/s, 300 ms shift Trace amplitude scaling for display</p>
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For seismic line 08GA-C1, 75-fold seismic reflection data were acquired to 20 s two-way time, using three Hemi-60 (60,000 lb) peak force vibrators. A Sercel 388SN recording system was used to record and correlate the seismic data. Three sweeps, 6-64 Hz, 12-96 Hz, 8-72 Hz, each 12 s long, with an 80 m vibration point interval, were selected as source acquisition parameters for this survey. Data were processed in the DISCO/FOCUS seismic processing package. The final processing flow for seismic line 08GA-C1 is summarised in Table 2.

Preliminary geological Interpretation of seismic line 08GA-C1

Almost the entire route of the seismic traverse was over concealed basement, with only a few drillholes that could be used as control points. Overall, the crust in the vicinity of the seismic section is relatively reflective, although the central part of the section contains an upper crust which has very low reflectivity (Figure 4). The lower two-thirds of the crust contain strong subhorizontal reflections. The Moho is not sharply defined, but is interpreted to occur at the base of the reflective package at about 13 s two-way travel time (TWT), which is a depth of about 40 km. The upper mantle beneath the Moho is essentially non-reflective.

The highly reflective crust can be tracked from the southern end of the seismic section, northwards, past the tie with seismic line 03GA-CU1, for a distance of about 200 km (to approximately CDP 13000). In the northernmost part of the section, where rocks of the Mount Painter and Mount Babbage Inliers are exposed close to the section, the crust has a marked lower reflectivity compared to that of the rest of the line. The contrast in crustal reflectivity suggests that the crust beneath the Mount Painter region is different to that beneath the Willyama Supergroup of the Curnamona Province in the south. Although not well imaged, a steep, apparent south-dipping boundary between the Mount Painter Inlier and the Curnamona Province is inferred.

Willyama Supergroup

The Curnamona Province consists predominantly of the Paleoproterozoic (~1720-1640 Ma) Willyama Supergroup and coeval magmatic rocks. These rocks were deformed and metamorphosed during the ~1600 Ma Olarian Orogeny, which was followed by an early Mesoproterozoic magmatic event. In South Australia, the Curnamona Province is mostly under cover of Neoproterozoic to Cenozoic sedimentary rocks (Preiss, 2009).

In the southernmost part of the seismic section, the Willyama Supergroup contains reflections with apparent dips to the south (between CDPs 2000 and 3800). We consider these to be thrusts; associated folded reflections are interpreted as hangingwall antiforms. We correlate these structures with structures that have apparent dips to the east in seismic line 03GA-CU1, which were interpreted to be D3 structures formed during the Olarian Orogeny (Korsch et al., 2006b), and field mapping by PIRSA and GSNSW shows that the folds associated with these structures verge to the northwest, and have faulted western limbs, as confirmed by the seismic data.

Farther to the north, between CDPs 3800 to 5200, there are a series of planar reflections with apparent dips to the north. In places, folds occur above the planar reflections; these folds are interpreted to be hangingwall antiforms that sit on thrusts, which have an apparent south-directed sense of movement. These folds are relatively open but it is unclear how these thrusts relate to the Olarian D3 structures farther south. One possibility is that these represent Olarian D2 structures.

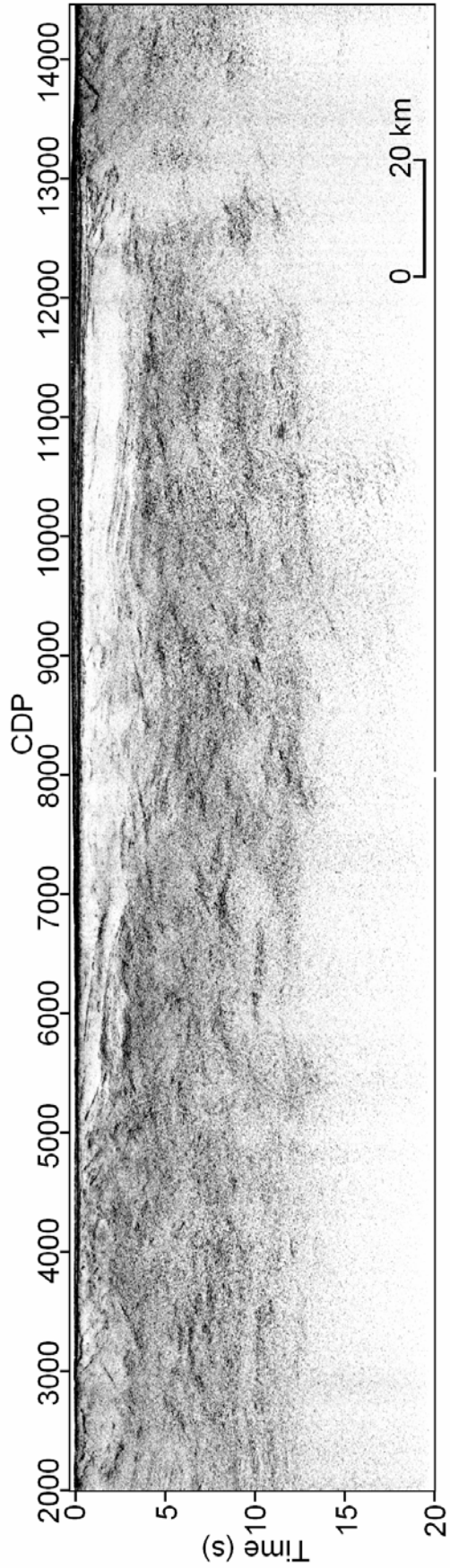


Figure 4. Migrated seismic section for line 08GA-C1 in South Australia. Display shows the vertical scale equal to the horizontal scale, assuming a crustal velocity of 6000 m s^{-1} .

The late structures overprint the earlier structures, which are difficult to observe in the seismic section. This is because the seismic image is one of the present day architecture of the crust; later structures tend to be the best imaged because they overprint and deform earlier structures, but are not deformed by later events. It is also difficult to image steeply dipping structures, and also those that are highly deformed.

Benagerie Ridge

Mesoproterozoic felsic and mafic volcanic rocks from the Benagerie Ridge in the northwestern part of the Curnamona Province are not exposed at the surface, but have been intersected in several drillholes (Fricke, 2009). These A-type volcanics are bimodal, and have a SHRIMP age of 1582 ± 4 Ma (Fanning et al., 1998). They are relatively flat-lying, and unconformably overlie deformed and metamorphosed rocks of the Willyama Supergroup. There is approximately a 10 Ma period of time between the cessation of the D3 Olarian deformation and extrusion of the subhorizontal Benagerie Volcanics over exhumed greenschist facies rocks of the Willyama Supergroup (Korsch et al., 2006b).

The Benagerie Volcanics, which are equivalent in age to the Hiltaba Suite-Gawler Range Volcanics, host of the giant Olympic Dam IOCGU deposit, are of interest to base metal and uranium explorers.

In the seismic section, there are two non-reflective packages, separated by a set of strong reflections that have an apparent dip gently to the north. The drillhole BWM1A-1 occurs ~10 km to the west of the seismic section and contains dipping metasedimentary rocks beneath a younger Neoproterozoic sedimentary package. If this drillhole is projected onto the seismic section using aeromagnetic data, then the lower, non-reflective package is interpreted to be part of the Willyama Supergroup. If this is the case, the Benagerie Volcanics are confined to the upper non-reflective package, which we interpret to have a maximum thickness of ~1.3 s TWT (~4 km). At this stage, the correlation of the lower, non-reflective package to other rock packages in the Curnamona Province is unknown.

Bumbarlow 1 Drillhole

The Bumbarlow 1 drillhole is located ~4 km to the west of CDP 9600 on the seismic traverse. This drillhole penetrated a succession of Mesozoic sedimentary rocks, followed initially by a succession of clastic sedimentary rocks and then a succession of interbedded mafic volcanic rocks and clastic sedimentary rocks (both of unknown affinity and age), before ending in metasedimentary rocks. The lower, interbedded, sedimentary and mafic volcanic succession has a relatively disrupted reflectivity pattern, possibly due to the irregular distribution of volcanic rocks in the subsurface.

Mount Painter and Mount Babbage Inliers

The northernmost part of the seismic section crosses Mesoproterozoic rocks of the Mount Painter and Mount Babbage Inliers that occur beneath a thin cover of Mesozoic to Cenozoic sediment. Here, the rocks are heavily faulted, with the main fault pattern having an apparent dip to the northwest.

In that part of the seismic section which is immediately south of the Paralana Fault (CDPs 13450 to 13000), there is a package of moderately reflective rocks, bound to the south by a northwest-dipping fault zone (CDPs 13000 to 13100); this package overthrusts the margin of a Neoproterozoic basin. Within this package, calcsilicate rocks of unknown affinity have been intersected in the SPH1 drillhole.

The Terrapinna Corridor separates the Mount Painter Inlier from the Mount Babbage Inlier. It contains Neoproterozoic Sturtian glacial rocks, which in the vicinity of the seismic line, have been mapped between CDPs 13520 and 13700. These rocks are not obvious on the seismic section and are probably relatively thin.

Neoproterozoic to Cambrian Basins

In the southern part of the seismic line, several remnants of Neoproterozoic and/or Cambrian sedimentary basins are preserved beneath a thin cover of Cenozoic sediment. The thickest of the remnant basins, also imaged on the tie line 03GA-CU1 (Goleby et al., 2006) is ~600 ms TWT (~1500 m) thick, using a seismic velocity of 5000 m s⁻¹.

The Neoproterozoic and Cambrian succession thickens significantly in the northern part of the line (CDPs 10200 to 13000), where it occurs at depth adjacent to the Mount Painter Inlier. The base of the Neoproterozoic succession is difficult to map, but could be as deep as ~2.4 s TWT (~6 km). The sedimentary succession also shows growth towards the north, implying the possible existence of an original syn-depositional, extensional fault. This thick component of the basin has been disrupted by syn-depositional to post-depositional faults.

The Neoproterozoic to Cambrian succession is currently of interest as a thermal blanket and also a resource for geothermal energy.

The original Neoproterozoic basin-bounding fault, with an apparent dip to the south, is now located deeper in the crust, with the original basin margin that was near the surface having been destroyed by later deformation. The present, near-surface boundary is a thrust fault (at ~CDP 13,000) with an apparent dip to the north, and has thrust calcsilicate rocks (of either Mount Painter or Willyama Supergroup affinity) over the Neoproterozoic to Cambrian succession. Note that this thrust is not active, as it is covered by essentially flat-lying Mesozoic and Cenozoic sediment. This implies that the juxtaposing of the calcsilicate rocks onto the Neoproterozoic succession occurred during either the Delamerian (~520-490 Ma) or Benambran (~455-440 Ma) Orogenies.

Mesozoic and Cenozoic Basins

Much of the basement in the northern part of the seismic section has a cover of Mesozoic to Cenozoic sediment, which reaches a maximum thickness of about 575 m in the vicinity of CDP 12800. The Cenozoic sediments are important because they are the host of the Beverley and Four Mile uranium deposits to the west of the seismic section.

Paralana Fault

To the southwest of the seismic section, the Paralana Fault is an active thrust fault, which is thrusting Mesoproterozoic rocks of the Mount Painter Inlier over Pliocene and Quaternary sediments (C  lerier et al., 2005). The high heat flow, distribution of current seismicity, and the location of the Paralana hot springs on the plains adjacent to the range front, all attest to the active nature of this region. The Paralana Fault occurs at the range front and dips 25   to the west, beneath the northern Flinders Ranges. In the seismic section, the Paralana Fault is imaged as a zone of reflections with an apparent dip to the northwest.

Tectonic Implications

The southern part of seismic transect 08GA-C1 has a reasonably well-defined Moho at ~13 s TWT (~40 km depth) with a strongly reflective middle to lower crust above a non-reflective upper mantle. In the northern half of the seismic section, however, the lower crust is only weakly

reflective, and the location of the Moho is not obvious (Figure 4). This implies that the crust in this region is significantly different to that farther to the south, and raises the possibility of an ancient crustal boundary between the two regions. This boundary could be similar to a series of crustal-scale, narrow zones with apparent dips to the east on seismic line 03GA-CU1, interpreted as a possible suture zone by Korsch et al. (2007).

In the southern part of seismic transect, there are a series of south-dipping thrusts cutting the Willyama Supergroup. This is consistent with mapped fold trends to the south, as the northwest-verging F3 folds in outcrops of the Willyama Supergroup are consistent with apparent north-directed D3 thrusting observed in the seismic transect. These late structures overprint the earlier structures, which are difficult to observe in the seismic section.

The Benagerie Volcanics are interpreted to be a relatively subhorizontal sheet, up to 4 km thick, with a gently undulating base. Rocks of the Willyama Supergroup can be tracked from the south to beneath both the volcanics and a lower, non-reflective package of unknown affinity.

The Neoproterozoic sedimentary rocks are associated with crustal extension related to the breakup of the Rodinian supercontinent. The original basin-bounding fault possibly represents reactivation of the ancient crustal boundary between the Curnamona Province and the Mount Painter Inlier. Minor contractional deformation of the Neoproterozoic succession has inverted the basin in places, and is inferred to be Delamerian in age. Nevertheless, the active Paralana Fault indicates that shortening across it is occurring today.

Conclusions

The Moho under the Curnamona Province is at ~40 km depth, and is slightly undulating in the south. The northern limit of the Curnamona Province is defined by a possible boundary between two different types of lower crust, with the crust in the north below the Mount Painter Inlier being overthrust by sub-Curnamona crust in the south. A sediment pile up to 6 km thick occurs in the northern part of the seismic transect, and contains Neoproterozoic, Cambrian, Mesozoic and Cenozoic rocks. Structural remnants of a Neoproterozoic basin occur in the southern part of the line. These rocks are important thermal blankets, and are of interest in geothermal exploration. In the north, the Neoproterozoic-Cambrian rocks are covered by Mesozoic to Cenozoic sediments, which are important hosts for uranium mineralisation and geothermal energy systems.

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Exploration for Broken Hill type deposits combining geological mapping and Niton soil geochemistry

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Introduction

This abstract looks at the effectiveness of combining detailed geological mapping and close spaced portable XRF Niton geochemical surveys in areas of reasonable outcrop to establish drilling targets. It extends the work described by McKinnon (2009) at this BHEI Conference.

Silver City Mining Limited

Silver City Mining Limited (SCI) was incorporated in May 2008 to undertake exploration in the Curnamona Province. It started with twelve tenements held through Sales Agreements (based on converting performance shares rather than cash) with five companies. In March 2009, SCI entered into a joint venture with CBH Resources Limited (CBH) over an additional seven tenements and acquired a further two Exploration Licences as a result of rationalisation by CBH of its landholdings (Figure 1).

Use of Niton data collected by CBH, and subsequent refinements

As part of the Joint Venture arrangement, SCI obtained access to Niton portable XRF multi-element dataset of geochemical results for over 100,000 sampling stations collected by CBH. Initially, the additive index (Zn + 2Pb + 10As; McKinnon, 2009) was used as a screening tool to commence investigations by SCI. The regional anomalies, outlined by McKinnon (2009), are shown on the SCI tenements (Figure 1), together with garnetite and quartz-gahnite distribution, both being BHT lode indicator rock types.

This broad regional geochemical and geological approach has been refined subsequently, by geologists from Silver City Mining, to combine the use of individual Niton elements (particularly Pb, Zn, Cu, Mn and As) at a detailed scale with geology, published metallogenic information, historical exploration data and further careful field inspections, in order to prioritise targets for follow-up work. So far, the data have also demonstrated extensions to known BHT mineralisation at Allendale, Native Dog, and Hepburn, and at several prospects in the Maybell area. It is also proving useful to track lode rock-bearing successions at Wolseley, Hepburn, Champion, Purnamoota, Silver King and Diamond Jubilee.

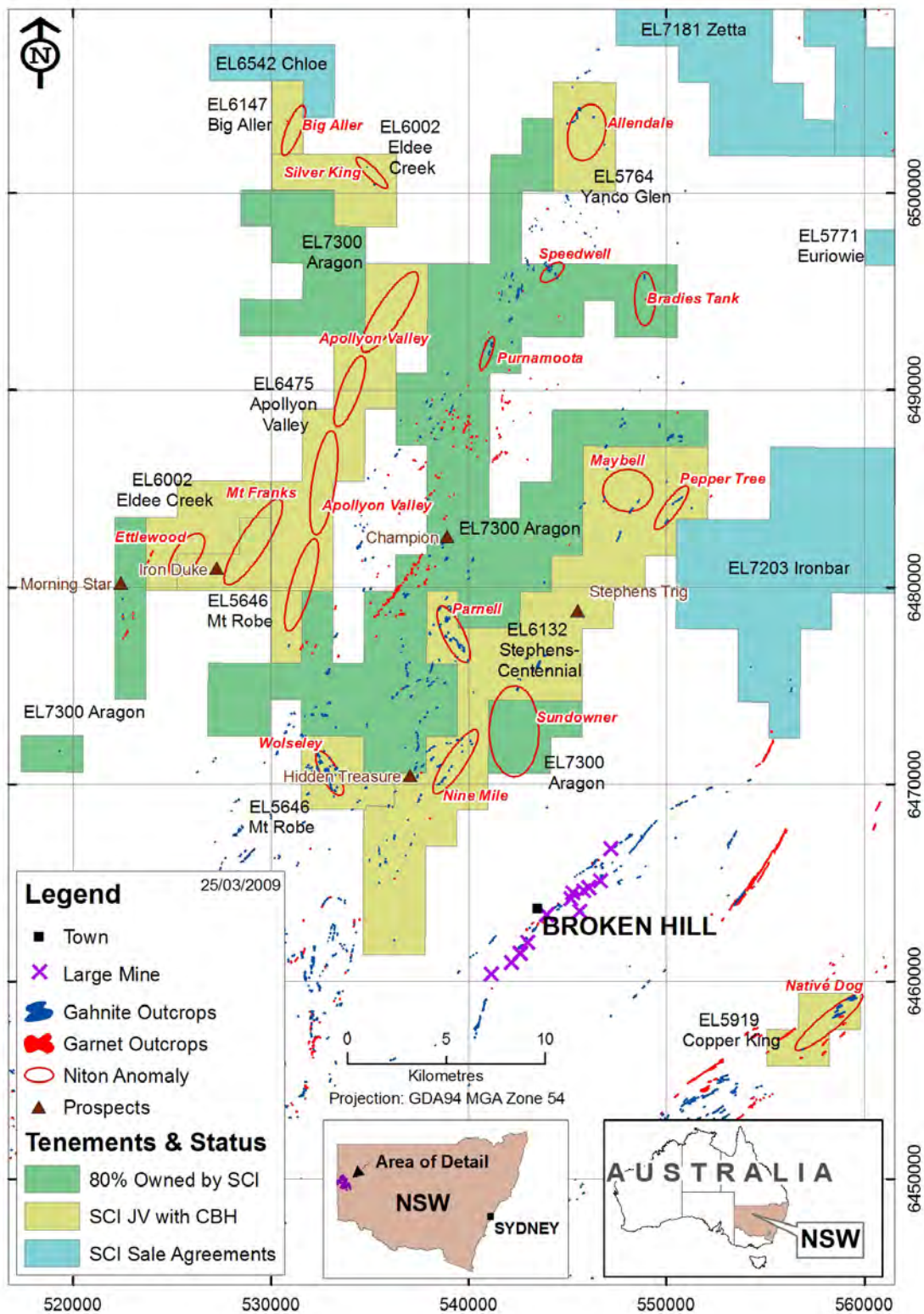


Figure 1. Tenements including the distribution of Niton anomalies, quartz-gahnite and garnetite occurrences.

Native Dog Prospects

Exploration Geology

This project area, 15 km southeast of Broken Hill, covers three prospective units in the Broken Hill Group, namely the Parnell Formation, Freyers Metasediments and Hores Gneiss, plus the less prominent Thackaringa and Sundown Groups. The axis of the structurally complex, overturned F1 (or attenuated F2) generation Little Broken Hill Antiform trends northeast through the centre of the area, and is subparallel to the regional strike of the mapped lode rock units.

The area rose to prominence in 1978, when regional mapping by Graham Bradley of the Geological Survey of New South Wales (GSNSW) drew attention to, and highlighted the strong similarity to, the Main Line of Lode at Broken Hill. Within the area, the Broken Hill Group contains many small Broken Hill type historic prospect workings, including classical BHT stratiform to stratabound BIF-associated and meta-chemical/altered sediment-hosted Pb, Ag, Zn, (Cu) as well as blue quartz-gahnite/blue quartz-psammite hosted Broken Hill type Zn, Pb, Ag, (Cu), and smaller associated Corruga Type W, Cu, Pb, Zn, Ag occurrences.

The prime target area in this package is herein referred to as the Native Dog lode zone, and includes the Rockwell Hope, Wilcannia Rockwell and Bismarck prospects. There are 75 recorded metallic mineral occurrences within EL5919 held by SCI, and 49 occur within, or close to, the 6 km long Native Dog zone.

Classical hallmarks which prove the BHT pedigree of the Native Dog zone are:

- thick, base metal-enriched, altered successions of highly manganiferous, fine-grained, garnet-bearing, black MnO-stained, plus blue quartz-bearing, psammitic metasedimentary rocks
- several classical, BHT-proximal, very extensive, very thick, stacks of mineralised lode and host-rock indicators, including blue quartz ± gahnite, garnet quartzite, spessartine-rich BIF, local calcite-rich calcsilicates, and Pb-contaminated green feldspar lode pegmatites
- similar whole rock geochemistry to Broken Hill.

Surface rock chip samples taken throughout the area by past explorers including CRAE, Aberfoyle, Pasminco and, most recently Sipa Resources, frequently were significantly anomalous in Pb, Ag, Zn, Mn and Cu. The usual blanket style geophysical surveys, including IP and EM by CRAE, Aberfoyle and Pasminco, failed to result in any significant economic intersections. Most geophysical anomalies, and even the early soil geochemical anomalies, have not been explained adequately as yet.

There is still a distinct lack of high quality, detailed geological grid mapping and sampling at a scale suitable for the delineation of higher priority, ore-bearing structures, or to explain Niton anomalous zones in sufficient detail.

Niton Interpretation

At Native Dog, a hilly area with approximately 80 % effective outcrop, systematic, close spaced, regional Niton plus check soil geochemical surveys have further confirmed the high prospectivity of the lode zone. The geochemical work, in conjunction with regional mapping, has helped prioritise the main target areas.

To date, a total of 6965 Niton GPS-located survey points on an initial 400 m x 40 m east-west grid lines, followed by 200 m x 20 m infill grid lines, were analysed for Ag, As, Cd, Co, Cr, Cu, Fe, Hg, Mn, Ni, Pb, Rb, Sb, Se, Sn, Sr and Zn.

Niton-generated ppm maxima were 31,300 Pb, 18,400 Zn, 16,900 Cu, 790 As and 2,250 Mn. Very encouraging high median values of 102 ppm Pb and 155 ppm Zn are nearly 60 % higher than the regional median values of 57 ppm Pb and 92 ppm Zn (Randell, 2007).

Following preliminary, reconnaissance style ground checking, plus a comparison with historical exploration data sets, it is clear that an excellent correlation exists between anomalous Pb, Zn, Cu, As and Mn values and the various prospective geological subdivisions shown on the regional 1:25 000 scale mapping of the Broken Hill Group as defined by the GSNSW (see Figures 2 and 3 for Zn and Mn as examples).

When interpreted in bulk, most of the anomalous subunits appear to make up variably expressed, internally more complex stacks containing well known BHT lode rock indicators, plus associated alteration types. Dimensions of these stacks vary from a few metres to over 300 m in width and up to 7 km in length. At the scale of the 1:25 000 scale published geology, they appear to encompass the bulk of the three stratigraphic units in the Broken Hill Group found on the Exploration Licence.

The broader geological picture is well reflected in the Niton geochemical data. Manganese reflects the broader stacks, plus lode zone surrounds as an alteration picture, whereas the base metals reflect both mapped and un-mapped individual lode rock stacks.

Both Pb and Zn, and even Cu, correlate well with lode stacks at a more detailed on-ground reconnaissance scale, whereas As, despite the low levels, effectively highlights most of the principal historic mining and exploration prospect areas. Copper clearly favours amphibolite rich zones, being anomalous in the highly prospective Parnell Formation. It is clearly also a pathfinder towards better developed, lode rock enriched, metasedimentary and metavolcanic units (e.g. Potosi) such as occur in the Hores Gneiss.

Focused soil orientation check surveys (total of 134 samples) by CBH were completed over the Hores Gneiss, at Wilcannia Rockwell, and over the Freyers Metasediments, near the Bismarck workings. Those over Wilcannia Rockwell have anomalous ppm maxima of 4,190 Pb (20 % > 350 ppm), 1,550 Zn (20 % > 520 ppm), compatible with the Niton values. Those over Bismarck have maximum soil values of 571 ppm Pb (as expected from the Niton results - high), 237 ppm Zn (unexpected - low), and 307 ppm As (as expected - very high), when correlated with the Niton data (McKinnon and Brigden, 2008).

As shown below for Maybell, it is clear that more detailed mapping, combined with carefully planned, closer-spaced Niton determinations, will lead to much more confidently defined drill target areas at the Native Dog prospects, compared with those drilled in the past (tested by seven widely scattered drill holes on seven sections ranging from 400 m to 1.7 km apart).

Maybell Prospects

Exploration Geology

This project area is located 21 km north of Broken Hill (Figure 1) and covers prospective units of the Broken Hill Group, including Freyers Metasediments and Parnell Formation.

Regional 1:25 000 scale GSNSW mapping reveals limited useful information beyond broad rock units, with few lode rocks being mapped in detail. A study based on earlier metallogenic work by R.G. Barnes (in Stevens et al., 2003), however, effectively highlights the distribution of mineral deposits in the Maybell Mines area. These occur in and around the hinge area of the large refolded north-plunging F2 (?) Maybell Antiform.

The prospect area covers the historic Clifton and Rob Roy small mine workings. A 600 m x 400 m pinned grid area has been mapped in detail at a scale of 1:1000 by Eaglehawk Geological Consulting Pty Ltd, followed by systematic lode rock and gossan geochemical rock sampling (51 samples). Results to date are very encouraging. These indicate the presence of numerous, often stacked or structurally repeated, strike extensive lode units. These were originally massive, base metal sulphide-bearing units, being variably siliceous and locally tourmaline bearing. Individual lode rock units range from <1 m to 15 m thick.

Careful rock chip sampling of lode units demonstrates that they are frequently strongly base metal anomalous, showing related Pb, Ag, Zn, Cu, Co, As and Mn values, plus patchy, weakly to locally strongly anomalous Bi, Sb, Ni, together with S and patchy, weakly to moderately anomalous Mo, Au, Cd. Geochemical analysis via ICP by AMDEL provides minimum to maximum ppm ranges of: Pb 10 to 17,000, Zn 21 to 5,700, Cu 34 to 19,200, As 22 to 4,000, and Mn 75 to 13,600.

Iron is highly variable, and a comparison with remnant S, plus a review of sample descriptions, suggests highly variable leaching as well as iron redeposition, but it also includes the possibility of iron-rich sulphides, such as pyrite and pyrrhotite, being present in some of the sulphide-bearing lodes.

A preliminary assessment from mapping and sampling has indicated that the target type is predominantly Broken Hill type which is present as layered stratiform, progressing through to poorly-layered stratabound bodies and, locally, to vein-like sulphides, probably via protracted prograde metamorphism. Small areas of spatially related and much later retrograde-associated, more clearly cross-cutting veined, Thackaringa Style quartz \pm siderite-hosted sulphides are also present, in close association with the earlier formed lode rocks.

Sulphides occur variably in tourmaline-poor to tourmaline-bearing or locally tourmaline-enriched, blue, grey and white siliceous quartz-rich lode units. Gahnite is present, is fine-grained, and is relatively rare. Garnet is also present, is manganiferous, fine-grained, and locally common in the biotite- and chlorite-altered, well-layered, host metasedimentary rocks, being most closely associated with the lode units themselves.

Thin weakly-mineralised, fine-grained, altered amphibolites are obviously part of this mineralised association, as is the probable local redistribution of sulphides during pegmatization events.

The area has never been drilled.

Niton Interpretation

An orientation program has just been completed at the Maybell prospects, which are located in a hilly area with approximately 60 % effective outcrop. Detailed geological grid mapping by Eaglehawk Geological Consulting, and a matching Niton survey by Brian Casey Services using a 20 m x 5 m grid spacing, have been employed to assist in defining follow-up drilling targets. A total of 1776 GPS grid-located, Niton soil survey points were analysed on 32 traverses normal to strike.

Niton-generated ppm maxima were 1,870 Pb, 523 Zn, 847 Cu, 326 As and 1,653 Mn.

Correlation of the anomalous, base-metal Niton data with detailed geology and controlled lode rock sampling is very good. Most lode units, greater than 1 m thick, mapped at this detailed scale, correlate well with traceable anomalous zones of Pb, Zn, Mn, Cu and, in some cases, As (Figures 4 to 7).

Cu, in particular, highlights the better developed lode units and structural thickenings in the lode stacks. Anomalous manganese effectively outlines broader altered successions surrounding the multiply-stacked, often refolded, lode zones. Mn also serves to highlight other prospective weaker lode zones within adjacent metasedimentary rocks, or along weakly developed strike extensions.

Local, poorly-exposed, difficult to map, predominantly scree-covered, thinner lode rock-bearing units are also highlighted by the same suite of elements, but at considerably lower levels.

Exploration Approach by Silver City Mining, and Conclusions

Encouraging prospects first were rated based on the GSNSW-generated regional geological and metallogenic mapping, together with the regional Niton soil geochemistry. These were further combined with useful historic information from old mine workings, plus previous exploration data sets.

The efficacy of close-spaced infill Niton determinations, when compared to a range of known empirical geological vectors as determined by detailed geological mapping, clearly has been validated by the orientation work of SCI at Maybell, and its probable direct usefulness is also indicated at the Native Dog area.

Detailed geological mapping and rock chip sampling, combined with more focused Niton infill surveys over suitably designed grid areas covering predominantly outcropping prospects, are clearly the keys to homing in on promising drilling targets in areas of fair to good outcrop.

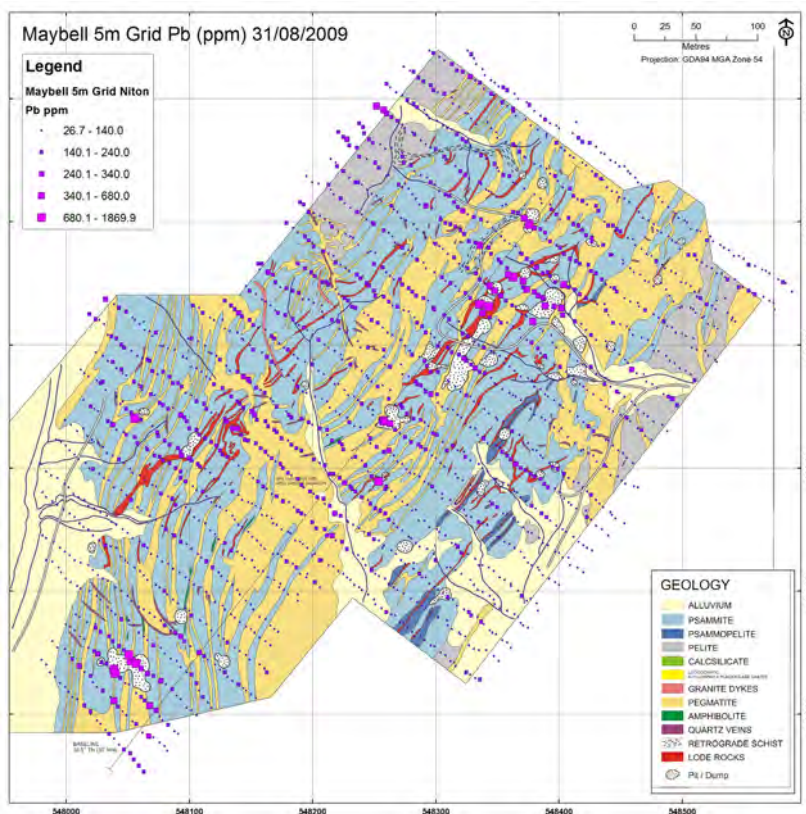


Figure 4. Maybell prospect, close-spaced grid, Niton Pb results and detailed geology.

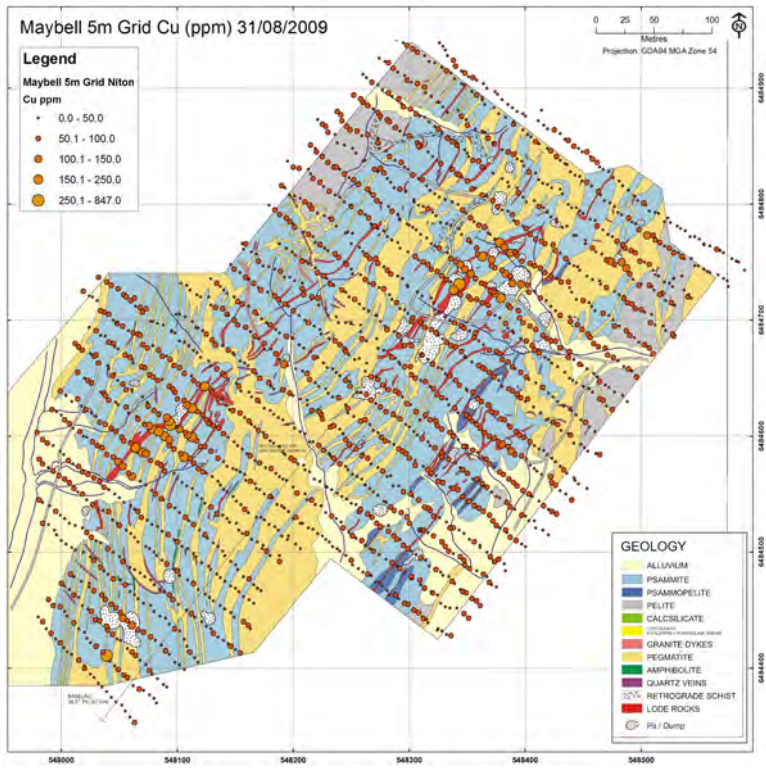


Figure 5. Maybell prospect, Niton Cu results, and detailed geology.

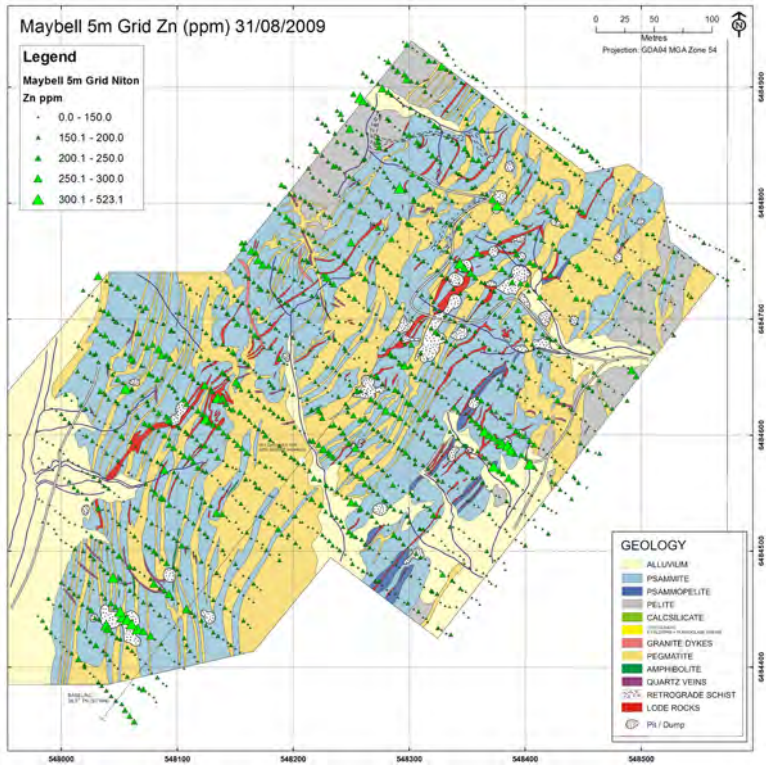


Figure 6. Maybell prospect, Niton Zn results and detailed geology.

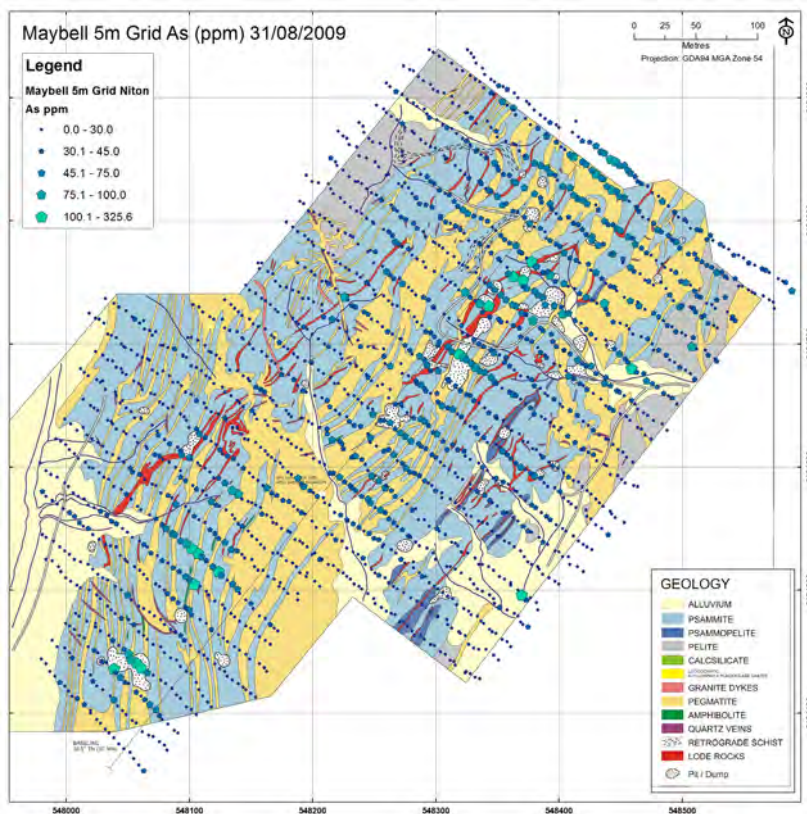


Figure 7. Maybell prospect, Niton As results, and detailed geology.

Further infill Niton programs, a number of RAB programs in poorly exposed or shallow cover areas, and some short RC percussion and aircore drilling, is planned over the next ten months by Silver City Mining Ltd. Based on progress and results to date, it is confidently expected that at least ten targets will be defined in this way, and will warrant significant RC percussion and diamond drilling programs by mid 2010.

Acknowledgements

This work is presented with the permission of all joint venture partners: CBH Resources Ltd (Broken Hill Operations Pty Ltd), PlatSearch NL and Eaglehawk Geological Consulting Pty Ltd, under the original ZincSearch JV.

Thanks are due to Bob Richardson, former Managing Director of PlatSearch NL, for designing the initial regional Niton surveys at both Native Dog and Maybell, and to Jeff Randell plus CBH Management for persevering in greater detail with the portable XRF geochemical methodology. Thanks are also expressed to personnel from Brian Casey Services for long hours spent climbing up rocks, hills and out of steep gullies.

Finally, our gratitude is strongly conveyed to many past workers of the Geological Survey of New South Wales for providing an excellent regional geological map base, numerous verbal discussions, and a plethora of useful publications which, as always, effectively support mineral exploration in the Broken Hill district.

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The Geologist's Other Right Hand – HyLogger™

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Introduction

A large portion of a geologist's life can be spent examining diamond drill core or percussion drill chips. This activity forms an important component of exploration and mining, but the efficiency and accuracy with which it is carried out can mean the difference between a successful venture and a financial disaster. There are three key factors that impact on the efficiency and accuracy of logging. First, is the competency of the geologist, determined by a combination of training, experience and aptitude. The second major issue is that there are some key minerals that cannot be identified readily by eye in hand specimen. The same minerals have compositional changes, which traditionally require laboratory analysis to determine. Thirdly, trends in abundance are often inexact, due to inconsistent estimation by the geologist.

New HyLogger™ technology, developed by CSIRO, addresses each of these issues, and provides scaled imagery of drill core along with its mineralogical interpretation. By providing a level of objectivity and interpretative support, the impact of variable logging styles of different geologists can be minimised. ShortWave InfraRed (SWIR) spectroscopy can identify key clay, mica and carbonate assemblages, as well as determining the chemistry of individual species. Spectroscopy also has applications to determine the redox states of iron-oxide minerals. Future upgrades of the HyLogger will provide thermal infrared spectroscopy to identify silicate mineralogy. Most significantly, geologists readily can access a semi-quantitative distribution of minerals down a drillhole or in a district.

Through the Australian Government, the National Collaborative Research Infrastructure Strategy (NCRIS) funding arrangement and the disbursement managers, AuScope, each State Geological Survey now has access to this technology. Both South Australia and New South Wales have taken delivery of HyLogger™ instruments, and have been scanning core since May this year. South Australia, which also boasts a large collection of legacy data scanned with previous prototypes of the HyLogger™ instrument and in collaboration with CSIRO, actively has been investigating database storage and distribution mechanisms.

Vectors to Ore and Regional Alteration

Work by CSIRO, in the 1980's, using PIMA II spectroscopy, established a role for shortwave infrared spectroscopy in establishing vectors to mineralisation. Clear chemical trends in white

micas, chlorites and kaolin were identified in relationship to a variety of deposit types and their alteration haloes (Huntington et al., 1997, 2004).

With the advent of hyperspectral core logging, regional subsurface alteration mapping has become a possibility. One example of how hyperspectral data might be used to map the geographic distribution of alteration is proposed here. Each drill hole samples the intersected mineral systems and, after scanning with HyLogger, records how many metres of a specific mineral are present in the drillhole (Mauger, 2008, 2009a, 2009b). Using this value as a semi-quantitative indication of abundance at that location, each mineral can be gridded, using the values from numerous drillholes to display its geographic distribution in the geological domain. By selecting mineral pairs with known associated geochemical gradients, a geochemical model can be established for exploration target generation.

The success of using mineralogy, in this way, depends on the understanding of alteration mineralogy associated with the target mineral systems. Mineral systems consist of source, conduit and repository. Where transport between the source and repository involves a fluid phase along the conduit, the fluid alters the substrate it passes through. This alteration involves the removal or addition of elements from existing minerals, and the creation or removal of entire mineral species.

In addition, as fluids travel through the substrate, their own nature is changed. Pressure and temperature conditions change. Different wall-rock interactions/reactions take place. Ions are added and removed. The effects of these changes can be observed as systematic changes in mineralogy, and mineral associations, over time and distance.

Minerals will precipitate when the fluid no longer retains the properties necessary for solubility:

- Pressure has changed (dropped)
- Temperature has changed (dropped)
- pH has changed
- Oxidation state has changed.

Many alteration minerals, important to exploration, have been studied in detail by thin section petrology, but this is not necessarily quantitative, for example:

- Albite (from Na metasomatism), K-feldspar, adularia
- Sulfides including: pyrite, marcasite, chalcopyrite, bornite
- Sulfates including: jarosite, alunite
- Hydrated mineral species including: smectites, kaolinite, dickite, muscovite/sericite, chlorite, tremolite, biotite
- Tourmaline, epidote, rutile, ferroan dolomite, phlogopite
- Hematite, magnetite.

When hyperspectral (VNIR/SWIR) data to map mineralogy is examined, it is found that a number of key traditional alteration minerals are not visible in the VNIR/SWIR part of the spectrum, such as anhydrous silicates.

An empirical study undertaken using PIMA II, which operates solely in the SWIR, established some useful relationships (Huntington et al., 1997). The first finding was that most mineral systems have only a few key SWIR responsive minerals to work with. Those key minerals, however, can often change abundance and composition along chemical gradients from barren material to ore-bearing environments. These changes can be measured using high resolution spectroscopy, such as HyMap, covering the VNIR/SWIR wavelengths.

Key mineral assemblages, visible in VNIR/SWIR spectroscopy, include:

- Kaolin
- White mica
- Smectites
- Chlorite
- Carbonate
- Iron oxides
- Sulphates
- Pyrophyllite and topaz.

One method of measuring the distribution of key mineral assemblages is to measure how many metres of the drillcore contain specific minerals. HyLogger™, in conjunction with The Spectral Geologist software, provides such a measure. For each scanned drillhole, the number of metres of a targeted mineral, for example, muscovite, phengite, siderite and magnesite, are recorded, and can be easily converted to graphs and statistics.

Although these vectors exist and are documented:

- They do not always behave the same between different deposits
- The relative position of high phengite abundance is often marginal to the ore (there could be a pressure control on its distribution)
- Fe-Mg chlorite vector seems to change from deposit to deposit
- Overprinting often distorts the record
- Gradients may be important indicators of mixing zones between oxidising and reducing environments.

Observing domains of homogenous spectral properties and changes, gradual or abrupt, in particular where these cross lithological boundaries, is valuable. Validation against, at least, some petrology and XRD is critically important to understand paragenesis, particularly when multiple events may be involved.

Elements of the system that need to be considered, when estimating the fertility of a region, include:

- Eh/pH
- Redox boundaries and gradients
- Suitable repositories (reducing beds)
- Permeable conduits (sediments or tectonic fracturing)
- Source and movement of hot fluids of the right composition
- Fluids mixing
- Source for metals.

If the elements of the model can be mapped by spectrally distinct minerals, hyperspectral analysis can be used to generate vectors to ore-bearing environments, or at least understand the architecture of a mineralised system.

National Virtual Core Library

The AuScope National Virtual Core Library (NVCL), being sponsored and funded by NCRIS, exists to facilitate access to, and distribution of, data captured by the State Government HyLogger™ systems. Each State Government agency represents a node of the NVCL. As the years go by, it is anticipated that the NVCL will be populated with data at the rate of several terabytes per year. The combined effort will make national drillhole data accessible on the laptops of geologists anywhere in the world.

Case Study 1: Thackaringa

To demonstrate the power of this technology, Thackaringa diamond drill hole DD95TH05 was scanned using the NSW NVCL Node HyLogger 2-4.

High grade metamorphic rocks in Broken Hill are challenging spectral targets, as the silicate mineralogy lacks diagnostic spectral responses in SWIR or VNIR bandwidths. Thackaringa-type siderite±quartz veins were selected for scanning because of their characteristic, spectrally-detectable, sericitic alteration halo, and relatively uncomplicated metallogenic evolution.

Thackaringa-type mineralisation is epigenetic, late- to post-structural (Delamerian-age) mineralisation common in the Broken Hill Domain (Both and Smith, 1975; Dong et al., 1987). Regionally, veins occur as curvilinear zones or clusters. Locally, veins are subparallel and discontinuous. The veinsets are typically associated with retrograde shear zones. In the Thackaringa area, 35 km southwest of Broken Hill, vein density is sufficient to warrant consideration of an open cut, lead-silver resource.

HyLogging of DD95TH05 indicates that the alteration associated with Thackaringa-type deposits includes an extensive, peripheral kaolinite halo and mineralisation-proximal muscovite and illite zones. Carbonate (calcite) and sulfate species occur in the footwall. Spectral results include:

- Measured muscovite and illite abundance increases approaching ore,
- An increase in mica intensity approaching ore (this is a change in the shape or steepness of the diagnostic peak, at the ~2200 nm wavelength response),
- A systematic increase in the ~2200 nm wavelength peak approaching ore, a measure in the increase in phengitic (increased Fe, decreased Al) muscovite chemistry, and
- A 50 m spectrally-zoned, alteration halo into both the hangingwall and footwall.

Interpretation includes:

- Kaolinite identified by the HyLogger is not considered to be a weathering product as it is well developed to 180 m depth.
- The spectral results for illite and muscovite (increasing wavelength and increasing mica intensity) indicate that fluid temperature increases towards mineralisation.

Kaolinite and illite are not typically described in existing literature on Thackaringa-type deposits. This observation, in conjunction with the described muscovite spectral characteristics, has possible ore-vectoring applications throughout the Broken Hill Domain. Retrograde shears might be assessed for fluid flow, and metal potential, using spectral detection and quantitative spectral characteristics of the alteration assemblage.

High quality, regional hyperspectral (HyMap) data, acquired over the Broken Hill Domain by in 2002 by HyVista has recently undergone, post-processing by CSIRO and the Geological Survey of New South Wales to a user-ready format, including a suite of 16 standard products (Cudahy et al., 2009). Release of these data will permit spectral vectoring information, determined using HyLogger, to be regionally applied, by data regression, to the entire HyMap survey area.

Case Study 2: Curnamona Study

One example of preparing a regional alteration plot is a study that was undertaken using HyLogger-1 data from the SA NVCL Node. Using the same criteria selected for a study from the Gawler Craton (Mauger, 2009b), four mineral pairs were selected by way of example of the technique: white mica, carbonate, iron oxide and chlorite.

1. *White Mica: Al depletion of muscovite (Mv)*

The mineral pair selected was muscovite and phengite. The muscovite to celadonite solid solution involves the depletion of Al and substitution of Fe and Mg. Phengite is the general term for Al-poor, Fe-rich muscovite approaching the celadonite end-member chemistry. It has been observed that the proportion of phengite increases in proximity to mineralisation, even as the abundance of muscovite might be decreasing. The transition can be measured by the wavelength of the ~2200nm absorption feature.

2. *Carbonate: Fe-Mg gradient and abundance of carbonate*

The mineral pair selected was dolomite and siderite. Fe-Mg substitution in carbonate is measured by the wavelength position of the ~2350nm absorption feature.

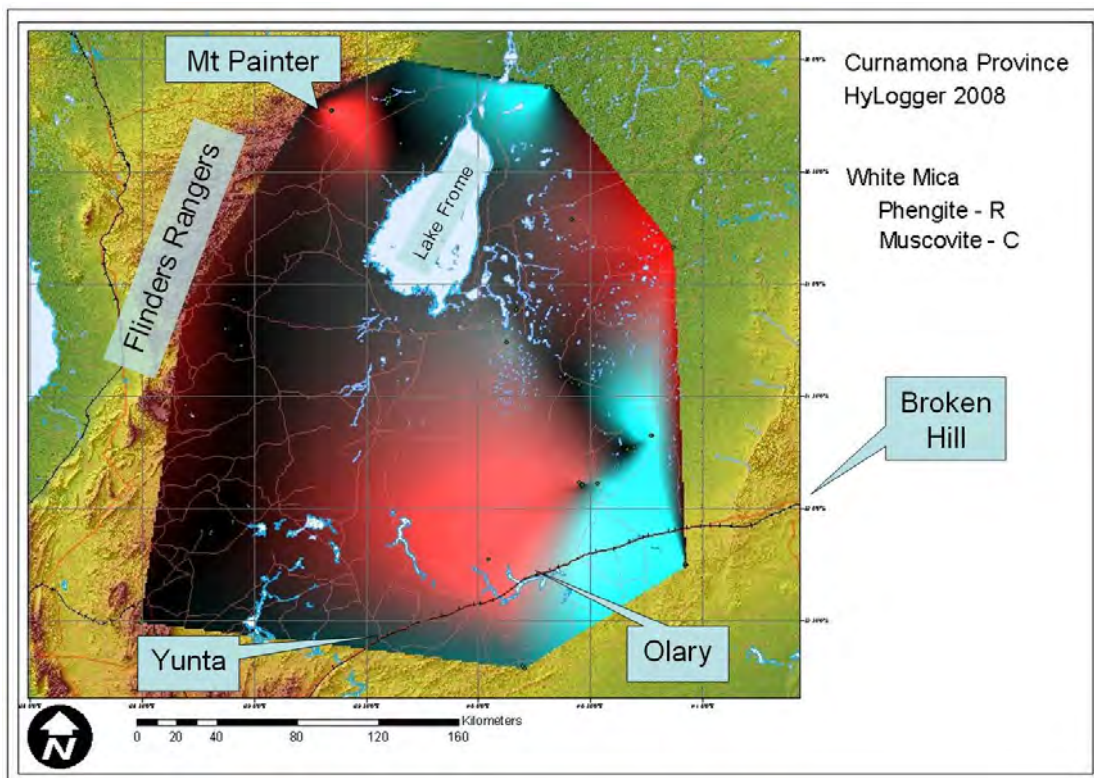


Figure 1. The chemical gradient in white mica: Al-rich (cyan) to Al-poor (red).

3. *Iron Oxide: Fe²⁺ and Fe³⁺ variants of goethite and their relationship to hematite*

The mineral pair selected was hematite/Fe³⁺ goethite and hematite/Fe²⁺ goethite. The spectral signatures of hematite and goethite are distinctive in VNIR. Goethite empirically has two spectral signatures from laboratory studies, identified as Fe²⁺ goethite and Fe³⁺ goethite:

- Fe³⁺ goethite, interpreted as after hematite
- Fe²⁺ goethite, interpreted as after pyrite (Fe²⁺ sulphide).

4. *Chlorite: Fe-Mg gradient in chlorite*

The mineral pair selected was Mg chlorite and Fe chlorite. Fe-Mg substitution in chlorite is measured by the wavelength position of the ~2350 nm absorption feature.

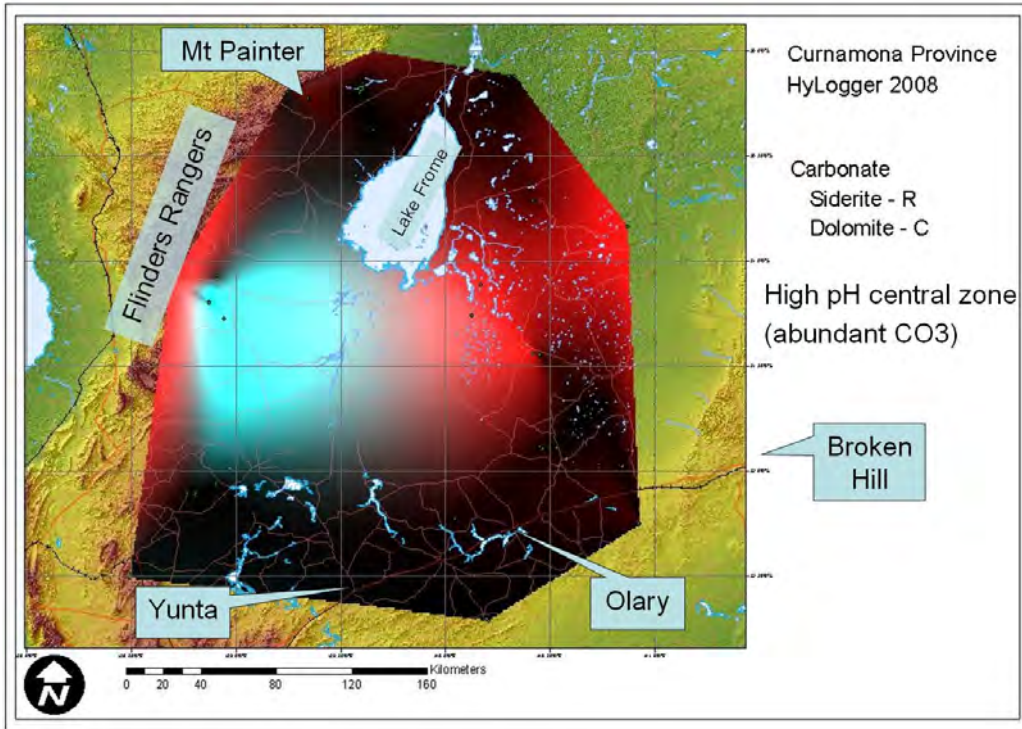


Figure 2. Variations in carbonate chemistry: Fe-rich (red) to Mg-rich (cyan).

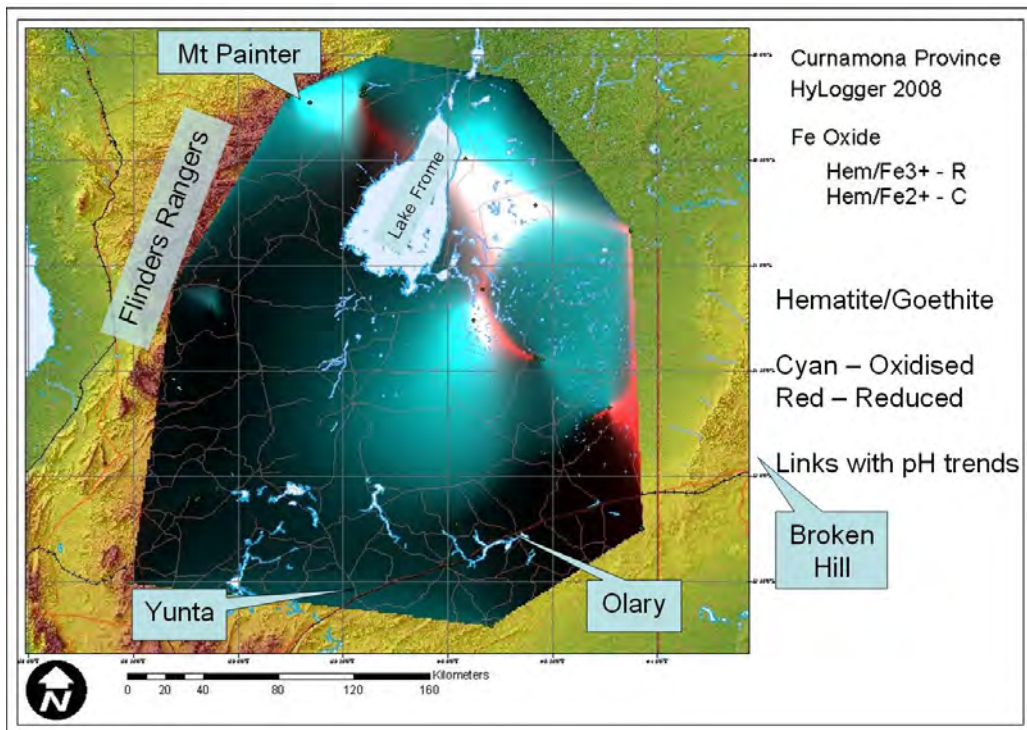


Figure 3. Variations in iron oxide chemistry: reduced (red) to oxidised (cyan).

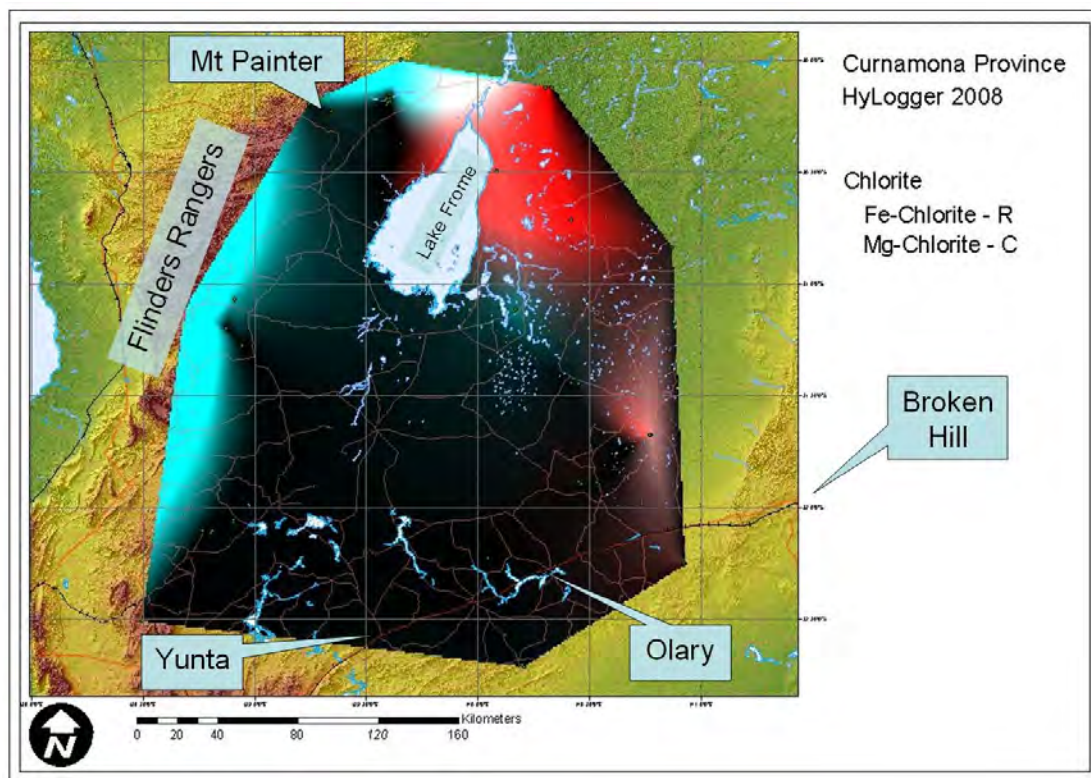


Figure 4. Chlorite chemistry: Fe-rich (red) to Mg-rich (cyan).

Figures 1 to 4 provide an insight into the gross chemical variations across the Curnamona Province. Paucity of data does hamper the interpretation. There appears to be a trend towards increasing Fe in the east, and increasing Mg to the west with a high pH zone in the centre, and a redox boundary trending northwest-southeast through Lake Frome. For a complete analysis, further work, filtering alteration mineralogy by stratigraphy, needs to be undertaken.

Conclusions

The images provided in Figures 1 to 4 provide new concepts for geologists, and understanding the implications will take some time, and will require corroboration with other sources of information. More holes need to be drilled and scanned, in order to improve the geographic spread of data points for meaningful gridding. Part of improving the distribution involves the vertical component; holes need to be drilled deeper and entire holes need to be scanned. One aspect of this study is that current geological models need to be applied to the data to provide context. Applying a stratigraphic filter, if it is considered that alteration might have stratigraphic controls, would be the next step in the process.

The same type of study could be undertaken at lease or mine scale with sufficiently dense drilling, which potentially could provide local geochemical vectors to mineralisation.

Acknowledgements

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Application of field portable XRF geochemical data in the Broken Hill Region

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Introduction

Field portable XRF (FPXRF) instruments have been utilised by numerous explorers in the Broken Hill region to collect geochemical data. The extensive outcrop in the region renders the technique particularly suitable, with rapid coverage of large areas being possible. Each measurement using a FPXRF instrument can take as little as 30 seconds, resulting in the compilation of large datasets in a short period of time. Corresponding with the BHEI 2009, FPXRF data collected by Perilya Limited and CBH Resources Limited, along with their JV partners, will be made available to other explorers. The combined dataset has over 200,000 individual FPXRF readings and provides geochemical coverage for more than 450 km² of prospective ground surrounding Broken Hill (Figure 1). As with any exploration tool, the technique has both advantages and disadvantages, and analysis of some of these aspects are described below, with specific reference to the CBH Resources dataset.

Data Collection and Quality

An FPXRF dataset, consisting of more than 115,000 readings, was compiled over a number of years as a part of regional assessment program at Broken Hill by CBH Resources. The program mostly consisted of readings collected by CBH with a NITON XLt 792Y Analyzer, but also includes more than 18,000 assays from a previous geochemical program in the Stephens Creek area, and around 12,000 assays from the Stirling Vale JV, collected by Perilya Ltd. The program was conducted on a nominal grid of 40 x 400 m, with higher-density infill sampling (as close as 10 x 10 m) over areas of particular interest. In many cases, additional readings were also taken around old shafts, pits and waste dumps. The assay suite consists of up to 19 elements, including Ag, As, Cd, Co, Cr, Cu, Fe, Hg, Mn, Mo, Ni, Pb, Rb, Sb, Se, Sn, Sr, Zn and Zr, although Mo and Zr were assayed only in a limited number of samples.

The detection limits of the instrument are not sufficient to allow the consistent detection of some pathfinder elements on a regional scale. The statistical distribution of data for Pb, Zn, Mn, Fe, Sr and Rb is most favourable, with their respective median values being well in excess of the quoted lower limit of detection (LLD) for the instrument. The distribution of values is less favourable for elements such as Cu and As, resulting in lower contrast results, which nevertheless, can still be useful. Nearly all data collected for potential pathfinder elements, such as Ag, Hg, Mo, Se, Sb, and Sn fall below the quoted LLD for the instrument, giving the results for these elements relatively little value.

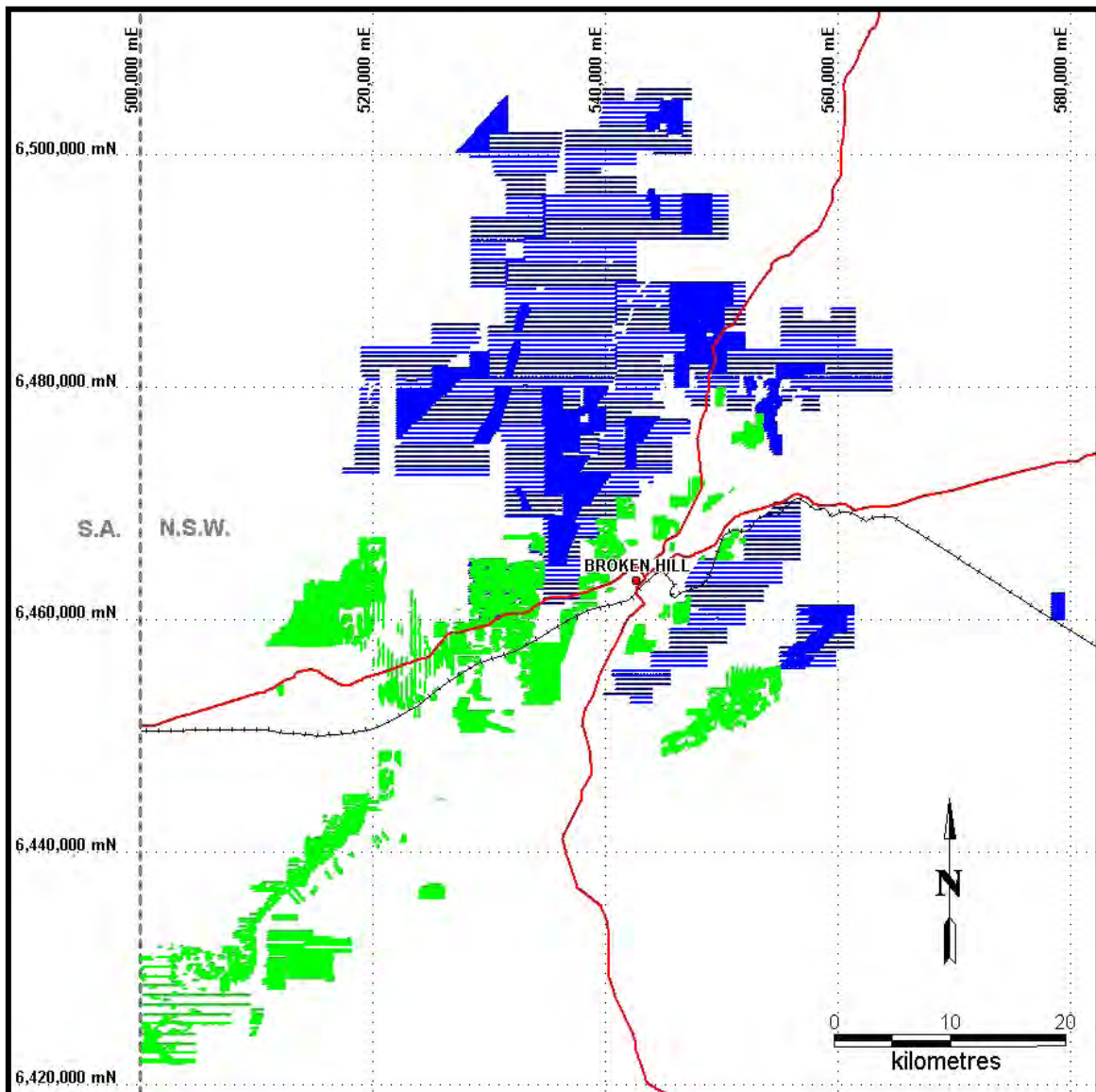


Figure 1. Regional coverage of field portable XRF readings taken by CBH Resource Ltd (blue) and Perilya Ltd (green).

Comparison of FPXRF with Conventional Soil Geochemistry

Orientation traverses were employed at several key locations to compare conventional soil geochemistry with FPXRF geochemistry. Figure 2 shows the Pb, Zn, As and Cu results for both FPXRF and conventional soils (coarse fraction) at a location in the Apollyon Valley. Although much of area traversed returns broadly similar geochemical results (especially for Pb and Zn), some high concentrations detected by the FPXRF instrument are not observed in the equivalent soil assays, and vice versa. Similar patterns were also repeated in the other traverses, resulting in only partial correlation between the two methods. The disparity between some of these results may be a reflection of a slightly different sampling position, as the conventional soil analyses were performed after the FPXRF analyses. The disparity may also be a reflection of the different soil fractions analysed in each method.

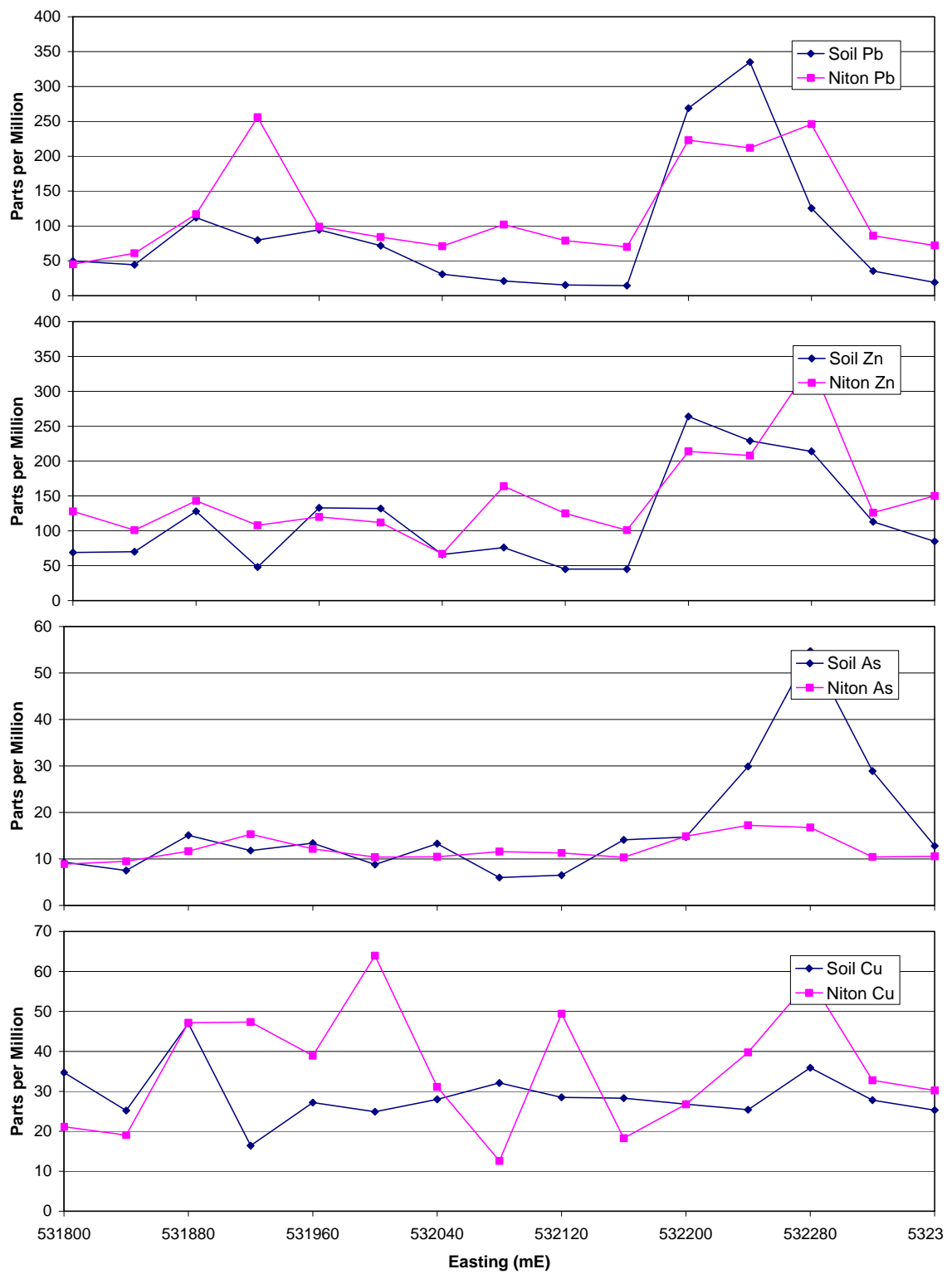


Figure 2. Comparison of Pb, Zn, As and Cu soil and FPXRF (Niton) geochemistry on the Apollyon Valley 6,482,800 N line.

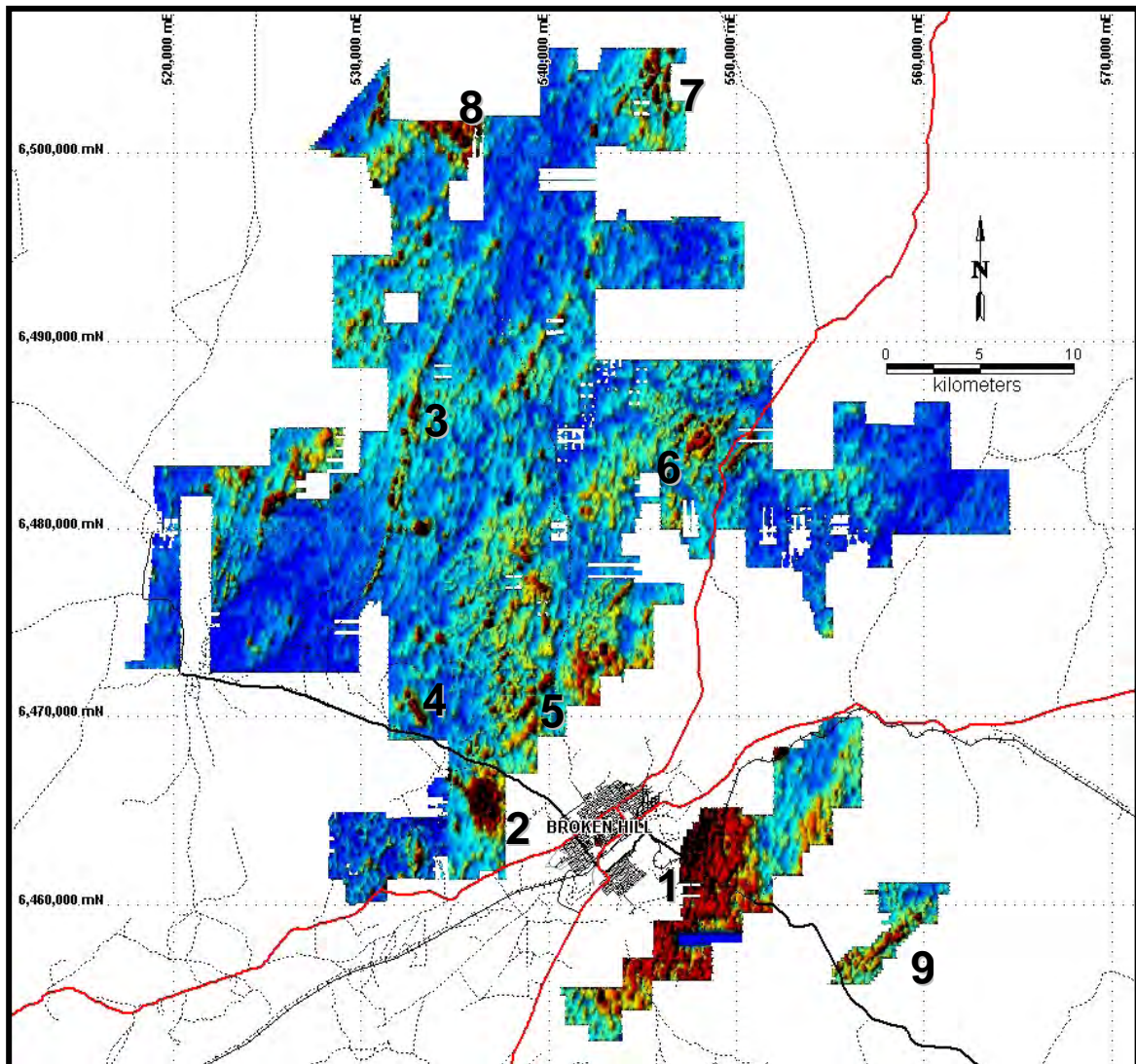


Figure 3. Gridded additive index (Zn + 2Pb + 10As) contour of FPXRF data, showing some of the major geochemical anomalies in the Broken Hill region. Anomalies: [1 & 2] contamination; [3] Apollyon Valley Shear Zone; [4] Wolseley; [5] Nine Mile; [6] Maybelle; [7] Allendale; [8] Silver King; [9] Copper King (Native Dog).

Data Treatment and Presentation

To avoid skewing the dataset in favour of high density sampling areas (usually in areas of known mineralisation), all data occurring outside the nominal 40 x 400 m 20 x 200 m grids were removed, when analysing and presenting the data on a regional scale. This modified dataset then was used to produce contour grids for key elements, including Pb, Zn, Cu and As. Additive indexes also proved useful for visualisation of the data, and a Zn + 2Pb + 10As ratio plot was used to illustrate mineralised and/or structural trends (Figure 3). Data was generally gridded using a linear stretch, with a 4 % clip at top and bottom. A number of different levelling regimes were also trialled, including for cover versus outcrop, rock type, stratigraphic unit, and the concentration of Fe or Mn in the samples. Only normalisation to cover and rock type appear to be useful in increasing the contrast of geochemical anomalies, with the other regimes tending to produce indistinct patterns, seemingly unrelated to mineralisation.

Major Geochemical Features in the FPXRF Dataset

The most distinctive feature in the CBH Resources FPXRF dataset is the very large anomaly to the east and southeast of Broken Hill (see Figure 3, anomaly 1). This anomaly is present in readings ranging from 3 to 7 km from the Line of Lode, and is considered to represent significant surface contamination from more than a century of mining and processing operations in the area, and. Those readings closest to Broken Hill are most anomalous, with median values exceeding 600 ppm for Pb and 1000 ppm for Zn. A distinctive subcircular anomaly, approximately 2 km in diameter to the west of Broken Hill (anomaly 2), is also related to historic ore processing activities.

The largest anomaly not related to anthropogenic activity is associated with the Apollyon Valley Shear Zone (anomaly 3). This anomaly can be traced in a north-northeast direction for at least 23 km, varying between 100 and 300 m in width. The feature displays anomalous Pb, Zn and As values, with the highest values occurring in the vicinity of known Thackaringa-style vein deposits.

Strong Pb-Zn(\pm As-Cu) anomalism associated with Broken Hill-type mineralisation can be found at a number of locations in the region. Northwest of Broken Hill, in the Nine Mile area, stratigraphic-parallel anomalies occur in rocks of the Hores Gneiss and Parnell Formation (anomaly 5). Highly anomalous results also are associated with exposed quartz-gahnite rocks at the Wolseley prospect (anomaly 4) further to the west. In the far north, in the vicinity of the Allendale mine, strong but patchy anomalism is associated with rocks of the Parnell Formation (anomaly 7). Southeast of Broken Hill, a northeast-trending linear anomaly of at least 4 km length is associated with lode-type rocks in the Native Dog area (anomaly 9).

Other major anomalies are associated with the Mount Robe Synform at the contact of the Silver King Formation and the Purnamoota Subgroup (anomaly 8), and in rocks of the Thackaringa Group in the Maybelle area (anomaly 6). Many other smaller or less significant anomalies have been defined in the region, often associated with historic workings.

Acknowledgements

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The coming of age of the Koonenberry Belt

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Introduction

The Koonenberry Mapping Project, carried out since 1995 by the Geological Survey of New South Wales, is coming to an end. The project was designed to explore, map and better understand the geology of an orogenic fold and thrust belt hugging the eastern margin of the Paleoproterozoic Curnamona Province in western New South Wales. The Koonenberry Belt has proved to be a significant, well-preserved portion of the late middle Cambrian Delamerian Orogen, which formed on the eastern margin of Gondwanaland in Australia and Antarctica. The Koonenberry region also records clear evidence of post-Delamerian Paleozoic and younger events. Over the fourteen years that the project has run there has been a revolution in the way in which field data are collected, recorded and stored, the quality of the geophysical and satellite support systems that are used to assist with the mapping process, and the manner in which the maps and field data is made available to end users. Although major mineral deposits have yet to be discovered in the Koonenberry region, the increase in knowledge and prospectivity has stimulated much current exploration interest.

Koonenberry –Early Exploration by White Man

On June 26, 1835, Surveyor General Thomas Mitchell, while tracing the south-west course of the Darling River, rode his horse onto a broad hill north of present Wilcannia, naming it Mount Murchison after Roderick Impey Murchison, a Cambridge geoscientist famed for defining the Silurian and the Permian periods. From there, Mitchell sighted the Koonenberry region for the first time, a broad sweep of low ranges, resembling waves on a sea without many defined peaks (Mitchell, 1939). He named the more prominent ranges and peaks after contemporary geologists George Scrope (Scropes Range), Charles Daubeny (Mount Daubeny), Charles Lyell (Mount Lyell), John Macculloch (Macculloch Range) and mathematician Charles Babbage (Mount Babbage).

Nine years later, the well-equipped expedition of Captain Charles Sturt lumbered up the Bancannia Plain with 200 sheep and a number of bullock drays, one of which carried a whale boat that would be launched on the Inland Sea (Sturt, 1849). The original whale boat was abandoned in Evelyn Creek near Milparinka, but a modern replica proudly stands today at the head of the main street of Tibooburra. Sturt identified what he thought was Mount Lyell, although this broad peak cannot be seen from Mount Murchison. In more recent times, this peak has been known as Kara Hill and currently Mount Lynn, a corruption of Lyell that arose through the misreading of the half-obscured name on a parchment map of old Gnalta station.

The names Mount Lyell and Mount Babbage have failed to survive on to modern maps of New South Wales. The original Mount Lyell was probably an end on view of the Coturaundee (formerly Copper Mine) Range, the highest elevation in the whole belt, whereas Mount Babbage may have referred to a small hill near White Cliffs. Following reports on the fattening of Sturt's sheep, the region was opened to large sheep runs in the 1850's. The ill-fated Burke and Wills expedition traversed the Koonenberry region in 1860.

Mineral Discoveries

In 1880, John Thompson, returning from Mount Poole, cashed in over 1 oz of gold at a bank in Wilcannia, and raised considerable public interest. In 1881, James Evans returned from nearby Mount Browne with 14 oz of gold, and the rush was on. Soon, up to 2000 hopeful prospectors were combing the Koonenberry region seeking their fortunes, mostly unaware of the harsh nature of Sturt's Stony Desert and the erratic and low rainfall. Enthusiastic schemes were often thwarted through the lack of water.

Alluvial gold was found at the base of the Mesozoic succession, as well as in modern water channels, and rich narrow auriferous veins were opened in the Wamberiga Range (Warratta Reefs – the Pioneer, Phoenix, and Rosemount). Settlements developed at Milparinka (near waterholes in Evelyn Creek), Tibooburra (in the north), Mount Browne (in the south) and Albert (near the reefs in the Wamberiga Range). Minor gold was also found at Williams Peak and Bonley Creek to the south. Milparinka became the main town, and stage coach destination from Wilcannia. Over a 20 year period from 1881, 1000-5000 oz of gold per year were recovered from the Albert Goldfield, before yields diminished. There have been recent drilling programs carried out by Proto Resources, at Warratta, and Rockwell Resources, at Bonley Creek and Kayrunnera.

Rich silver lodes, resembling the Thackaringa quartz-siderite veins, were found on Wertago in about 1889, and the town of Noonthorangie sprang up rapidly. The town was dismantled just as rapidly in 1893, when the miners moved to White Cliffs, where opal discovery offered much greater rewards. There have been attempts to revive the silver mines, and some test drilling carried out, without much success. A minor silver-lead occurrence was also mined on the eastern side of Scropes Range at Bilpa.

The copper deposits of the Wertago Copperfield were exploited over a 10 year period, from 1898 to 1908, when copper prices were favourable. Parcels up to 27 tonnes were dispatched, but the cost of cartage over enormous distances took most of the profits. With lower copper prices, and lack of capital, the mines closed down and a proposed extension of the Silverton tramway, from Torrowangee Quarries to Wertago,, and on to White Cliffs, became a pipe dream. A smelter operated briefly at Wertago, but local timber fuel was soon exhausted. Other copper mines were developed at Grasmere, Cymbric Vale, Sullivan's Ponto Mine, Koonenberry Gap and Bilpa where various parcels of ore were brought to grass, but the tyranny of distance prevented much development. Some intermittent drilling and geophysics have been carried out since 1945. The latest ventures have been with Graynic/Proto at Wertago, Black Range Minerals at Grasmere, and Platsearch at Cymbric Vale.

Precious opal was found at White Cliffs in 1890, and by 1893 the population had swelled to 2500, with 1000 miners. White Cliffs was the major opal producer in New South Wales until 1925 when Lightning Ridge became dominant. Redfire Resources carried out some systematic grid drilling near White Cliffs from 1991 1997, identifying further opal occurrences.

The discovery of a potential kimberlite pipe near Kayrunnera in 1978 brought on 20 years of enthusiastic diamond exploration, by several companies, but with little success. Some early aeromagnetic work uncovered a number of circular magnetic anomalies, and some limited work was carried out. Two small alluvial diamonds were reported.

CRA investigated the nickel potential of the Wyndonga ultramafic body in 1971. In recent years, nickel has been sought by Vale (formerly Inco), working on the Neoproterozoic Mount Arrowsmith Volcanics on the western side of the Koonenberry Belt, and Mithril Resources, working on the Cambrian tholeiitic basalts and intrusions on the eastern side of the belt.

Water is another precious resource that has been sought in this parched area. Kenny (1934) summarised the early knowledge. Groundwater of useful quality is met in bores sunk in the Mesozoic Eromanga Basin and in the Devonian quartz-rich sandstone successions. Groundwater in pre-Devonian rocks is usually brackish, and in small quantity, except in some more porous fault zones.

Petroleum search in northwest New South Wales has undergone four main episodes of development:

- 1945-1948 - Gas exploration, spilling over from South Australia;
- 1958-1971 - A major push was made in the Bancannia Trough and Darling Basin, and several deep stratigraphic holes were drilled;
- 1979-1987 - Eromanga Basin recognition and development;
- 1996-2009 - Some reassessment of geochemistry and fluid inclusions. Some of the latest work by Black Rock Petroleum and Petrofocus on soil gas analysis.

An important spin-off of the petroleum work has been the discovery of fossils. The first Cambrian fossils were reported by Rayner (1957) and Hall (1960). Geological Survey mapping of the 1:250 000 sheet series over the period 1961-1974 also uncovered some new finds.

Revelations: 1983-1988

Subdivision of the Wonominta beds

Kingsley Mills was introduced to the Koonenberry region during a five week field excursion with the University of Sydney in 1983 aimed at locating new fossil finds, and he spent the next several winters mapping the low grade slates and sandstones of the Wonominta beds to better understand the region.

This work enabled the subdivision of the older rocks into three distinct lithological units, now known as the Grey Range Group (Neoproterozoic shallow marine shelf deposits of muddy and silty character containing some dolomites, clean quartz-rich sandstone beds and the Mount Arrowsmith Volcanics), the Teltawongee Group (dirty turbiditic sandstones with minor silty and muddy beds) and the Ponto Group (highly deformed phyllites, fine-grained turbiditic sandstones, and rare tholeiitic pillow lavas and distinctive layers of felsic airfall tuffs). The Teltawongee Group was found to contain rare Cambrian fossils and trace fossils, whereas the apparently unfossiliferous Ponto Group was thought to be Precambrian (Mills, 1992). Together these pre-Delamerian rocks define an important segment of the extensive Delamerian Orogen.

Koonenberry Fault

The Koonenberry Fault is a major central feature that can be traced the whole length of the Koonenberry Belt, either in outcrop or using geophysical imagery. Where exposed, the fault surface revealed the following observations:

- The fault displaced rock units as young as the Late Devonian-Carboniferous Ravendale Formation;
- The exposure of the fault surface can be knife sharp, or marked by high level crush breccias;

- The fault surface is vertical in outcrop and is very rarely cross-faulted;
- When Devonian cover is absent, the Ponto Group is invariably found on the western side of the fault, and the Teltawongee Group on the eastern side of the fault;
- The Ponto Group near the fault is more intensely deformed, and more metamorphosed, than the Teltawongee Group on the eastern side of the fault;
- Tholeiitic magmas have tapped the fault, and intruded as thin dykes along much of the length of the fault, along with several basaltic plugs; and
- The fault appears to bend clockwise through 85°, along with the Delamerian rock cleavages, around the Grasmere Knee Zone.

Post-Delamerian Unconformity

An angular unconformity, between the strongly deformed and cleaved Neoproterozoic-early to middle Cambrian rocks and weakly-deformed, late Cambrian to Ordovician successions, was confirmed at several locations. This is the physical evidence for the Delamerian Orogeny. Neoproterozoic and early to middle Cambrian rocks below the unconformity have been strongly deformed, folded, cleaved and metamorphosed during the orogeny, whereas the unconformity surface has been formed by erosion and encroachment of the sea, with overlying, weakly-deformed, shallow marine sediments containing late Cambrian trilobites and other fossils.

The unconformity was also a key feature that separated the pre-Delamerian Neoproterozoic to middle Cambrian rocks, as a continental margin shelf-slope succession, from the post-Delamerian shallow marine to fluvial succession.

Highlights of the Koonenberry Project: 1995-2008

The mapping of twelve standard 1:100 000 map sheets has enabled a much clearer definition of the succession and distribution of rock units in the Koonenberry district. In the southern and central parts of the district, subdued topography, and a long period of deep chemical weathering through the Palaeogene and Neogene, has made detailed mapping of rock units difficult, but in the north sufficient exposure and variability of rock types have permitted the production of four new 1:25 000 maps. The study of magnetic susceptibility in several drill holes has revealed that magnetism can be greatly reduced in a weathered zone, which can extend to 50 m, or more, in depth. Both pyrrhotite and magnetite are major contributors to the magnetism in fresh rocks at depth, and are responsible for the distinctive striped aeromagnetic patterns in the pre-Delamerian Koonenberry Belt.

New Technologies

Over the period of this project we have seen an amazing increase in new and advanced technologies. In the field of geophysics, there have been new aeromagnetic, radiometric and digital terrain coverages. These new geophysical maps have been invaluable in developing a better understanding of the terrain, especially where deep weathering and surficial cover is dominant. Many new structural features have been revealed, including potential diamond pipes that have yet to be adequately tested.

In 1999, a deep seismic reflection line (99AGS-C1) was acquired across the Koonenberry Belt, and provided evidence for the deeper structure of the region, and a basis for constructing cross-sections across the area.

The introduction of satellite GPS instruments has enabled the recording of accurate ground locations. Satellite communication has become particularly valuable when beyond normal telephone networks.

New mapping tools, such as computer-aided mapping with hand held PDA or portable computers, have become important aids to field mapping. Improved computer graphics and software now enable accurate map overlays. We also have access to more detailed satellite imagery of visible ground surface features.

Age Determinations

The new mapping revealed a number of new fossil finds and the areal distribution of potentially fossiliferous rock successions. The history of the Koonenberry district could not have been worked out without the very important work completed by palaeontologists (e.g. Zhen and Percival, 2006; Young, 2009) that has helped us unravel the Palaeozoic succession.

In unfossiliferous rocks containing suitable zircons, important isotopic age work was carried out by Lance Black at Geoscience Australia and by GEMOC, Macquarie University. The isotopic work showed that the Ponto Group was one of the youngest pre-Delamerian units, as it contained middle Cambrian felsic air-fall tuffs that were of similar age to the felsic tuffs and volcanics of the Cymbric Vale Formation of the Mount Wright Volcanics (Mills and Black, 2006)

Mapping Highlights

Careful mapping of the Koonenberry Fault, and associated fault splays, has better defined late Cambrian to Ordovician post-Delamerian basin segments, and has revealed some important fossil discoveries. Structures in the post-Delamerian units can have an important bearing on understanding the structural development of the Delamerian Orogen.

Mapping to the east of the Koonenberry Fault has revealed considerable eastern extension of the Teltawongee Group projecting below Cretaceous cover. Low gravity values, that were previously used to suggest the presence of the Morden Trough filled with porous Devonian sediments, are probably now better interpreted as resulting from a thickened Cambrian subduction-related accretionary wedge composed of quartz-rich turbidites of the Teltawongee Group.

New bedrock exposures of late Cambrian Warratta Group were discovered in the Yancannia Range beneath extensive silcrete scree.

Neoproterozoic metasedimentary rocks around Mount Arrowsmith have been further subdivided, and one unit found to contain small algal balls. The better exposures around Milparinka and Tibooburra, in the north have been more thoroughly mapped and age determinations have helped define the relationship between the Delamerian and Thomson Orogens. The prospectivity of the auriferous veins and country rock in the Wamberiga Range has been examined more closely.

Acknowledgements

Over the term of this project, there have been many contributors, both boots-and-all field mappers, as well as technical workers, and those in head office, who conceived and drove the project forward. Local landholders and explorers have been kind, helpful and sympathetic to our efforts. Most contributors will find their efforts acknowledged in the many products that will stem from this project. Kingsley Mills has worked with the project throughout its tenure, and especially would like to thank John Cramsie, who encouraged the initiation of the project, and Lindsay Gilligan, who continued to crack the whip where necessary. David Robson, Vladimir David, Bob Musgrave and John Watkins have provided geophysical and logistic support. Ian Percival has enthusiastically sought and described fossils from the area that, along with the meticulous isotopic age determination work of Lance Black, has helped tie down our geological column. Those who persistently tackled the weather in the field need special mention (in temporal

order): Michael Hicks, Peter Buckley, Ian Cooper, Joseph Ogierman, Tim Sharp, John Greenfield, Bill Reid, Nancy Vickery and Bob Brown. Barney Stevens has maintained an enthusiastic interest in the project throughout, and Phil Gilmore has been a major driving force in bringing the project to a satisfying conclusion.

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Accretionary capture: interface between the Thomson and Delamerian orogens in the Koonenberry Belt

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Late Neoproterozoic rifting of the Curnamona margin of Gondwanaland initiated development of the Koonenberry Belt (Figure 1), which extends for more than 350 km across the northwest of New South Wales. This event resulted in the production of the Mount Arrowsmith Volcanics, a strongly differentiated alkalic suite with minimal crustal interaction, which together with associated metasedimentary rocks form the Grey Range Group. Early Cambrian post-rift sedimentation, expressed as the Teltawongee and Ponto Groups, was punctuated by eruption of the Mount Wright Volcanics, a calcalkaline suite with mixed arc–rift geochemistry. Tholeiitic to alkaline basalts of the Bittles Tank Suite appear as volcanics and intrusives through the Early to mid Cambrian succession. Deformation during the Delamerian Orogeny imposed the northwest-striking grain of the belt, expressed very visibly as the series of intense linear magnetic anomalies that define the Wonnaminta Geophysical Zone, between the Lawrence and Koonenberry Faults. Northeast of the Koonenberry Belt, in the Kayrunnera Geophysical Zone that extends to the Olepoloko Fault, Delamerian deformation is equally intense, but the absence of igneous lithologies greatly reduces the amplitude of magnetic anomalies in this zone. Northeast of the Olepoloko Fault, in the Thomson Orogen, long-wavelength magnetic and gravity anomalies indicate basement fault-bounded blocks below the Late Cambrian to Early Ordovician Warratta Group, which extends across both the Delamerian (Koonenberry Belt) and Thomson Orogens.

Potential field modelling accompanying the Koonenberry mapping program has revealed the deeper structure of the Koonenberry Belt to an unprecedented extent (Figures 2 and 3). A chain of large magnetic sources, buried below 3 to 7 km of Devonian sedimentary rocks filling the Bancannia Trough, appear to represent volcanic edifices considered equivalents of the Mount Wright Volcanics, and define the Mount Wright Arc.

Cambrian rifting in the Bancannia Trough (with near-pure extension accompanying emplacement of the large magnetic source bodies) is suggested by conducting a simple exercise in reconstructing the Wonnaminta Zone against the Curnamona Province by a rotation of 20° clockwise around an Euler pole at 140.60 °E, 30.35 °S. The resulting fit (Figure 4) aligns not only the margins of the Bancannia Trough, but also significant gravity and magnetic features on the two sides. This observation, together with the geochemistry of the Mount Wright Volcanics, and similarities between the geophysical modelling parameters of the Bancannia Trough and the Taupo Zone of New Zealand, support the interpretation of the Mount Wright Arc as a rifted arc developed on a continental margin. Intriguingly, the rifting of the arc divides Delamerian structures, indicating that at least part of the Delamerian deformation developed in a subduction accretion setting, rather than in a terminal orogeny.

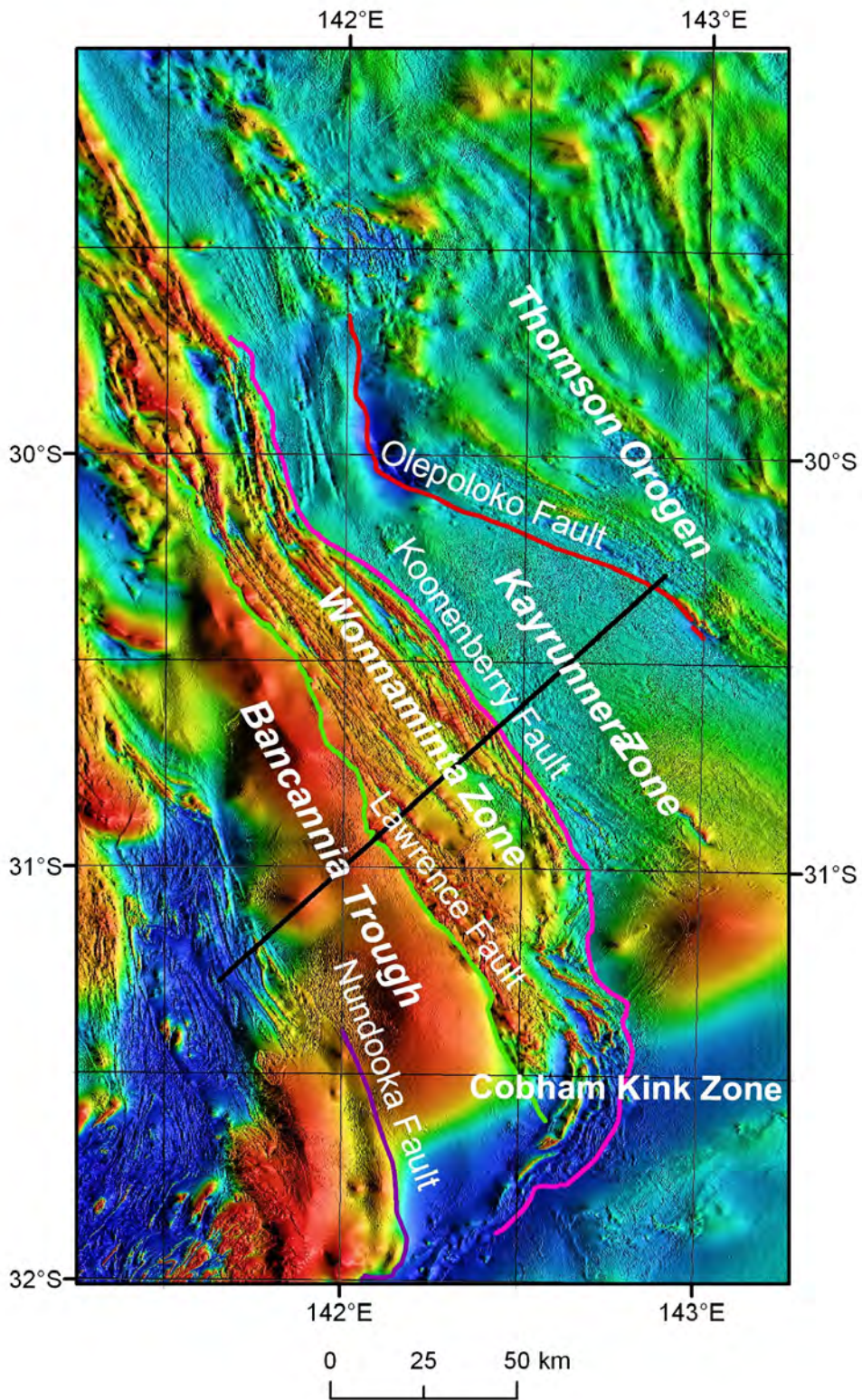


Figure 1a. Total magnetic intensity image of the Koonenberry Belt. Solid line shows the location of the section modelled in Figures 2 and 3.

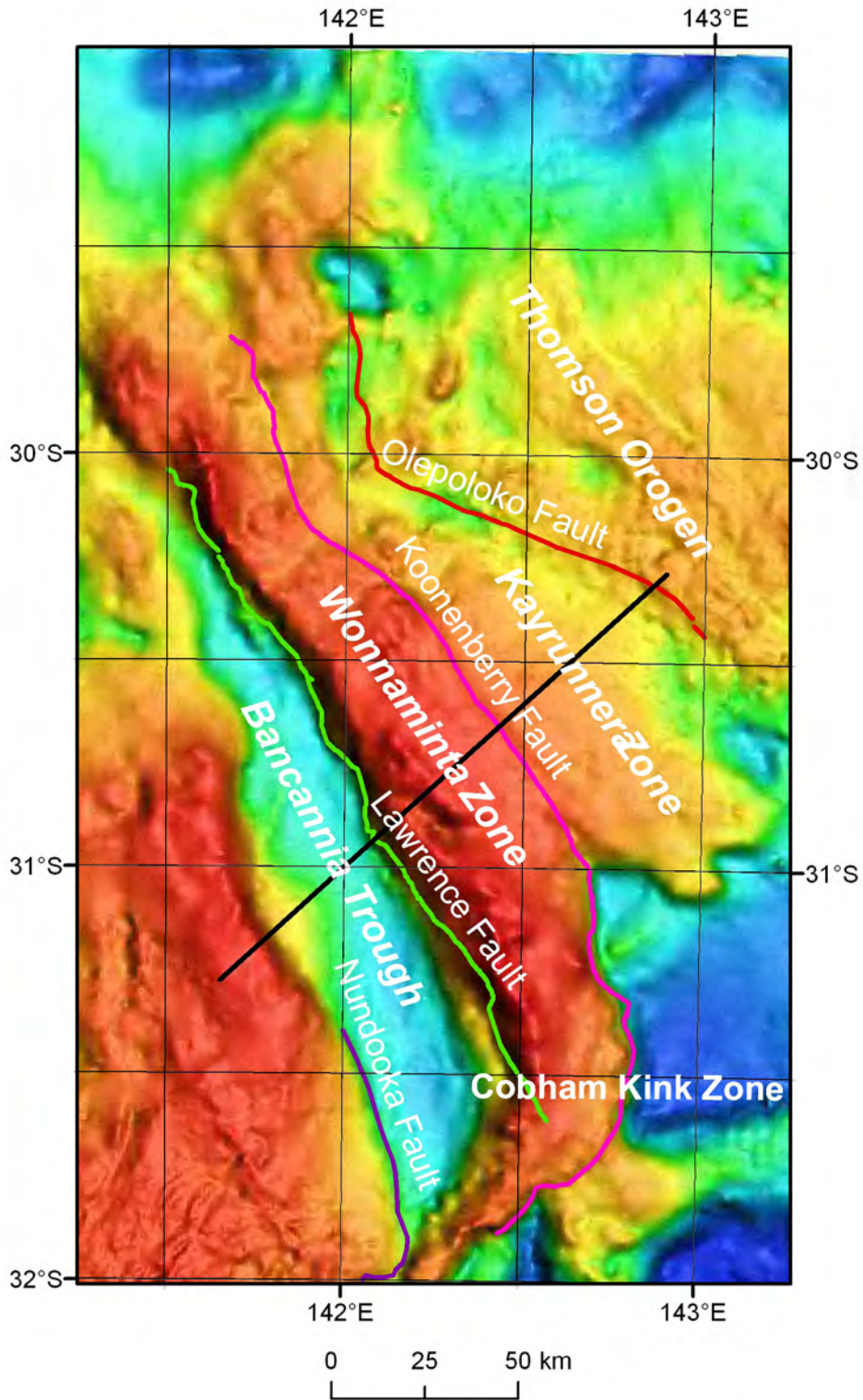


Figure 1b. Isostatically reduced Bouguer gravity image of the Koonenberry Belt. Solid line shows the location of the section modelled in Figures 2 and 3.

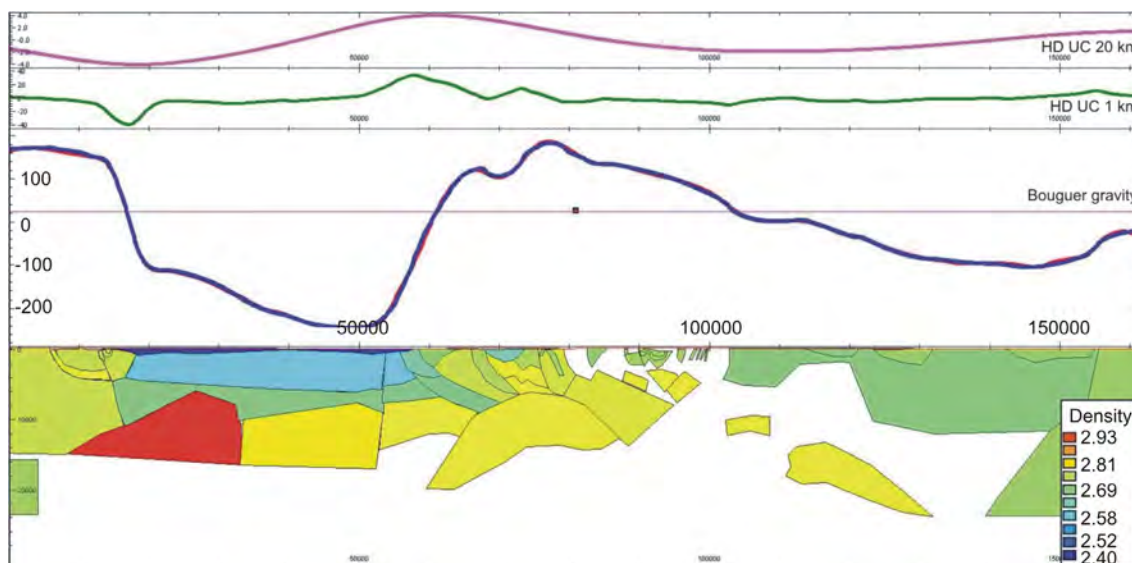


Figure 2. Gravity model across the middle of the Koonenberry Belt.

Bodies are coloured according to density. Background density is 2.70 gcm^{-3} . Lower profile panel shows measured gravity in red, model gravity in blue. Regional gravity is the constant line at $25 \mu\text{ms}^{-2}$. Upper two panels show horizontal derivatives of upward continuations to 1 km and 20 km; local maxima and minima on these panels represent synthetic gravity edges calculated from the model, for comparison with edges determined from the gravity grid. Bancannia Trough is towards the southwest (left), where denser (red and yellow) volcanic edifices underlie Devonian sedimentary fill (blue). Large antiformal dense (yellow) body near centre of profile is interpreted as a thick pile of rift volcanics equivalent to the Mount Arrowsmith Formation.

Below the Wonnaminta Zone, a large magnetic source defines a 3 to 5 km thick body which can be traced along the length of the belt. Overridden by a thrust stack of rocks from the Grey Range, Ponto and Teltawongee Groups, this body is mostly planar and dips towards the east, although it is deformed into a broad antiform in the central part of the belt, where it can be recognised as a feature in a deep seismic reflection profile. Physical properties suggest that this body may be a thick rift-volcanic pile, equivalent to the Mount Arrowsmith Volcanics. This broadly accords with the interpretation of Direen and Crawford (2003), although this feature is now clearly distinguished from the volcanic sources below the Bancannia Trough. Acting as a rheologically more competent feature, this body formed the base onto which the elements of the Wonnaminta Zone were thrust, to form the accretionary wedge of the Mount Wright Arc.

In the southern part of the belt a re-entrant in the linear anomalies of the Wonnaminta Zone faces a large magnetic anomaly sourced in the basement of the Kayrunnera Zone. The geometry of the re-entrant, and the development of Silurian and Devonian basins in the surrounding area, suggests analogy with structures observed in modern accretionary margins associated with the subduction and underplating of seamounts. A second indentation of the Wonnaminta Zone further north – the Cobham Kink Zone – may owe its origins to a similar process.

Given the arc polarity defined by the inferred arc below the Bancannia Trough and the accretionary wedge of the Wonnaminta Zone, the Kayrunnera Zone should represent the forearc of the Delamerian arc. Seismic reflection, however, presents evidence of overprinted northeast- and southeast-facing thrusts in this zone, and deformation features of the Cobham

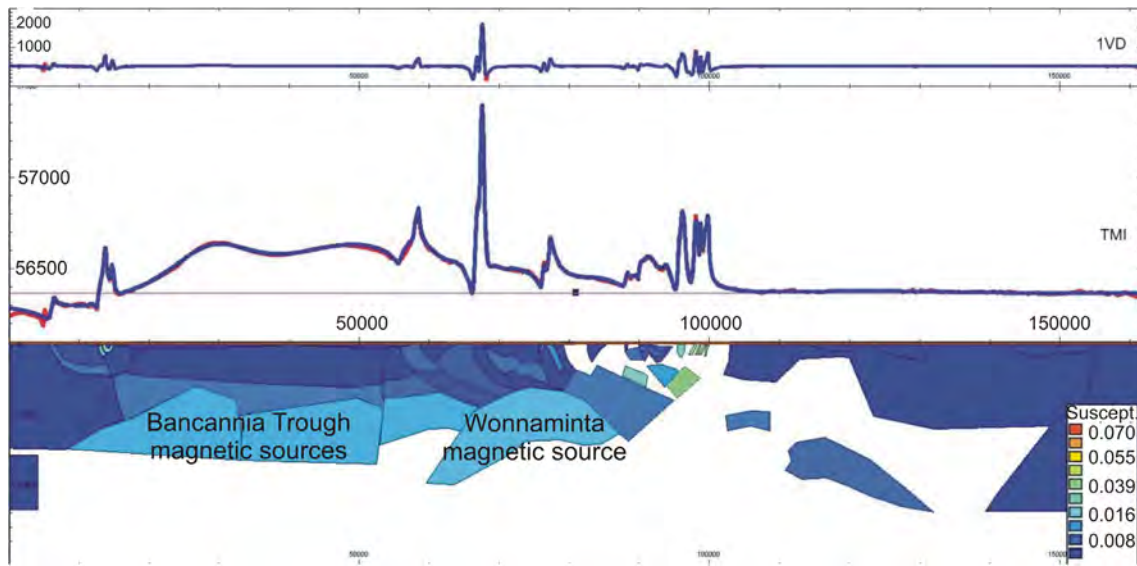


Figure 3. Magnetic model across the same profile as Figure 2.

Bodies are coloured according to magnetic susceptibility: note that the scale is absolute (i.e., $0.01 \equiv 1000 \times 10^{-5}$). Background susceptibility is 0. Lower profile panel shows measured TMI in red, model TMI in blue. Regional magnetic field is the constant line at 56365 nT. Upper panel shows first vertical derivative of TMI; red is measured 1VD, blue is model 1VD.

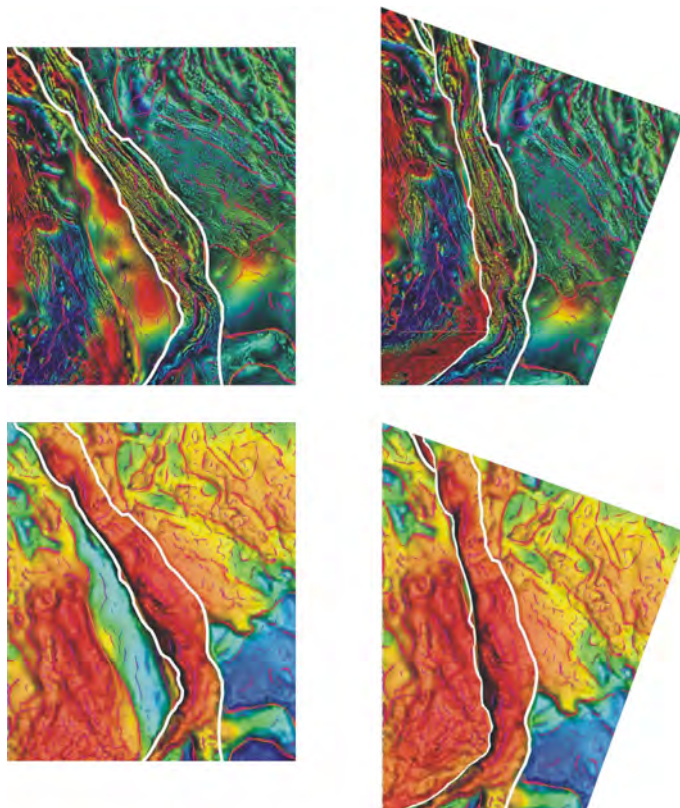


Figure 4. Euler reconstruction of the Wonnaminta Zone against the Curnamona Province, assuming pure Cambrian rifting under the Bancannia Trough.

Upper panels show an image generated by draping a pseudocolour TMI layer over a magnetic tilt-filter intensity layer (Cooper and Cowan, 2006). Lower panels are isostatically reduced Bouguer gravity. Boundaries of the Wonnaminta Zone, shown as white lines, follow prominent gravity edges. Right-hand panels show reconstruction by 20° clockwise around an Euler pole at 140.60 °E, 30.35 °S.

Kink Zone project both towards the Wonnaminta Zone and towards the Thomson Orogen. Both the Delamerian Orogeny and the Benambran Orogeny (locally associated with the Thomson Orogen) significantly deformed the Kayrunnera Zone. A plausible explanation of the local expression of the Benambran Orogeny is as an arc-arc collision between the Delamerian Mount Wright Arc and a Thomson Arc. Propagation of the frontal thrust of the Thomson forearc, represented by the Olepoloko Fault, resulted in capture of the former Mount Wright forearc, leading to the geometry observed around the Cobham Kink Zone, and to crosscutting relationships between the Thomson and Delamerian structures.

Acknowledgements

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New SHRIMP geochronology from the Mount Painter Province, South Australia

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Introduction

The Mount Painter Province is located in the northern Flinders Ranges, South Australia and consists of the Mount Painter and Mount Babbage Inliers. Following early investigations of the Mount Painter Province, there have been two major publications that discuss the geology of this region. Bulletin 43: 'Regional and Economic Geology of the Mount Painter Province' (Coats and Blissett, 1971) provided a detailed overview of the structure, stratigraphy and economic geology of the region and was accompanied by the 1:125 000 Mount Painter Province map sheet (Coats et al., 1969). The second main summary of the inliers by Teale (1993a, 1993b) is published within Bulletin 54: 'The Geology of South Australia Volume 1' (Drexel et al., 1993) and included new geochronological, metamorphic and structural data and revised the interpretation of the stratigraphy of the inliers.

Recent work has focused on the age and geochemistry of Paleozoic magmatic bodies (e.g. Elburg et al., 2003; McLaren et al., 2006) and the tectonic evolution of the basement and cover during the Proterozoic and Phanerozoic (Mildren and Sandiford, 1995; Sandiford et al., 1998; Paul, 1998; McLaren et al., 2002).

Geological Framework

The geological framework of the Mount Painter and Mount Babbage Inliers, outlined below, is based on the stratigraphic summary of Teale (1993a, 1993b), which represents the most recent overview of lithological relationships of the Mount Painter Province. Proterozoic lithologies of the Mount Painter Province have been divided into two broad groups: multiply deformed Paleoproterozoic metasedimentary and metigneous units, and Mesoproterozoic siliceous volcanics, sedimentary successions and granites. Paleozoic granites within the Mount Painter and Babbage Inliers are associated with metamorphism and deformation during the Delamerian and Alice Springs Orogenies.

The first group (equivalent to the Lower Proterozoic Radium Creek Metamorphics of Coats and Blissett (1971)) have been reclassified by Teale (1993a) into six Paleoproterozoic units: Migmatite (suite 1), Augen-textured gneiss (suite 2), Layered gneiss (suite 3), Metasediment (suite 4), Quartzite (suite 5) and a Metavolcanic-granitic suite (suite 6). Originally, the proposed Paleoproterozoic age for these units was interpreted from stratigraphic and lithological similarities with the Willyama Supergroup of the Olary and Broken Hill Provinces (Teale, 1993a). More recent geochronological work (Fanning et al., 2003), however, suggests that metasedimentary units from this package have maximum depositional ages of ~1590-1580 Ma.

This is also consistent with a maximum depositional age of 1590 ± 8 Ma for metasedimentary rocks from Hidden Valley (equivalent to Suite 5 of Teale, 1993a), reported by Ogilvie (2006).

Within the Mesoproterozoic stratigraphy, Teale (1993b) subdivided sedimentary and volcanic successions into three units. Micaceous phyllitic siltstones of unit 1 (which includes the Yagdlin Phyllite) grade into quartzites of unit 2, which are correlated with the Mount Adams Quartzite and Freeling Heights Quartzite described by Coats et al. (1969). Silicic volcanics of unit 3 includes the Pepegoona Porphyry of Coats and Blissett (1971). Fanning et al. (2003) reported maximum depositional ages of ~1590-1580 Ma for the Freeling Heights Quartzite and Mount Adams Quartzite. Shafton (2006) also reported a maximum depositional age of ~1592 Ma for a sample from the Mount Adams Quartzite.

The main period of magmatism within the Mount Painter Province occurred from ~1575 Ma to 1550 Ma (e.g. Teale, 1993b; Fanning, 1995) and includes the Mount Neill, Yerila, Wattleowie, Box Bore and Terrapinna Granites.

New Results

A number of samples were collected from the Mount Painter and Mount Babbage Inliers for SHRIMP U-Pb zircon geochronology. Two samples were collected from basal metasedimentary rocks in the Paralana Hot Springs area to compare to maximum depositional ages previously reported from samples further north within the Mount Painter Province. Secondly, gneisses and granites from both inliers were analysed to determine whether magmatism in this area occurred semi-continuously over a ~25 Ma period (~1575 to 1550 Ma) or as distinct pulses.

Two samples were collected from the Radium Creek Metamorphics in the Paralana Hot Springs area. The first sample is a quartzofeldspathic metasedimentary rock (equivalent to Suite 4 of Teale 1993a), and it yields a maximum depositional age of ~1595 Ma. The second sample is a quartzite from Suite 5 (Teale 1993a), which records a maximum depositional age of ~1590 Ma. These results are consistent with the maximum depositional ages reported by Fanning et al. (2003), and others, and suggest that metasedimentary units from both the Palaeoproterozoic and Mesoproterozoic packages identified by Teale (1993a, 1993b) have similar depositional age constraints. Also, these ages further reinforce the observation that there are currently no known equivalent rocks to the Willyama Supergroup in the Mount Painter Province.

New U-Pb zircon data from the Mount Neill Granite, Box Bore Granite, and migmatite and gneisses in the Paralana Hot Springs area (Suite 1, 2 and 3 of Teale), provide magmatic crystallisation ages of ~1585 to 1575 Ma. The three samples from the Paralana Hot Springs area also have low Th/U zircons which yield ages of ~1550 Ma, which may record metamorphism at this time. New U-Pb zircon data from the Terrapinna, Wattleowie and Yerila Granites, provide magmatic crystallisation ages of ~1565 to 1555 Ma.

Two samples from the Paralana Granodiorite (Neumann, 2001; McLaren et al., 2006) were also analysed – one from the Four Mile Creek area and another from south of the British Empire Granite. Both samples have a group of zircons which yield a weighted mean age of ~1550 Ma. In addition, both samples also contain zircons with low Th/U zircons which yield a range of ages between ~520 and ~460 Ma. One interpretation for these results is that these granodiorites crystallised at ~1550 Ma and were metamorphosed between ~520 and ~460 Ma, consistent with the monazite age of ~440 Ma reported previously (Elburg et al., 2003; McLaren et al., 2006).

Discussion

The new SHRIMP results, in conjunction with existing geochronological data, can be used to revise the temporal framework for the Mount Painter Province. Currently, the oldest identified

stratigraphic units in the area were deposited at or after ~1595-1590 Ma, and include the Radium Creek Metamorphics, Mount Adams Quartzite and Freeling Heights Quartzite. Magmatism in the area can be divided into two distinct pulses – the first stage occurred between ~1585-1575 Ma, and includes the Mount Neill Granite, Pepegoona Porphyry, Box Bore Granite and gneisses from the Paralana Hot Springs area. The second stage at ~1565-1555 Ma consists of the Terrapinna, Wattleowie and Yerila Granites, as well as smaller granitic bodies in both inliers. This second pulse was followed by emplacement of the Paralana Granodiorite at ~1550 Ma, and high-grade metamorphism recorded by the Hot Springs gneisses.

Acknowledgements

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Mingary geophysical interpretation and investigation of the boundary between the Broken Hill and Olary Domains

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The Mingary 1:100 000 map sheet, which covers the boundary between the Broken Hill Domain and the Olary Domain, has been interpreted using a range of geophysical data and tools:

- Total Magnetic Intensity (TMI) data, from the Broken Hill Exploration Initiative (BHEI) (MESA_BHEI) survey in 1995 and Targeted Exploration Initiative, South Australia (E1) survey in 2000. The area not covered by these two surveys was filled using the 1976 (1976SA01) Mingary survey.
- Gravity data, acquired for the BHEI in 1995.
- New South Wales (NSW) datasets (P617, P633 and gravity), downloaded from the Geophysical Archive Data Delivery System (GADDS), which is managed by Geoscience Australia (GA), were used to assess the continuity of features across the border between South Australia and New South Wales.
- After compiling the base TMI grids, these were filtered to create a first vertical derivative (1vd) grid and an Auto Gain Control (AGC) grid. The newly created grids were used to assist in the geophysical interpretation.
- Gradient strings (worms) were created for both TMI and Gravity grids using the WormE tool from Intrepid. The Mingary 1:100 000 map sheet was the initial subject area, but several worm features were found to cross the map's eastern border, hence:

What is the boundary between the Broken Hill Domain and the Olary Domain? This will depend on our understanding of the nature of the Olary and Broken Hill Domains. The concept of two domains arose from the perceived differences between the geology of the Broken Hill region (mainly in NSW) and the Olary region (in South Australia). Perhaps the most important difference was the suggestion that the upper part of the Broken Hill Group was restricted to the Broken Hill region – now known to be incorrect, because Broken Hill-like units, although thin and sporadic, are known at least as far west as the MacDonald Corridor. Crooks (2006), in mapping the Mingary 1:100,000 sheet area, which is in the transition zone between the Olary and Broken Hill Domains, indicated that, at least on the ground, there was no clear distinction between the two domains. Results stemming from the BHEI program, however, have shown that the Curnamona Group apparently is restricted to the Olary Domain; also, the lower part of the stratigraphy in the Broken Hill region is absent from the Olary region, that is, the Clevedale Migmatite, Thorndale Composite Gneiss, and Rantygga and Thackaringa Groups (Conor and Preiss, 2008; Conor, this volume). It might be expected that the Curnamona Group is present below the stratigraphy known at the surface at Broken Hill. Preliminary magnetotelluric (MT) traverses (Gill, 2002; Adam, 2007) indicate a fundamental difference in conductivity at depth between the Olary and Broken Hill regions. It is possible that this dataset suggests the absence

of the Curnamona Group below the Broken Hill region. Supporting this the observation is the fact that magmatism of the ~1719~1711 Ma, mantle-derived, A-type Basso Suite is restricted to the Olary Domain, whereas the ~1705~1685 Ma, S-type Silver City Suite is found only in the Broken Hill Domain, where it is thought to be sourced by partial melting of metasedimentary rocks of the Willyama Supergroup.

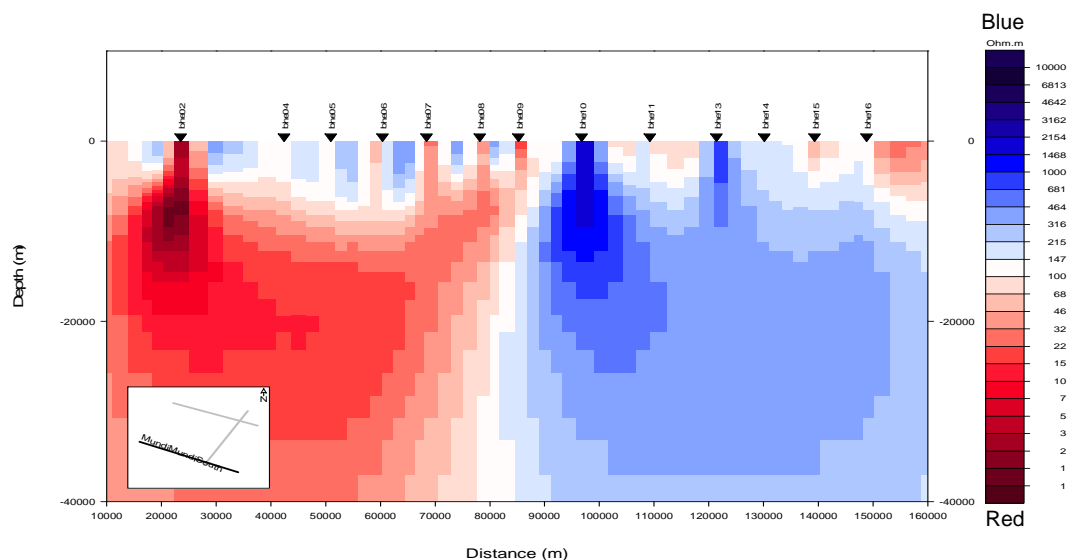


Figure 1. Broken Hill magnetotelluric traverse, from Gill (2002), modelled by Adam (2007). The red area to the left is the Olary Domain, whereas the blue area to right is the Broken Hill Domain.

It is considered that the southern Curnamona Province is a part of a Paleoproterozoic rift, with the Broken Hill region representing the rift basin and the Olary region a rift shoulder (Willis et al., 1983; Laing, 1996; Conor and Preiss, 2008). There is the expectation, therefore, of major growth faults being present between the shoulder and rift regions, that is, between the Olary and Broken Hill Domains. Worms derived from the upward continuation of the regional aeromagnetic data were employed in an attempt to define a structure, or structures, which would define the rift boundary between the Olary and Broken Hill Domains. A number of worm traces do approximate the expected boundary (Figure 2), but the situation is not straight forward.

What is impressive, however, is the presence of three worm sets that indicate major, steeply dipping, slightly curvilinear, northeast-trending structures, which are all deeply penetrating, possibly to the mantle through the ~40km thick crust (Figure 2). One of these, the Broken Hill worm set, traverses the Broken Hill Mines area, where the worm traces possibly suggest a slight flattening of dip to the northwest. Another aeromagnetic worm set, the Aggrennon Dam worm set (Figure 2), is coincident with the change in resistivity shown in Figure 1. The curvature of both the Aggrennon Dam worm set and the Sara Dam worm set, which has a southeast-trending tail, is consistent with a broad, regional megakink. The structural grain to the south trends to the northeast, but is more north-south oriented in the north. The structures which give rise to these three worm sets are relatively steep, and hence are different to the shallow, southeast-dipping structures which were imaged by the earlier BHEI seismic reflection line (Korsch et al., 2006). Are these structures fundamental relative to the evolution of the Broken Hill rift system?

The Broken Hill worm set is associated spatially with the Pb-Zn lodes, and the other two structures, indicated by the Aggrennon Dam worm and Sara Dam worm sets, all potentially

define structures which cut deep into the crust, possibly even to the Moho, and thus are zones worthy of concentrated exploration for base metals and gold.

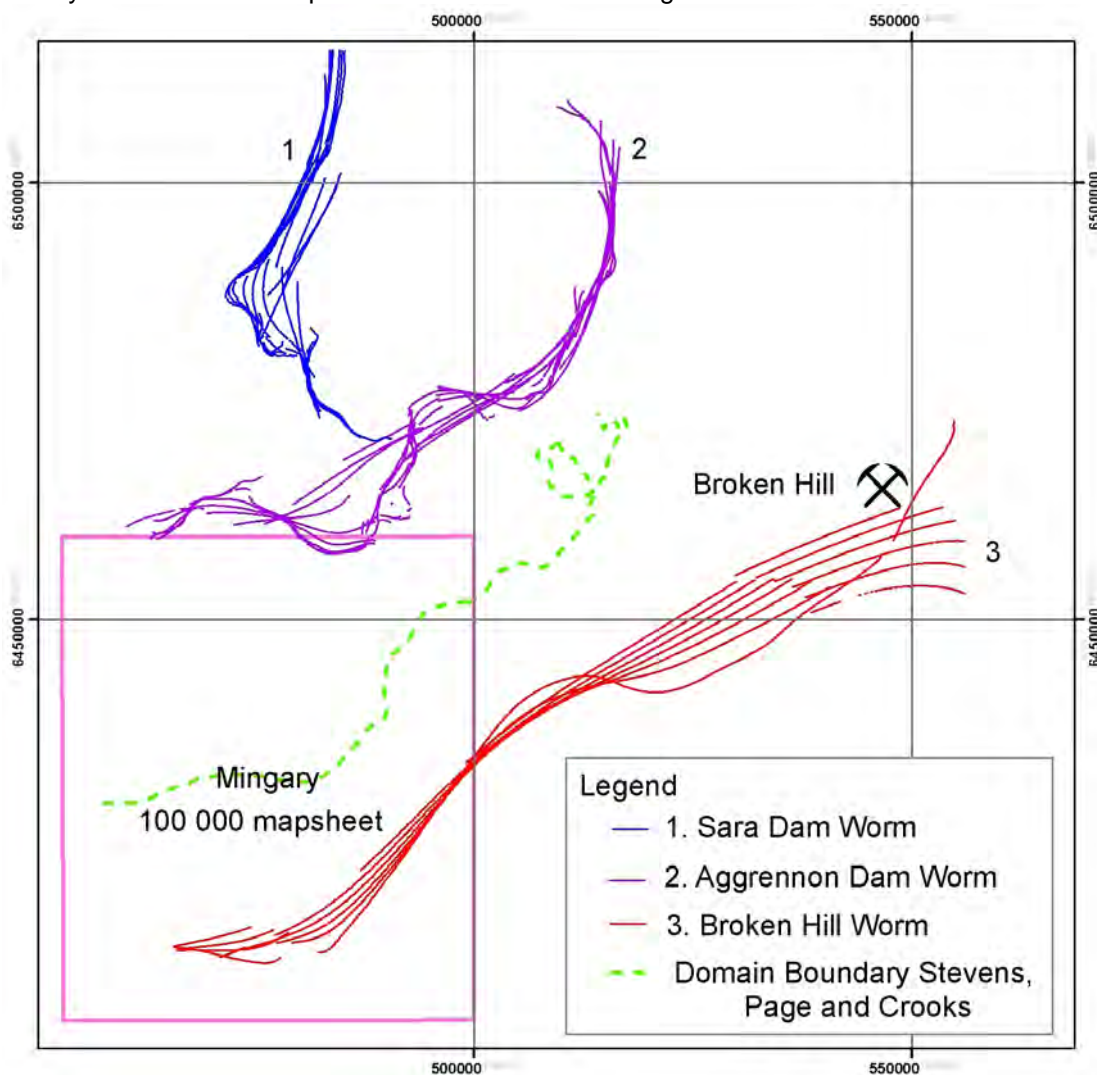


Figure 2. Map showing location of domain boundary and worm features. The dashed domain boundary is taken from Stevens et al. (2008).

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The Curnamona Province – 1700 million years of tectonic evolution

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Introduction

The Curnamona Province is a near-circular remnant of Palaeo- to Mesoproterozoic crust that is bounded by much younger structural boundaries (Robertson et al., 1998; Conor and Preiss, 2008). At the surface, it records a history of sedimentation and synsedimentary magmatism from 1720 to 1640 Ma (Willyama Supergroup), deformation and metamorphism in the ~1600 Ma Olarian Orogeny, and early Mesoproterozoic sedimentation and magmatism coeval with magmatism in other provinces (e.g. the Hiltaba event on the Gawler Craton). The substrate of the supracrustal Willyama Supergroup is unknown, and inferences can be drawn only from analogy with other provinces (e.g. Mt Isa) and from two deep seismic transects (Goleby et al., 2006; Korsch et al., this volume). The shallow-water facies and stratigraphic relationships of some of the oldest exposed sedimentary rocks, preserved despite Olarian deformation and metamorphism, suggests deposition upon continental crust in rift basins.

Much of the Curnamona Province is under cover ranging in age from Neoproterozoic to Holocene. The southern portion of the province, however, crops out intermittently as the Willyama Inliers (Preiss and Conor, 2001) and the northwestern portion as the Mount Painter and Mount Babbage Inliers. The Willyama Inliers include the large Kalabity (SA) and Broken Hill (NSW) Inliers as well as smaller areas of exposed Willyama Supergroup surrounded by Neoproterozoic metasedimentary rocks (e.g. Bimbowrie, Euriowie Inliers).

A new 1:100 000 scale geological map of the exposed Curnamona Province in South Australia, as well as description and refinement of its stratigraphy, are currently being compiled at PIRSA.

Curnamona in relation to other late Palaeoproterozoic provinces in Australia

Northern Australia

Sedimentation of the Willyama Supergroup was at least partly coeval with deposition in epicontinental basins in the North Australian Craton, such as the MacArthur Basin, Mount Isa and Georgetown Inlier (Betts and Giles, 2006). Isotopic and detrital zircon evidence has been used to deduce a central Australian source region for the sedimentary rocks of the Willyama Supergroup (Barovich, 2003; Page et al., 2005).

Gawler Craton

On the eastern Gawler Craton, the ~1760 Ma Wallaroo Group metasedimentary rocks and metavolcanics overlap in age with the older rift packages at Mt Isa, but are sedimentologically not unlike the younger Willyama Supergroup (Conor, 1995). Metamorphic grade and intensity of deformation in the Wallaroo Group decrease to the east, so it is possible that equivalents could extend eastward, with little evidence of pre-Olarian deformation, beneath the Willyama Supergroup. Such successions are potentially much thicker than the exposed Willyama Supergroup, and may account for much of the layered mid-crust imaged on the Curnamona seismic transects.

Adelaide Geosyncline basement

Basement to the Neoproterozoic sedimentary rocks includes the Mount Painter Inlier, which contains a younger (early Mesoproterozoic) metasedimentary and metavolcanic package (Teale, 1993). In the basement inliers of the Mount Lofty Ranges, the Barossa Complex contains a granitic orthogneiss recently dated at 1718 Ma, similar in age, though not in chemistry, to syn-Willyama magmatism of the Basso Suite (Belousova et al., 2006; Szpunar et al., 2006).

Subdivision of the Curnamona Province

The Curnamona Province is divided into domains based on the criteria of age, sedimentary facies and thickness, magmatism and metamorphism (Figure 1):

- Broken Hill Domain: relatively thicker, more complete stratigraphy, with well-developed Broken Hill Group, including the Broken Hill orebody. Metamorphism from lower amphibolite facies in the north to granulite in the south (Phillips, 1980). Synsedimentary mafic and S-type felsic magmatism related to rifting.
- Redan Domain: characterised by calc-albitic Redan Gneiss, granulite metamorphism, and a high Total Magnetic Intensity signature.
- Olary Domain: Thinner, less complete stratigraphy; Broken Hill Group equivalents thin and only locally developed. Synsedimentary A-type felsic (~1715 Ma Basso Suite) and minor mafic magmatism (~1685 Ma Lady Louise Suite). Polyphase deformation and metamorphism from greenschist facies in north to upper amphibolite facies in south (Clarke et al., 1987; Webb and Crooks, 2003).
- Mulyungarie Domain: Relatively weakly deformed greenschist facies metasedimentary rocks with significant stratigraphic differences from both Broken Hill and Olary Domains.
- Moolawatana Domain: Early Mesoproterozoic rocks of the Mount Painter and Mount Babbage Inliers and extending eastward as a buried ridge. Delamerian and possibly Proterozoic high-grade metamorphic events are recorded in the basement.
- Mudguard Domain: A relatively undeformed sheet of ~1580 Ma volcanics inferred from geophysics to unconformably overlie folded Willyama Supergroup on the Benagerie Ridge.
- Erudina and Quinyambie Domains: Unknown basement deeply buried by thick Cambrian and Neoproterozoic cover of the Moorowie and Yalkalpo Sub-basins respectively west and east of the Benagerie Ridge.

Domain boundaries are subject to further refinement based on new mapping, drilling and seismic data. In particular, the Olary-Broken Hill Domain boundary is currently being reassessed in the course of solid geology and stratigraphic interpretation on the Mingary 1:100 000 map sheet (C.E. Fricke, in prep.).

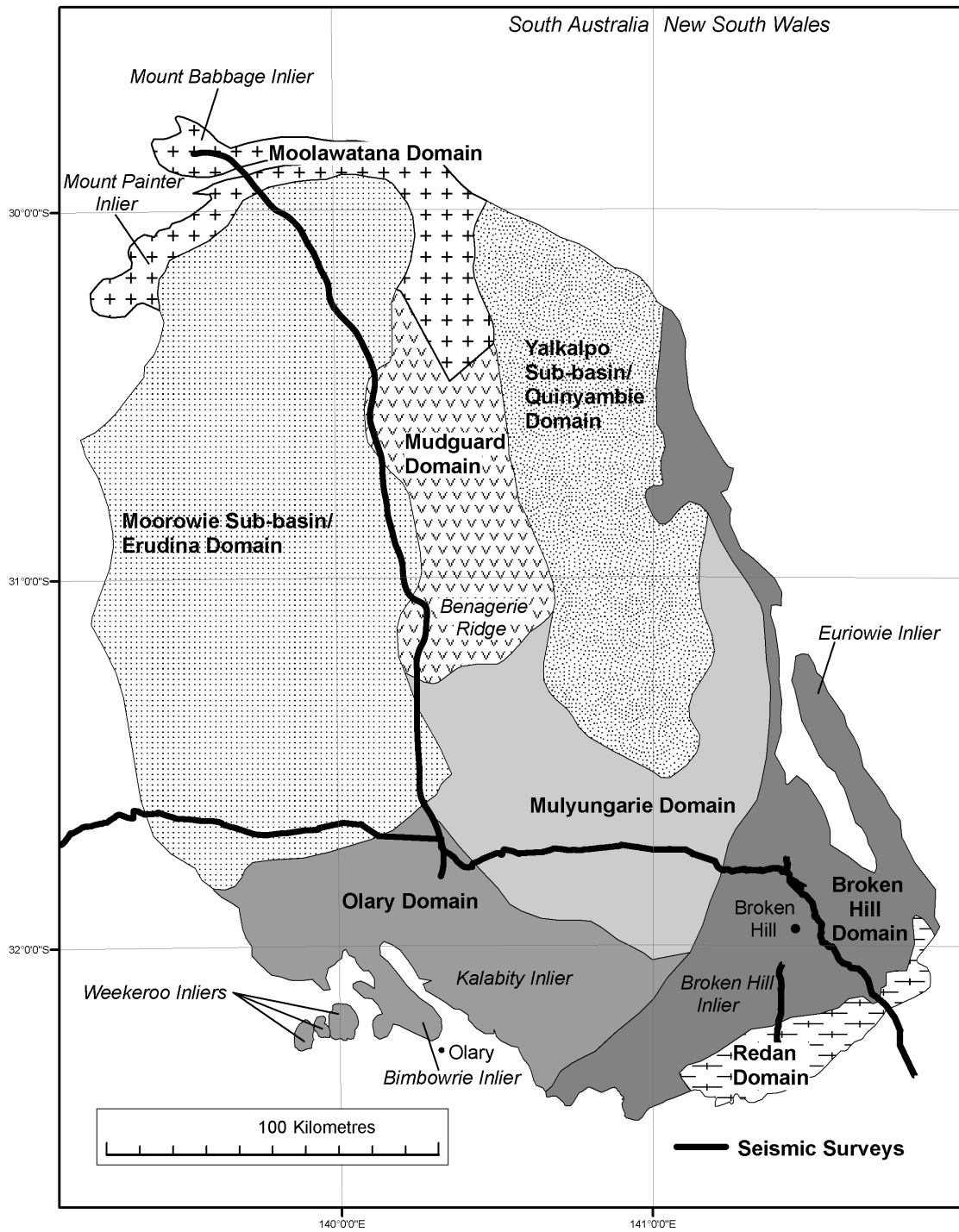


Figure 1. Domains of the Curnamona Province (after Conor and Preiss, 2008).

Tectonic evolution of the 1720-1640 Ma Willyama depositional basin

Early crustal extension, mafic and felsic magmatism, ~1720-1700 Ma

The oldest known metasedimentary rocks of the Willyama Supergroup (Stevens et al., 1988) are variably albitised, fine- to medium-grained clastic rocks of the Curnamona Group of the Olary Domain (Conor, 2000). The lithologically similar Thackaringa Group of the Broken Hill Domain (Willis et al., 1983) has traditionally been correlated (e.g. Laing, 1996), but recent geochronology shows that the Curnamona Group is 10-15 m.y. older (Page et al., 2003; Stevens et al., 2008). The ≥ 1715 Ma Curnamona Group records rifting, accompanied by felsic A-type magmatism (Basso Suite) in the form of widespread quartz-phenocryst-rich flows and volcanoclastic sediments, high-level granitic intrusives, and restricted mafic magmatism in the form of locally pillowed basalt flows. Conor (2006) outlined a new stratigraphic scheme for the Curnamona Group based on belts of differing facies, first identified by Laing (1996). These lend support to concepts of growth faulting, and onlap of sediments onto tilted fault blocks. Only the lowest parts of the exposed stratigraphy in the Broken Hill Domain (in particular the calc-albitic Redan Gneiss) possibly overlap partly in age with the uppermost parts of the Curnamona Group.

The ~1700-1705 Ma Thackaringa Group also represents rifting, but is accompanied by felsic, mostly S-type magmatism of the Silver City Suite, derived from melting of sediments of similar composition to the Thackaringa Group (Barovich and Hand, 2004). Granite of this type (e.g. Alma Granite Gneiss) is intruded into, and felsic ?flows (in the Cues Formation) are intercalated within, the Thackaringa Group. This suggests that the older Curnamona Group (?and still older Wallaroo Group) could extend into the Broken Hill Domain beneath the exposed Thackaringa Group and Redan Gneiss. Being deeply buried and undergoing crustal extension, these rocks could then have been the source of the S-type magmas generated during deposition of the Thackaringa and Broken Hill Groups.

Upper rift packages and magmatism, ~1700-1670 Ma

In the upper (i.e. post-Thackaringa) Willyama Supergroup there are also important differences between the domains. The thin sulfidic carbonate, psammite and calcsilicate marker unit, the Bimba Formation, in the Olary Domain has long been correlated with the Ettlewood Calc-Silicate Member of the Allendale Metasediments in the Broken Hill Domain, near the base of the Broken Hill Group. Correlation is strongly supported by the ~1693 Ma age obtained on the inferred volcanoclastic metasilstone of the Plumbago Formation, which directly overlies the Bimba Formation, and its equivalent in the Broken Hill Domain (Page et al., 2005). Thus the Bimba/Ettlewood–Plumbago couplet forms a through-going link between the two domains. However, the overlying stratigraphies differ markedly, reflecting the different tectonic settings of the Olary and Broken Hill Domains. Over most of the Olary Domain, mudstone-dominated metasedimentary rocks of the Saltbush Group overlie this couplet, and may be equivalent to either Broken Hill Group or Sundown Group, or both, but mostly lack the distinctive lithologies, including “lode rocks” such as quartz garnetite, quartz-gahnite rocks and iron formations, which occur in the Broken Hill Group of the Broken Hill Domain. The volcanoclastic “Potosi-type” gneisses such as the Hores Gneiss have no known equivalent in the Olary Domain. Mafic intrusives of the same age as those of the Broken Hill Domain do occur in the Olary Domain (Lady Louise Suite), but are mostly seen intruding the Curnamona Group (Conor and Fanning, 2001). Only in the Cathedral Rock-Blue Dam area are there thin intercalations of quartz-garnet rock and iron formation, and intrusive mafic sills in the Saltbush Group, which suggest correlation with the Broken Hill Group. These observations support earlier concepts that the Broken Hill Group was deposited in an active rift system, and that its sediments lap out against an uplifted rift shoulder in the Olary Domain (Conor and Page, 2003), but the precise geometry of this rift system and indeed the location of the bounding normal faults are yet to be elucidated.

Sag-phase sedimentation, ~1660-1640 Ma

The Paragon Group in the Broken Hill Domain and Strathearn Group (redefined to exclude the Saltbush Group) in the Olary Domain are the youngest known successions, which are dominated by graphitic pelite with a psammitic unit in the middle. They are mainly known from the northern parts of the outcropping Olary, Mulyungarie and Broken Hill Domains and probably extend far to the north under cover. At Mount Howden and Alconie Hill (northern Olary Domain), graphitic pelite directly overlies Plumbago Formation. A tectonic origin (extensional excision) has been invoked for such juxtaposition (Noble et al., 2003), but Conor and Page (2003) preferred either of two overlapping sedimentary models. Such a relationship would be consistent with other evidence that the stratigraphic succession in the Olary Domain is less complete than in the Broken Hill Domain. Moreover, if the Paragon Group is considered to have resulted from sag-phase sedimentation, it may have been very widespread originally, overstepping the earlier rift packages, and may also have been much thicker than what is currently preserved, thus contributing to the depth of burial of the Willyama Supergroup required by its metamorphic grade. Interpretation of geophysics suggests that such thick successions of uppermost Willyama Supergroup are likely to be preserved under cover in the Mulyungarie and northernmost Olary Domains. Being at least partly coeval with the Mount Isa Group, they must be regarded as having high Pb-Zn mineralisation potential, and warrant extensive exploration.

Tectonics of the Olarian Orogeny, ~?1620-1580 Ma

Deformation and metamorphism

During the ~40 million year time span after deposition of the youngest preserved Willyama Supergroup, sedimentation is likely to have continued to produce the ≥ 10 km cover required by even the lowest recorded metamorphic grade. At the end of this period, the Willyama Supergroup underwent a major thermal and contractional event, the Olarian Orogeny, with evidence of polyphase ductile deformation. Several structural schemes have been proposed, but the paucity of hard evidence for correlating locally-derived structural sequences has resulted in a lack of consensus. However, some elements are common to most observations:

- Ubiquitous layer-parallel foliation.
- Evidence of very early heating in the form of migmatitic veining parallel to this foliation, and early pegmatites.
- Relatively early isoclinal recumbent folds of markedly different orientations and vergences, and the formation of near-regional scale overturned limbs.
- Relatively late upright folds that refold the isoclinal folds.
- S-type (and locally I-type) granite intruded late in the structural sequence.
- Retrograde shear zones cut across all the earlier structures and affect the late granites.

The implication is that the sedimentary pile was subjected to heating very early in its deformation history (W.P. Laing, 1995, pers. comm.; Stevens, 2006). Extensional tectonics have been invoked to explain this heating, but critical geochronological evidence does not support ideas of metamorphism coeval with sedimentation as proposed by Gibson and Nutman (2004), that is, prior to the Olarian Orogeny, which began at ~1600 Ma, and possibly as early as 1620 Ma. Although the data permit extension immediately before the onset of contractional deformation to produce the early heating and layer-parallel foliation, the evidence for such extension is not strong, and there are no associated mafic magmas of that age. One possibility is that burial under a thick, largely pelitic (hence insulating) sedimentary blanket under conditions of high heat-flow, perhaps resulting from radioactive heating (Stevens, 2006) might produce an early, horizontal high-grade fabric. Another is that recumbent folding may have

accompanied this heating, producing horizontal axial-plane fabrics, as suggested by Marjoribanks et al. (1980).

Available metamorphic dates indicate peak Olarian metamorphism at 1610-1590 Ma (Page et al., 2005; Rutherford et al., 2007). Until geochronology is able to resolve discrete deformation events within this narrow interval, the simplest hypothesis is to view the deformation as continuous and progressive under a thick sedimentary cover. By this process, earliest isoclinal recumbent folds in the internal part of the orogen, probably in the southeast, would be associated with flat-lying foliations. As deformation propagates to the more external zones in the northwest, so the early-formed foliations would themselves be folded isoclinally. Discovery of true F1 folds (i.e. folds which do not fold a pre-existing foliation) would be highly improbable. The variable orientation of isoclinal folds may be explained by a sheath-like geometry within a regime of overall northwest-directed tectonic transport (Forbes et al., 2004).

Repeated isoclinal folding greatly thickened the sedimentary pile and led to peak metamorphic conditions. Subsequently, the pile reacted to the deforming forces by more upright folding, traditionally termed F2 in the Broken Hill Domain (Marjoribanks et al., 1980) and F3 in the Olary Domain (Berry et al., 1978). While there is likely to have been a continuum between sheath folding and cylindrical folding in the Olarian Orogeny, the later folds have more consistent orientations than the early isoclinal folds, forming a sweeping arc from east-northeast- (in the southern Olary Domain) through northeast- to north-south-trending axial traces (in the Broken Hill and Mulyungarie Domains). Plunge and plunge directions vary greatly and even these later folds are clearly not all cylindrical. The vergence of the upright folds is also not consistent, though NW vergence is common in the Olary Domain. Upright folds in the Broken Hill area have been reconstructed with a slight easterly vergence (Stevens, 2004), and the tectonic relationships remain unclear. Metamorphic grade during upright folding also varies in different areas, being retrograde in much of the Olary Domain but still very high grade in the southern Broken Hill Domain, where a later phase of minor upright folding is considered retrograde (F₃ of Marjoribanks et al., 1980). At least some of these, with north-south trends, could be associated with deformation of the Neoproterozoic cover, and thus be of Delamerian age.

Granites~1595-1580 Ma

Intrusion of dominantly S-type felsic magmas (Ninnerie Supersuite; Fricke, 2006) at 1580-1590 Ma coincides with widespread magmatism and hydrothermal activity elsewhere in Australia, for example, the Hiltaba event on the Gawler Craton (Ferris et al., 2002). In the Curnamona Province, the granites intruded into a newly formed orogen, but postdate peak metamorphism and most of the deformation. The formation and emplacement of these magmas may be largely incidental to the orogeny, but reflect deep crustal heating of source rocks of different compositions in a variety of tectonic environments. In the case of the southern Curnamona Province, late Paleoproterozoic metasedimentary rocks such as the Willyama Supergroup (?and perhaps underlying Wallaroo Group) were at sufficient depth, due to a combination of sedimentary and tectonic burial, to undergo partial melting to form S-type magmas. Barovich and Foden (2002) noted the presence of more mafic, I-type variants in the Crocker Well area, so input of heat from the mantle is likely. On the Benagerie Ridge, however, the A-type volcanics of similar age must have had different or mixed sources from the deep crust or mantle. Such mantle-derived heating is consistent with concepts of a moving mantle hot-spot or plume (Betts et al., 2007).

Late Olarian deformation <~1580 Ma

Late Olarian deformation took the form of retrograde shearing in various orientations, but north-northeast and north-northwest trends are particularly common. Some shear zones affect intrusives of the Ninnerie Supersuite, and are therefore <1580 Ma. Associated east-west folds are locally quite intense. It is possible that exhumation of high-grade rocks in the southern part

of the Curnamona Province took place at this time, since the overall trend of metamorphic isograds is east-west, consistent with uplift on a network of such retrograde shears. The Curnamona Province thus probably underwent overall northward tilting as a result, which allowed extrusion and subsequent preservation of ~1580 Ma volcanics over eroded, folded, low-grade Willyama Supergroup in the Mudguard Domain, while the southern regions continued to be exhumed.

The large-scale arcuate trends of the upright Olarian folds, which define its overall tectonic grain, may be partly inherited from the original rift geometry of the basin or, if these trends were originally straighter, may have been imparted or modified during this late Olarian deformation to form an orocline. These arcuate trends were already in place by the time of Neoproterozoic rifting.

Radium Creek Metamorphics and felsic magmatism of the Moolawatana Domain

Dating of detrital zircons in quartzitic metasedimentary rocks of the Radium Creek Metamorphics in the Mount Painter inlier indicates a maximum depositional age of ~1590 Ma (Fanning et al., 2003; Ogilvie, 2007; Neumann et al., this volume). Felsic magmas include the ~1580 Ma Mount Neil Granite, the ?extrusive Pepegoona Porphyry of similar age, and the ~1560 Ma high heat-producing granites of the Moolawatana Suite. The structural relationships of the intrusives are subject to considerable debate. It is also difficult at present to prove Proterozoic deformation and metamorphism in the Radium Creek Metamorphics because of intense Paleozoic overprinting.

Neoproterozoic Tectonics, ~830-700 Ma

Neoproterozoic rifting that eventually led to the breakup of Rodinia commenced in early Willouran time at ~830 Ma, an event recorded in the Curnamona Province by the intrusion of mafic dykes correlated with the Gairdner Dyke Swarm on the Gawler Craton (Wingate et al., 1998). Around the Mount Painter and Broken Hill Inliers, mafic volcanics of this age were extruded over a thin basal sediment package that may represent a southern extension of the Centralian Superbasin. Rifting continued to the west in the Adelaide Geosyncline during late Willouran and Torrensian time (~800-750 Ma), but had little effect on the Curnamona Province (Preiss, 2000).

During the ~660 Ma Sturtian glaciation, the locus of rifting shifted eastward within the Adelaide Geosyncline, resulting in normal faults that encircle and define the present boundaries of the Curnamona Province. Some faults may have used pre-existing structural discontinuities in the basement, but others were newly formed. Sturtian sedimentation records deposition in a number of eastward-tilted half-graben on both sides of the province, with marked changes in thickness of stratigraphic units across normal faults. Proximal, extremely coarse-grained, glacial debris (including megaclasts up to hundreds of metres) was dumped into a half-graben adjacent to the active MacDonald Fault (Preiss, 2006).

The remainder of Neoproterozoic and Early Cambrian sedimentation around and above the Curnamona Province records sag-phase deposition and deep burial of the marginal zones of the province, for example in the Moorowie Sub-basin, as imaged at the western end of the seismic section (Goleby et al., 2006). In the central cratonic portion of the province, the cover is much thinner and flat-lying, being represented mainly by Marinoan and Cambrian deposits, apart from a small Torrensian to Sturtian-aged graben identified from the seismic section and very limited outcrop. The early Marinoan Upalinna Subgroup that onlaps basement on the Benagerie Ridge extends eastward into NSW, where Mississippi Valley Type basemetal mineralisation in its basal carbonate is currently undergoing active exploration.

Delamerian Tectonics, ~515-490 Ma

Deformation

Delamerian deformation is recorded in the Neoproterozoic cover as the arcuate folds of the Nackara Arc, reflecting overall northwest-directed tectonic transport. At the southwestern margin of the Curnamona Province, two interfering fold phases produced the partly fault-bounded, partly unconformity-bounded, dome-like basement inliers (e.g. the Weekeroo Inliers). The syndepositional rift architecture of the basement strongly influenced the first deformation phase at the province margins; rotated half-graben fills were further steepened and folded, and rift-faults reactivated. Delamerian effects within the basement are less clear – some shear zones were reactivated, as were the Sturtian rift faults. The folded unconformities, as well as the buckling of early Neoproterozoic dykes, suggest some north-south shortening during the second fold phase, and the MacDonald Fault, bounding the main Kalabity Inlier in South Australia, underwent dextral oblique-slip movement (rather than true strike-slip as suggested by Marshak and Flöttmann, 1996). Delamerian reorientation of Olarian structures must also be taken into account when interpreting the Proterozoic tectonic history.

Metamorphism

Delamerian metamorphic grade in cover rocks ranged from essentially unmetamorphosed in the central, cratonic portion of the Curnamona Province to lower amphibolite facies in the south, as recorded by calcsilicates in the basal Adelaidean succession. Geochronology has dated the growth of at least some garnet, kyanite and staurolite in basement rocks in the south as Delamerian (Dutch et al., 2005; Rutherford et al., 2006). Metamorphism of the lower Adelaidean cover over the Mount Painter Inlier attained lower amphibolite grade, and Delamerian metamorphism in the basement may have been of even higher grade. So was there really a Proterozoic orogeny affecting Mount Painter or are all the effects Delamerian?

Post-Delamerian magmatic and hydrothermal activity

Post-Delamerian events include intrusion of Early Ordovician felsic dykes in the Radium Hill area (Jagodzinski et al., 2006) and intrusion of granites and high-temperature veins in the Mount Painter Inlier at ~440 Ma (Elburg et al., 2003). The high-level hydrothermal system of the Radium Ridge Breccias and Mount Gee Sinter (Drexel and Major, 1987) are probably of Permo-Carboniferous age (Idnurm and Heinrich, 1993). Within the Mount Painter Inlier, enigmatic dyke-like bodies of diamictite containing unmetamorphosed Mesoproterozoic rhyolite clasts derived from the Benagerie Ridge are most likely Permo-Carboniferous glacial debris filling deep fissures in this hydrothermal system.

Neotectonics

As a result of the onset of late Cenozoic east-west compression of Australia, much of the deeply eroded Delamerian mountain chain has been uplifted, at least partly on reactivated Delamerian and older faults. The Mundi Mundi Fault is one such neotectonic feature, which today forms the prominent western boundary of the Broken Hill Inlier. The Delamerian Anabama Shear Zone, south of Olary, has also been reactivated, forming the northern margin of the Cenozoic Murray Basin. No such structure, however, defines the northern limit of outcrop of the Curnamona Province, which dips gently northward below Mesozoic and Cenozoic strata. As a result of uplift, much of the Mesozoic deep weathering profile, such as is preserved near Adelaide, has been largely stripped from the main exposed portions of the Curnamona Province (Crooks, 2002).

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Developing large scale, base load EGS power: the Paralana Project, South Australia

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Abstract

The Paralana Engineered Geothermal System (EGS) Project, located 600 km north of the city of Adelaide in South Australia, provides a natural laboratory for the development of an Engineered Geothermal System. Anomalously high-heat production basement rocks cropping out in the Mount Painter Inlier provide the local heat source, and are overlain by a thick sedimentary package of Mesozoic to Neoproterozoic age in the adjacent Poontana Sub-basin, within a favourable *in situ* stress regime. Early exploration drilling indicates an elevated geothermal gradient and heat flow at the project site.

Petratherm Limited, in joint venture with a major oil and gas company (Beach Petroleum) and a power industry energy utility (TRUenergy) initially are seeking to build a 7.5 MWe commercial power development to supply a local mine. A local microseismic monitoring network has been deployed to record background seismicity prior to drilling of the first deep well into the resource, which began in June 2009. An innovative strategy for development of the EGS reservoir is planned, involving massive hydraulic stimulation of multiple target zones within the sedimentary overburden. This paper will provide an update on progress at the Paralana EGS site.

Introduction

The Paralana EGS Project is located east of the Northern Flinders Ranges on the plains area between Lake Frome and the Mount Painter Inlier, within the South Australian Heat Flow Anomaly (SAHFA) (Figure 1). To the east of the Mt Painter Inlier, a system of subparallel, northeast–southwest trending faults juxtapose flat-lying sedimentary successions against the high-heat producing Mesoproterozoic Mount Painter basement. In this area, 2D reflection seismic survey data and potential field geophysical (aeromagnetic, magnetotelluric and gravity) data delineate a major structure informally termed the Poontana Sub-basin (Figure 2). Based on the interpreted geophysical data, Petratherm postulates that the high-heat producing basement rocks, observed in outcrop, continue under the insulating cover material, with the maximum thickness of the sedimentary cover in sections of the Poontana Sub-basin being modeled at greater than five kilometres. This favourable arrangement of thick sediments overlying anomalously radiogenic basement suggests that the Paralana area is an ideal location to test the development of an Engineered Geothermal System.

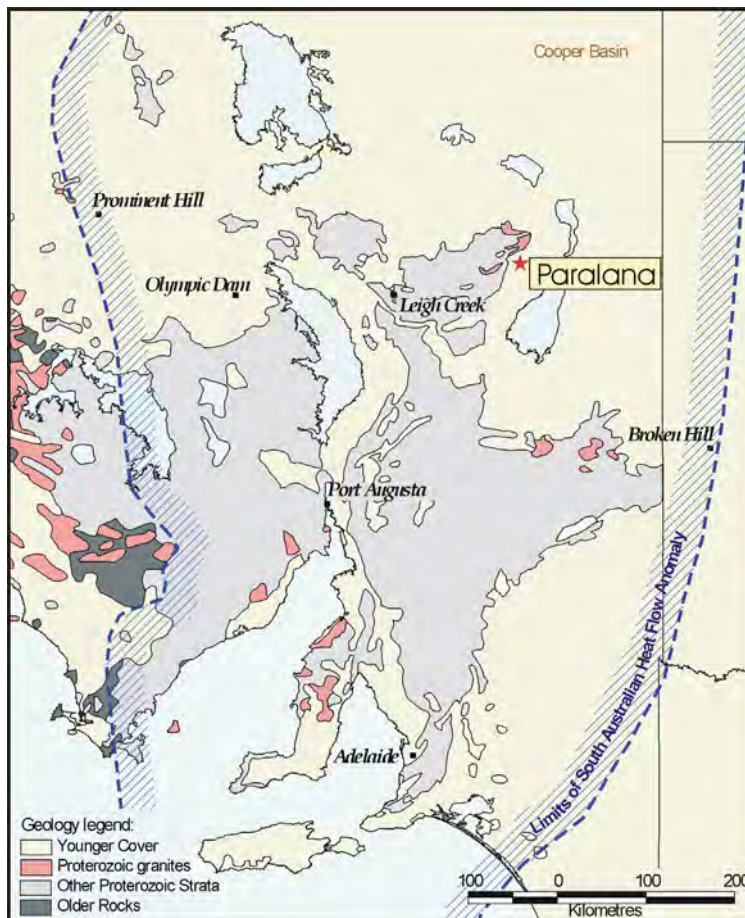


Figure 5. Regional locality map of the Paralana Geothermal Project site, which is located on the plains between Lake Frome (east) and the northern Flinders Ranges (west), approximately 600 km north of Adelaide.

Geological Overview

The Mount Painter Inlier forms the western boundary of the Lake Frome Embayment, and consists of multiply deformed, polymetamorphic, Paleoproterozoic to Mesoproterozoic metasedimentary and volcanic rocks, intruded by granitoids (Drexel et al., 1993). The basement rocks in the Mount Painter Inlier generally contain elevated uranium and thorium contents resulting in high to very high heat production rates compared to average Proterozoic rocks. For example, the average heat production in the Mount Painter Inlier is $10 \mu\text{Wm}^{-3}$, which is around 4 times that of average granite, with individual granites such as the Yerila Granite producing up to $62 \mu\text{Wm}^{-3}$ (Neumann et al., 2000). These extraordinary basement heat production values point to the existence of a major thermal energy resource domain.

A long-lived and geometrically complex fracture system, known as the Paralana Fault System, forms the eastern boundary to the Mount Painter Inlier. Tectonic activity on this fault system has led to the development of a half graben, known as the Poontana Sub-basin (Figure 2), and juxtaposes the basement rocks against the thick succession of sedimentary rocks within the sub-basin, which represent successive depositional sequences within the stacked Neoproterozoic Adelaide Geosyncline, Cambrian Arrowie Basin and Mesozoic Eromanga Basin.

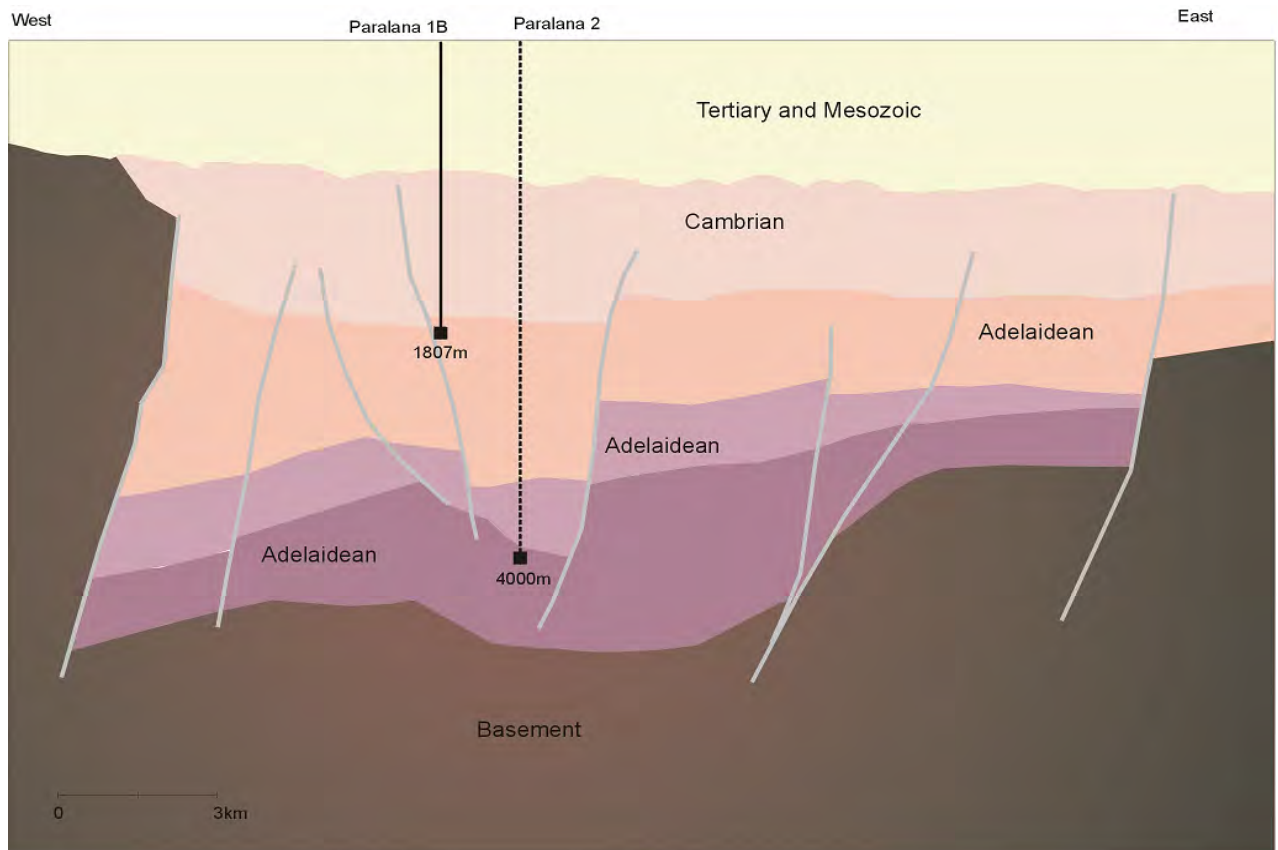


Figure 2. Schematic cross section of the informally termed Pootana Sub-basin.

As such, the sub-basin has a complex structural history, and contains sedimentary fill from two distinct depositional times. The first megadepositional cycle spans the Neoproterozoic to Early Cambrian periods (~830 Ma to 520 Ma), and underwent regional metamorphism to low-grade greenschist facies during the subsequent Delamerian Orogeny (~500 Ma). Interpretation of reflection seismic data indicates complex multiphase extension and faulting of the area, with subsequent reverse movement on reactivated faults during the Delamerian Orogeny. The succession consists of a range of lithologies. The Neoproterozoic sedimentary rocks are dominated by shale-siltstone assemblages, including matrix supported diamictite, with lesser sandstone and dolomite. The Cambrian sedimentary rocks consist of approximately equal proportions of cryptalgal shale, siltstone, sandstone and limestone.

The second depositional period spans Mesozoic to Quaternary sedimentation. These later cycle sediments consist of marginal marine mudstones and claystones, overlain by fluviatile silts and Holocene colluvium. There is evidence of reactivation of older extensional faults in the early part of Mesozoic and Cenozoic sedimentation, and evidence along the eastern margin of the Mount Painter Inlier of continued Neotectonic movements indicating a reverse sense of movement.

Although the existing data are sparse, indications are that the present-day stress environment in this region is compressional to strike-slip (Hillis et. al., 2008), which will favour development of fractures in a horizontal to subhorizontal plane in response to hydraulic stimulation. This creates an ideal environment for HDR developments (Swenson et. al., 2000)

Exploration Operations Undertaken At Paralana

Based on the recognition of high-heat producing basement rocks cropping out in the Mount Painter Inlier, and supporting evidence of radiogenic heating of groundwater at the Paralana Hot Springs, Petratherm began exploration activities in the Paralana region with the drilling of a shallow test well (Paralana 1B) to 491 m. The well penetrated poorly-consolidated Cenozoic to Mesozoic sediments and yielded a high geothermal gradient measurement (ave. 77 °C/km). Paralana 1B was subsequently deepened to 1807 m in 2006 through Cambrian and Adelaidean aged strata of the Adelaide Geosyncline, which made up the remainder of the basin fill. The equilibrium bottom hole temperature recorded at this depth was 109 °C and a measured heat flow of $129 \pm 3.6 \text{ mWm}^{-2}$ calculated. The Cambrian and Adelaidean sequences have on average higher thermal conductivities than the overlying Tertiary and Mesozoic sediments, so corresponding temperature gradients ranged between 30 °C and 55 °C degrees per kilometre dependent on the lithology. Thermal modelling studies using data gathered from the Paralana 1B well, indicated temperatures in excess of 200 °C were possible at less than 4000 metres depth (Hand, 2006).

Due to the structural complexity of the basin architecture a 2D reflection seismic survey was acquired over the area in 2007, coincident with trial magnetotelluric studies, and a microseismic monitoring network was deployed in the area to record background seismicity prior to the commencement of drilling and stimulation operations. Subsequent geological and thermal modeling was used to site Paralana 2, the first deep geothermal well to be drilled into the inferred resource. Drilling of Paralana 2 commenced in June 2009, and is planned to target Adelaidean sedimentary rocks at 4000 metres depth.

Proposed Heat Exchange Development Plan – The Hewi Model And Multizone Stimulation

The HEWI Model

One of the principal limiting factors towards the commercialisation of EGS has been the inability to manufacture a heat exchanger of sufficient size and fluid production rate. Existing technical difficulties in achieving a robust subsurface heat exchanger in EGS applications generally relate to the practice of developing the subsurface heat exchanger within the heat-producing granite rock. Granite is, by nature, an impermeable and mechanically strong rock. As a result, it is inherently difficult for fluid to flow through granite, or to mechanically fracture the rock to develop an effective reservoir artificially. By comparison, the rocks which make up the overlying insulating sediments tend to have greater naturally-occurring porosity and permeability, are mechanically weaker, and more susceptible to induced chemical and mechanical stimulation, if enhancement of the reservoir is required.

The Heat Exchanger Within Insulator (HEWI) model (Figure 3) aims to exploit naturally permeable and porous insulating sedimentary rocks above the granite heat source, or where intrinsic permeability is inadequate, delivering greater control over the development of the reservoir via hydraulic stimulation of these units. This strategy more closely approximates the systems successfully used in petroleum reservoirs and conventional geothermal projects, enabling the application of techniques for stimulation and geochemical mitigation developed and successfully used on a routine basis in these industries.

Multi-Zone Stimulation

Historical hydraulic fracture stimulations have generally been single massive stimulations in an open hole. The limitation of this method is that the operator has minimal control over the location and distribution of the developing fracture network, with most fractures propagating at the base of the casing shoe near the top of the openhole section. The inability to selectively

initiate propagation of fractures in the remaining openhole section means that the development of the heat exchanger has been severely compromised.

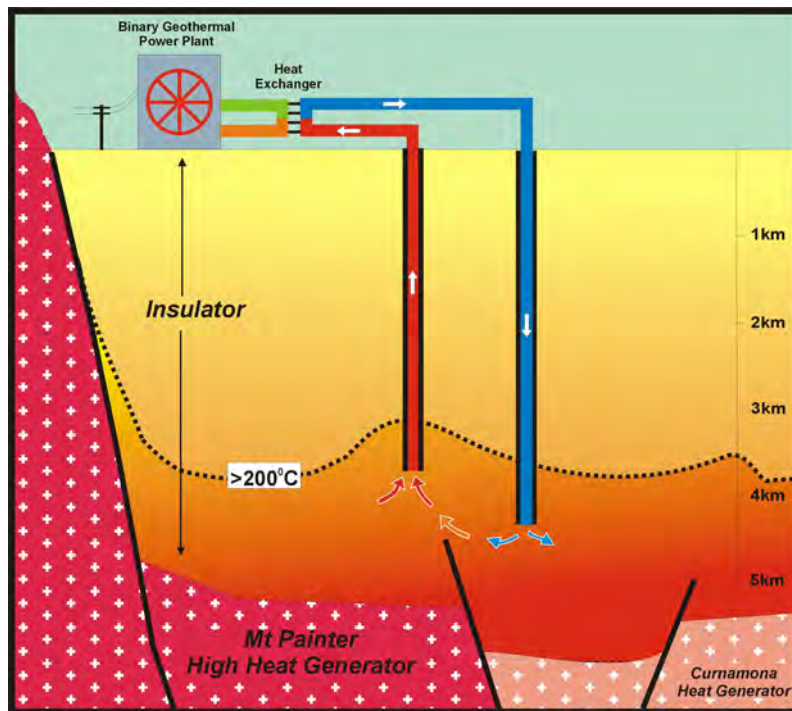


Figure 3. Schematic diagram demonstrating the basic concept of an Enhanced Geothermal System using the HEWI (Heat Exchanger Within Insulator) model.

Given that the development of a complex, thick, interconnected fracture network is the optimal configuration for the engineered reservoir, it follows that undertaking multiple stimulation operations initiated at different levels in the well could achieve the desired outcome. Such an operation would enable greater control; both in terms of the location of initiation of fracturing in the well bore, and the potential to develop stacked multiple fracture horizons within suitable single or multiple geological units.

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Illusive or elusive? Exploration vectors in the Curnamona Province and Neoproterozoic succession in New South Wales

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Introduction

The Willyama Supergroup in New South Wales is highly mineralised. Barnes (1988) described more than 3500 showings and workings, representing at least 25 discrete styles of mineralisation from syn-sedimentary through to post-orogenic. Exploration, however, is hampered by complex structure, the metamorphic overprint on pre-metamorphic alteration and textures, regolith and cover, and, ironically, the vast volume of data.

Regional interpretive mapping throughout the Proterozoic of the Curnamona Province in NSW, in conjunction with an established geodynamic and metallogenic framework and new data and ideas, provide fresh possibilities to vector towards mineral systems in the Broken Hill region.

Background

The Curnamona Province in New South Wales, and the bounding Neoproterozoic rocks, includes the Broken Hill Domain, Redan Domain and eastern Mulyungarie Domain of the Willyama Supergroup, and the basal Warrina Supergroup and Heysen Supergroup of the Neoproterozoic Adelaidean succession (Preiss, 1982; Scheibner and Basden, 1998; Conor and Preiss, 2008).

Correlation between the Curnamona Province in NSW and other Palaeoproterozoic and Mesoproterozoic belts, such as the greater Curnamona Province, Eastern Succession in the Mount Isa Province, Wernecke Mountains of northwest North America and the Gawler Craton in South Australia, are established, or proposed, by inclusion of the Willyama Supergroup in the Diamantina Orogen, the Australian Proterozoic Pb-Zn-Ag Province and the Australian Proterozoic IOCG Province (Laing, 1996b; Preiss, 2000; Page et al., 2005a; Conor and Preiss 2008).

In the Neoproterozoic succession in NSW, correlations are made with the Callanna Group (Willouran1) and Umberatana Group in the Adelaidean Geosyncline in South Australia, the Grey Range Group in the Koonenberry Belt, and the upper Officer Basin (Cooper and Tuckwell, 1978; Preiss, 1987, 2000; Preiss et al., 1993; Crawford et al., 1997; Scheibner and Basden, 1998; Foden et al., 2001, 2006; Greenfield, 2009a).

The Curnamona Province and the Neoproterozoic succession in NSW benefit from an immense amount of study, either directly or by correlative studies (see above). These include detailed

mapping, geochronology, geochemistry, metallogenesis, structural studies and geophysics (e.g. Hobbs, 1968; Thomson, 1969; Majoribanks et al., 1980; Willis et al., 1983; Stevens, 1986; Haydon and McConachy, 1987; Preiss, 1987; Barnes, 1988; Parr and Plimer, 1993; Burton, 1994, 2000; Webster, 1994; Laing, 1996a; Crawford et al., 1997; Gibson et al., 1998; Skirrow and Ashley, 1998; Willis, 2000; Stevens et al., 2003, 2008, Page et al., 2005a, 2005b; Foden et al., 2006; Gilmore et al., 2007; Conor and Preiss, 2008).

From these data, geodynamic controls in NSW are established:

Willyama Supergroup

- 1720-1703 Ma incipient rifting and A-type magmatism.
- 1695-1685 Ma intracratonic rifting and Pb-Zn-Ag event (Broken Hill).
- 1704-1683 Ma coeval bimodal magmatism, including emplacement of S-type Silver City Suite.
- ~1650-1630 Ma I-Type magmatism – not described in NSW.
- 1640 Ma Pb-Zn-Ag mineralisation in the Proterozoic Pb-Zn-Ag belt – not observed in NSW.
- ~1600/1620 Ma (Page et al., 2005; Forbes et al., 2005) -1585 Ma Olarian Orogeny.
- ~1595-1580 Ma Mundi Mundi-Ninnerie intrusives and thermal event.
- 1600-~1500 Ma Proterozoic IOCG Province Fe-Cu-Au thermal event.

Neoproterozoic succession and Willyama Supergroup

- ~827 ± 6 Ma Willouran tectonothermal event (incipient Rodinian continental rifting), with evidence of rifting extending into the early Sturtian (~770 Ma).
- 830-~770 Ma rifting and associated deposition of Burra Group – not described in NSW.
- ~505-498 Ma Delamerian Orogeny.

Neoproterozoic succession

- 586 Ma rifting (Rodinian Breakup).
- Post-Delamerian (Ordovician?) intrusive event.

Discussion

The Willyama Supergroup and Neoproterozoic succession in NSW preserve evidence for periods of geodynamic convergence and periods of divergence, based on correlations with other provinces and domains. Each event, and the presence or absence of associated metal systems, is essential to understand potential mineralisation styles and vectoring towards them. Some deposit styles are considered here.

Willyama Supergroup

Many of the mineral deposits in the Willyama Supergroup in NSW have a direct relationship to identified geodynamic events. For example, Broken Hill-types (BHT) and other syn-sedimentary deposits have a strong correlation to a rifting event. Syn-sedimentary, rift-related models for ore genesis include a requirement for feeder zones. Plimer (1979) and, more recently, Groves et al. (2008) suggest that the C-lode was the feeder for the Line of Lode, characterising it as a siliceous, blue quartz-gahnite-pyrrhotite mineralised alteration zone, crosscutting stratigraphy. Of note, the authors highlight that 45% of the Line of Lode orebody (by metal volume) is proximal to C-lode, which represents only 13% of total strike length - a significant BHT exploration target, if identifiable during exploration.

Additionally, a syn-sedimentary model for BHT genesis suggests the presence of pre-metamorphic alteration in the footwall, and possibly the hangingwall. Alteration studies on BHTs

indicate a hydrothermal halo on the deposit-type (summarised in McConachy et al., 2003). A geochemical approach is particularly valuable for pre-Olarian deposits, where much of the subtle details of deposit texture and alteration may be overprinted and masked by metamorphic textures.

The potential for Mt Isa- or MacArthur-type deposits occurring in the Paragon Group (Strathearn Group) is highlighted by Stevens et al. (2003) and Page et al. (2005a). The target horizon in New South Wales is predominantly under shallow to moderate depths of Neoproterozoic or Phanerozoic cover. Interpretive mapping of these regions (Stevens, 2009; Stevens et al., in prep.) provides a framework for exploration.

Most of the late vein deposits, but not all, are demonstrated to be emplaced late- to post-Delamerian (Both and Smith, 1975). These are discussed further below.

As distinct from the correlated geodynamic-mineralisation events, several of the recognised geodynamic events have no established metal association. These include: ~1700 Ma A-type magmatism, Silver City Suite intrusives, the prograde Olarian deformation, and the 1640 Ma mineralising event in Mount Isa (MacArthur-type). These events, or attempts to identify mineralisation related to them, may represent under-tested exploration targets.

An interesting example is the iron-oxide copper-gold event, demonstrated to coincide with, or post-date, the retrograde Olarian Deformation (OD3), but it lacks characteristic geodynamic controls.

Iron Oxide Copper-Gold-Uranium (IOCGU)

IOCGU deposits are correlated with A-type and I-type magmatism, and generated by mixing of magmatic and meteoric fluids. They are prospective for Cu-Au±Ag, U, REE, Bi, Co, and are characterised by Na-Ca regional-scale alteration and subsequent K-Fe alteration. A- or I-type magmatism provides both heat and the saline, relatively oxidised fluids required for oxide-rich, sulfide-poor, metalliferous fluids to be generated (Corriveau, 2007).

In the Curnamona Province, IOCGU mineralisation (e.g. Portia, Kalkaroo, White Dam) is noted to occur close to the position of the Curnamona Group-Saltbush Group boundary, equivalent to the Thackaringa Group-Broken Hill Group boundary in NSW (Leyh and Conor, 2000). The boundary represents the position where sedimentation in the Curnamona Province changes from oxidic, quartzofeldspathic facies to sulfidic metasedimentary facies, a consequence of a developing and deepening rift-related succession. Mineralisation is late- to post-tectonic (~1590-1580 Ma), and best developed in iron oxide-rich lithologies, such as iron-oxide dominated exhalatives or syntectonic ironstones, which act as the reductant controlling mineralisation.

In NSW, I-type magmatism is not observed. The cessation of A-type magmatism (1703 ± 3 Ma; Page et al., 2005b) is penecontemporaneous with the accelerated development of volcanosedimentary rift-fill, namely, the Broken Hill Group. Despite a 100 Ma hiatus, however, IOCG mineralisation does occur in the Broken Hill Domain as late deformational deposits (e.g. Copper Blow).

A possible mechanism for IOCG-type deposits in the Broken Hill region is now discussed. Heat, as a geodynamic driver, is a cumulative product of the high thermal gradient of the pre-metamorphic attenuated crust, syn-sedimentary magmatism, orogenic thickening and late, syn- to post-structural granite emplacement of the Mundi Mundi Suite. The anomalous crustal radiogenic content of the east Australian Proterozoic (McLaren et al., 2003) may also represent a significant contributor to the high thermal gradient in Broken Hill. Fluids potentially are generated during retrograde crystallisation of melt phases throughout the region. Timing is bounded by peak metamorphic conditions, 750-800° at 5-6 kb at 1600 Ma (Stevens, 1986) and

Ar-Ar closure temperatures in hornblende, ~500° at 1575 Ma (Harrison and McDougall, 1981). The required saline fluid chemistry plausibly is generated from albitised, evaporitic sediments characteristic of the Lower Willyama Supergroup in the Broken Hill Domain (Redan Zone and Thackaringa Group; Slack et al., 1989). Possible non-magmatic IOCG analogies include the Wernecke Breccias in Canada and the Cloncurry District (Corriveau, 2007, Fisher and Kendrick, 2008).

Increased sedimentation rates at the oxide-sulfide boundary, and the transitional nature of the Allendale metasedimentary rocks from oxidic to sulfidic, may result in a less prospective chemical front for IOCG mineralisation at this boundary in NSW (Skirrow and Ashley, 1998; Leyh and Conor, 2000; Willis, 2000; Fisher and Kendrick, 2008). The transition from Sundown Group to the graphitic, reduced Paragon Group, however, may represent another sharp redox boundary amenable to mineralisation.

Neoproterozoic Succession

Metal potential in the Neoproterozoic succession in NSW is poorly tested, and information presented here is a first pass synthesis of geodynamics and metallogenesis. Stratigraphy and evolution generally correlate with the Adelaidean in South Australia. Exceptions include the absence of the Burra Group (and associated rift development), and the presence of Marinoan (~586 Ma) rifting and coeval transitional alkaline magmatism (Mount Arrowsmith Volcanics and the Picnic Creek Basalt).

Established mineralisation in the Neoproterozoic succession in NSW, summarised from Cooper and Tuckwell (1978), Scheibner and Basden (1998) and Gilmore (2007), includes:

- Altered, weakly copper-mineralised basalts associated with rifting (830 Ma) – Wendalpa Subgroup.
- Iron-rich Braemer Ironstone in the Yalcowinna Subgroup (Brewster et al., 2009).
- MVT Pb-Zn in the basal Farnell(?) Group (King, 2009)
- Vein-hosted gold in the Farnell Group.
- Stratiform Pb-Zn in the Grey Range (Farnell) Group.
- Orthomagmatic Ni in the Grey Range (Farnell) Group.
- Copper-bearing (Delamerian-aged?) veins in the Corona region.
- Argentiferous galena (location uncertain).

Mineralisation in equivalent stratigraphic horizons in the Adelaidean succession in South Australia is summarised from Preiss (2000). Although many of these deposits have local structural controls, the strong correlation between the evolution of the Neoproterozoic in NSW and SA suggests that they represent plausible exploration models in NSW. Metalliferous occurrences include:

- Copper in carbonaceous shale, hosted in the basal Nepouie (Euriowie) Subgroup.
- Vein-hosted gold in the Nepouie (Euriowie) Subgroup.
- Stratabound and vein copper in the upper Nepouie (Euriowie) Subgroup.
- Stratabound gold in the basal Wilochra (Teamsters Creek) Subgroup.
- Cu-bearing dolomite in the upper Wilpena (Farnell) Group.

The Neoproterozoic succession is variably affected by the Delamerian Orogeny, with deformation decreasing from east to west. A south to north decrease in metamorphic grade is also proposed (Rutherford et al., 2006), with amphibolite-grade metamorphism in the Willyama Supergroup in NSW. Delamerian-age mineralisation occurs within the Willyama Supergroup in NSW, and, almost certainly, occurs in the adjacent Neoproterozoic succession. Mineralisation types include (Barnes, 1988; Willis, 2000; Both and Smith, 1975):

- Siderite-quartz veins with argentiferous galena (Thackaringa type).
- Copper-bearing, quartz-carbonate veins with gold potential.
- Auriferous quartz veining (orogenic gold).
- Lead-fluorite veins (Mt Robe type).
- Copper-rich pyrite veins.

Further potential may be associated with post-Delamerian intrusives (diorite dykes) and, to the north of the region, where Neoproterozoic and Willyama rocks are covered by Mesozoic and Cenozoic sediments.

Conclusions

Willyama Supergroup

Correlating mineralisation to established geodynamic events, or identifying possible mineralisation associated with these events, serves as a framework for target generation and vectoring. Recognition of feeder zones, in syn-sedimentary base metal deposits, may represent an important vector to high grade-high tonnage mineralisation in elusive BHT systems. Likewise, understanding the effects and chemical expression of metamorphism-obscured alteration has significant vectoring potential.

Given the possibility that IOCG mineralisation does not require magmatism to evolve, a discrete geodynamic history in NSW, and a potential migration of the controlling chemical boundary, are proposed as potential vectors to Cu-Au mineralisation in the Willyama Supergroup.

Neoproterozoic succession

The Neoproterozoic succession in has a strong likelihood of hosting mineralisation, based on direct observation, correlations made to adjacent Neoproterozoic domains and their metallogenic and geodynamic evolution. Identified Delamerian-aged mineralisation cutting the Willyama Supergroup almost certainly occurs.

Although well exposed in some areas, most of the Neoproterozoic succession is under Mesozoic and Cenozoic cover, inaccessible to historical prospecting. Targeting the Willyama Supergroup basal to the Adelaidean succession represents a legitimate target, particularly to the north of Broken Hill.

Marinoan, transitional alkaline rift-related magmatism is a discrete tectonothermal event with untested potential in the Neoproterozoic succession in NSW.

Acknowledgements

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Future mineral sands opportunities in the Murray Basin

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Introduction

Bemax Resources Limited is a mineral sands explorer and producer in the Murray Basin. They are currently operating the Ginkgo mine located 65 km west of Pooncarie, and approximately 200 km southeast of Broken Hill (Figure 1). The mineral sands are mined from ancient (approximately 6 Ma) beach sands presently buried 20 to 30 m below the current surface. Titanium bearing minerals, such as rutile, leucoxene and ilmenite, as well as zircon are mined and processed from the sands.

The titanium bearing minerals are used predominantly in the pigment industry for production of titanium dioxide. Titanium dioxide currently is the whitest pigment known to man, and is used as the white base in glossy paper, plastics and in particular paint. Zircon is predominantly used in the ceramics industry as a fine glaze on tiles.

This abstract outlines the evolution of Bemax Resources Limited and its affiliation with its parent company Cristal Global. It provides an update on the Ginkgo mine, as well as development at the new Snapper mine site. A review of the current Bemax resource base is given, with implications for future development in the Murray Basin.

Evolution of Bemax

Bemax commenced as a junior gold explorer on the ASX in the early 1990's. The company moved into mineral sands exploration in the Murray Basin in 1997 and made a major discovery of the Ginkgo prospect in November 1998. This was followed in August 1999 with the discovery of the Snapper deposit (Figure 1). In 2003, Cristal became a 31% shareholder of Bemax.

In 2004, Bemax acquired the mineral sands assets of Sojitz and Sons of Gwalia. This acquisition included the Cable Sands Limited (CSL) mines and processing operations in Western Australia, as well as further substantial prospective exploration tenements in the Murray Basin. This transformed Bemax from a junior explorer to a mineral sands producer with operations and markets.

The Ginkgo mine and associated mineral processing plant at Broken Hill came into operation in December 2005. Environment Approval for the Snapper development was achieved in mid 2007, followed by Mining Approval in early 2008. The Snapper mine is presently under construction.

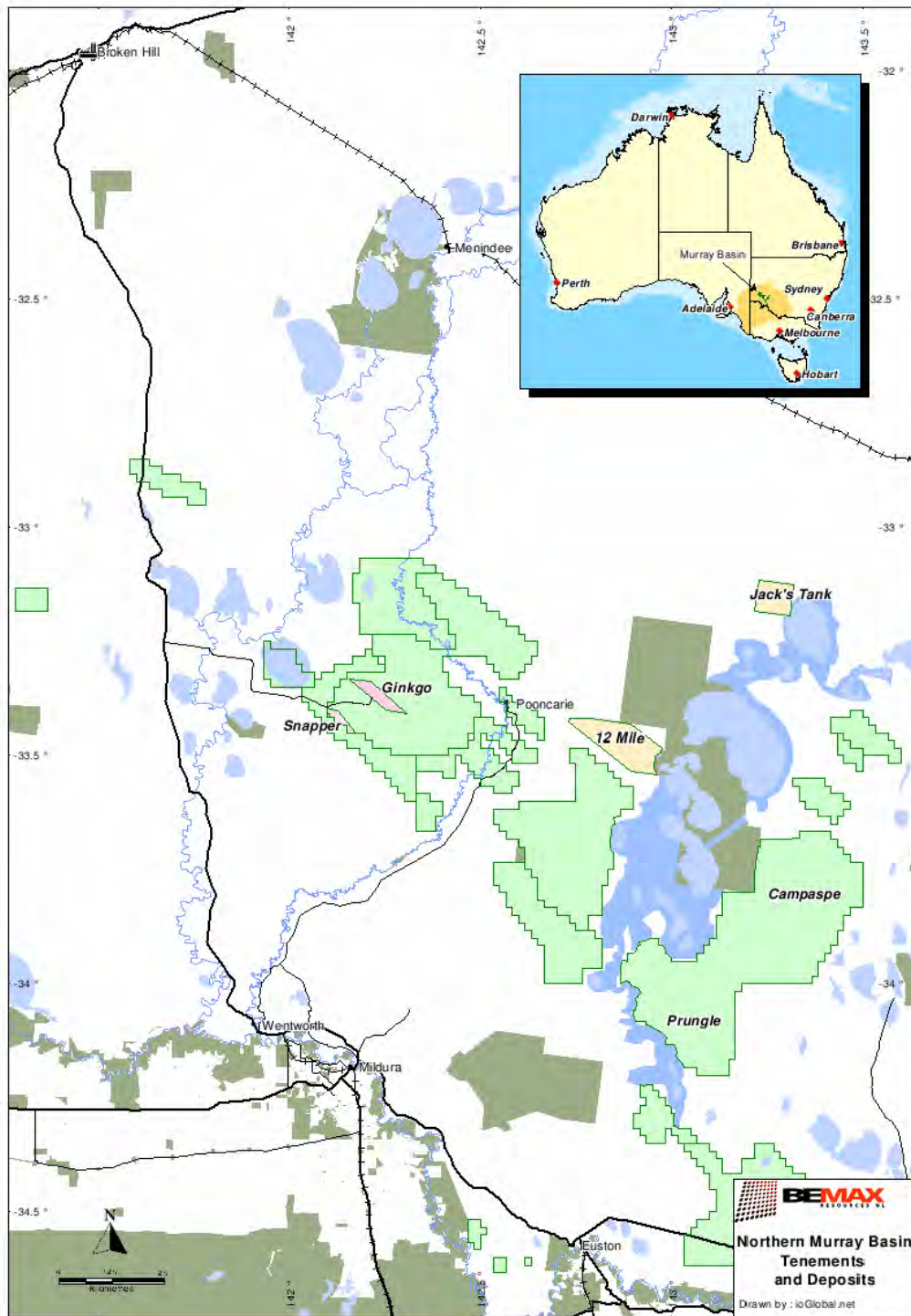


Figure 1. Locality map of the Ginkgo mine, with tenements as at 2006.

In September 2008 Cristal Global acquired 100% ownership of Bemax. Cristal Global is a Saudi Arabian-based company, which began in 1991 with the building of the chloride pigment plant at Yanbu; it has its headquarters in Jeddah. In 2007, it acquired the world-wide assets of Millenium, with chloride pigment plants in America, UK, and in Australia at Bunbury, south of

Perth, as well as sulfate pigment plants in Brazil and France. The acquisition moved Cristal into second position in the world, behind DuPont, for titanium dioxide pigment production.

Bemax retains its Australian head office in Brisbane. Major production is from the Murray Basin, where 68 Bemax staff are employed in the dredging and processing at the Ginkgo mine plus a further 70 contract employees primarily involved with overburden removal. The Broken Hill site employs a further 60 people. Australia wide, including the operations in Western Australia, an office in Newcastle, and the exploration team based in Mildura, Bemax employs over 260 personnel.

Product Flow

A heavy mineral concentrate, representing about 5% of the ore is produced on site at Ginkgo. The heavy mineral concentrate is magnetically separated by a wet high intensity magnetic separator (WHIMS), which produces two magnetic components containing ilmenite and leucoxene, and a non-magnetic product containing the more valuable rutile and zircon minerals.

These products are transported by truck 220 km to Broken Hill, where the ilmenite products are upgraded to higher TiO₂ products, and the non-magnetic product is cleaned up on wet tables to a higher-grade concentrate.

The Broken Hill products are railed to Adelaide, where the ilmenite products are shipped directly to DuPont in America, and to other markets, including China. The non-magnetic product is shipped to Bunbury for further processing into separate rutile, zircon and leucoxene products, for sale and shipment to plants and markets in America, Europe and China.

Ginkgo Mine

Construction of the Ginkgo mine commenced in 2005. A construction pit 300 m by 300 m was dug originally to within 1 m of the groundwater table. The dredge and floating concentrator were built within the construction pit, which was subsequently flooded to float the dredge, enabling it to dig itself down into the ore. The dredge floats in the local groundwater, with salinity levels greater than sea water. No fresh water is brought on site, with all fresh water requirements met by a reverse osmosis unit on site.

The original Ginkgo reserve was 187 Mt @ 2.9% HM. The Ginkgo deposit is approximately 10 km in length and 500 m wide. Mining commenced in the centre of the deposit to take advantage of the highest grade ore (initially running up to 8% HM). A two-pass mine path was designed to follow the high grade zone (300 m wide) along the southwestern side of the deposit. To date, the Ginkgo dredge has advanced 2.7 km to the north. There is a further 2.1 km to the north before the dredge will turnaround at the end of 2010, and come back the return path to finish at the southern end by 2018.

The dredge has a feed rate of approximately 1700 tph, and mines around 12 Mt of ore per annum. In 2009, we are forecast to produce 466,000 t of heavy mineral concentrate and remove 10.3 million cubic metres of overburden. Overburden removal was initially by scrappers and dozers, but a conveyor system is presently being constructed, which will substantially reduce overburden costs.

Transport of concentrate to Broken Hill is by local contractors using AB triples. The change from road trains to AB triples has again provided significant cost savings.

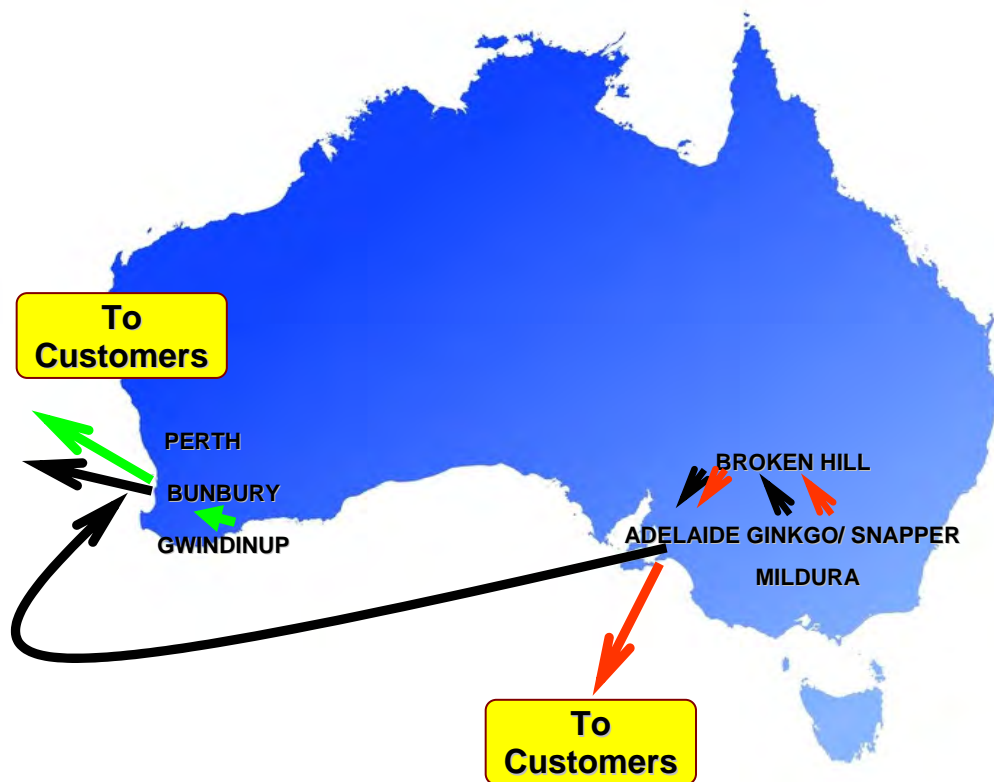


Figure 2. Bemax Product Flow.

Snapper Mine

The Snapper deposit is 10 km away from the Ginkgo mine site (Figure 3). Construction has commenced, with completion of the construction pit, and the initial off-path tailings dam, as well as the water storage pit. Plant construction is due to start and Snapper will be into production by mid 2010. Mining will commence at the far southern end of the deposit along a single path for the first six years, before splitting into a two path scenario, with mining ending in 2025.

Bemax Resource Base

Bemax has a total of 96 Mt of contained heavy mineral within its 40 known deposits. Considering that Ginkgo and Snapper each contain approximately 6Mt of contained heavy mineral, the long term extent of the resource base is evident.

Ginkgo and Snapper lie within the Pooncarie region. However, there are extensive resources along two topographic ridges known as Willandra East and Willandra West (Figure 4). There are also large, deep resources in the Balranald area, as well as the Coombah and Massidon resources south of Broken Hill. The vast majority of the Bemax resources are in NSW, with only minor deposits in Victoria near Ouyen, immediately north of the Kulwin deposit, which has just been brought into production by Iluka.

Ranking of Deposits

The issue facing Bemax is to appropriately rank the deposits to ensure that the most efficient long term strategy is followed. There are numerous aspects of each deposit, including: grade, tonnes, continuity, mineralogy, overburden ratios, water table location and groundwater quality;

as well as location, transportation and infrastructure to take into account, to assess each deposit. To date, a qualitative approach based on global resources has been undertaken. More sophisticated analysis based on “mineable resources” is now being undertaken to rank each deposit in terms of NPV. This can be undertaken only as improved geological and geotechnical data, and financial information, are obtained.

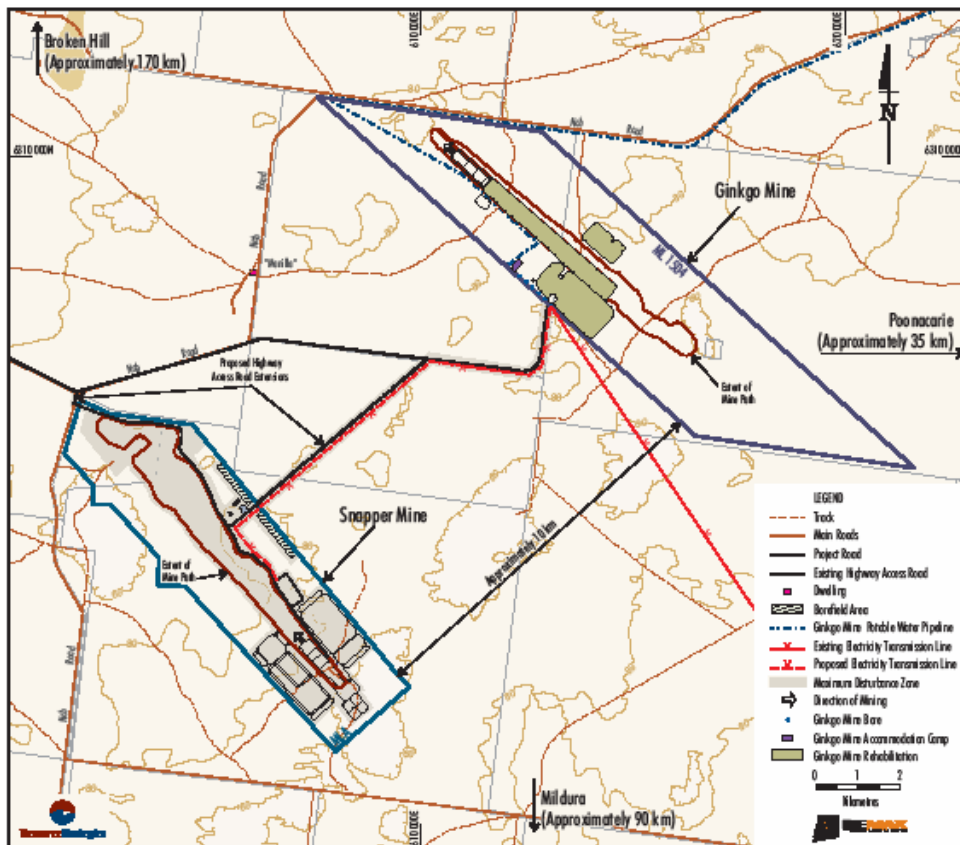


Figure 3. Layout of the Ginkgo and Snapper mines.

Infrastructure is a major issue in assessment of prospect viability. The Ginkgo Project had a Capex of approximately \$170 Million, of which 25 % was for infrastructure. Bemax had to fully fund a haul road 65 km to the Silver City Highway, as well as build a 66KV power line 125 km to the site. Lesser projects will clearly not carry these types of costs. If the benefits of these projects, and the infrastructure they provide, are recognised by governments, then assistance with funding, or assistance with access to funding, at the start up of the projects, may be a way forward.

Issues of CPRS and biobanking need to be carefully considered, as these policy decisions can have unintended retrospective negative impacts on project viability.

Progress

Bemax has demonstrated its ability to deliver projects on time and on budget. It is now a major world producer of titanium feedstock and zircon. Bemax has identified abundant resources for future growth to ensure it, and the Murray Basin, is a major, long-term supplier of mineral sands.

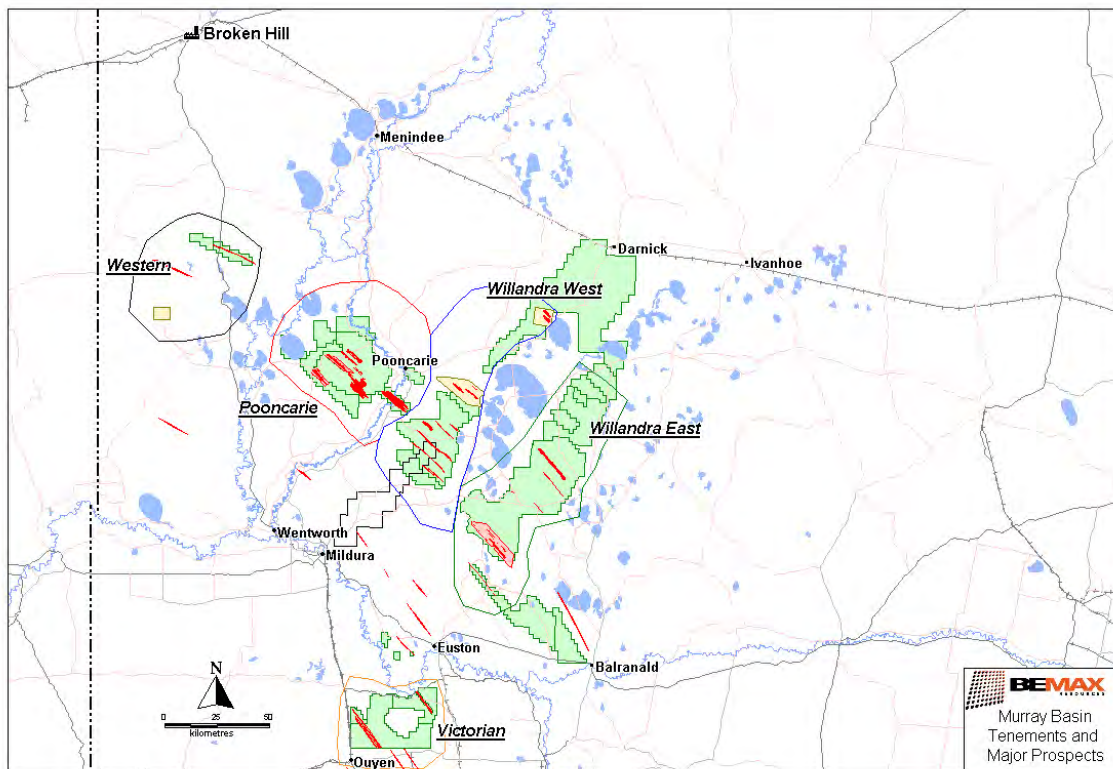


Figure 4. Bemax tenements and locations of resources.

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Reprocessing of the Broken Hill radiometric data and its impact for geological mapping

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Introduction

In 1995, Geoscience Australia acquired and released airborne radioelement data over the Broken Hill Domain covering the Corona-Fowlers Gap, Broken Hill-Taltingan, and Thackaringa-Redan airborne surveys.

Reprocessing of these survey data, to further assist geological mapping, were undertaken in early 2009 on the raw 256-channel spectral gamma-ray data. After the initial processing, and improvements in modern-style radiometric data processing techniques, such as spectral smoothing, the reprocessing produced significant improvements in data quality.

This abstract describes the processing parameters and processes, together with examples of applying the reprocessed radioelement data to better define geological units and boundaries.

Background

After consultation with Geoscience Australia (GA), the Geological Survey of New South Wales (GSNSW) contracted the radiometric reprocessing to Baigent Geosciences Pty. Ltd., based in Banjup, Perth. GA provided the original 256-channel data acquired in 1995 and GSNSW managed the contract.

The survey areas were flown during 1995 with GA's specially equipped survey plane (VH-BGE Aero Commander). The radiometric data were acquired in the aircraft with an Exploranium GR820 Self Calibrating Spectrometer, incorporating eight NaI (TI activated) crystals, with a total crystal volume of 33.6 litres. The survey was flown along preplanned east-west oriented lines, at interline spacing of predominantly 100 m, with limited areas covered with an interline spacing of 200 m and 400 m (Broken Hill-Taltingan), at a survey flying height of 60 metres. The 256-channel radiometric spectrum was acquired over a 1-second period and, depending on aircraft speed, gave a sample interval of between 60 to 80 m. Magnetic data was simultaneously acquired at a 0.1-second sample interval of between 6 to 8 m.

A ternary red-green-blue (RGB) image of the reprocessed radioelement data for the combined three areas is shown on Figure 1. The Corona-Fowlers Gap survey area (GA Project 642) lies to the north and 47,943 line km of data were acquired and released on 1 July 1995. The Broken Hill-Taltingan survey area (GA Project 617) lies over the central area and 56,310 line km of data were acquired and released on 26 April 1995. The Thackaringa-Redan survey area (GA Project

633) is the southern most survey and 55,233 line km of data were acquired and released on 2 April 1995.

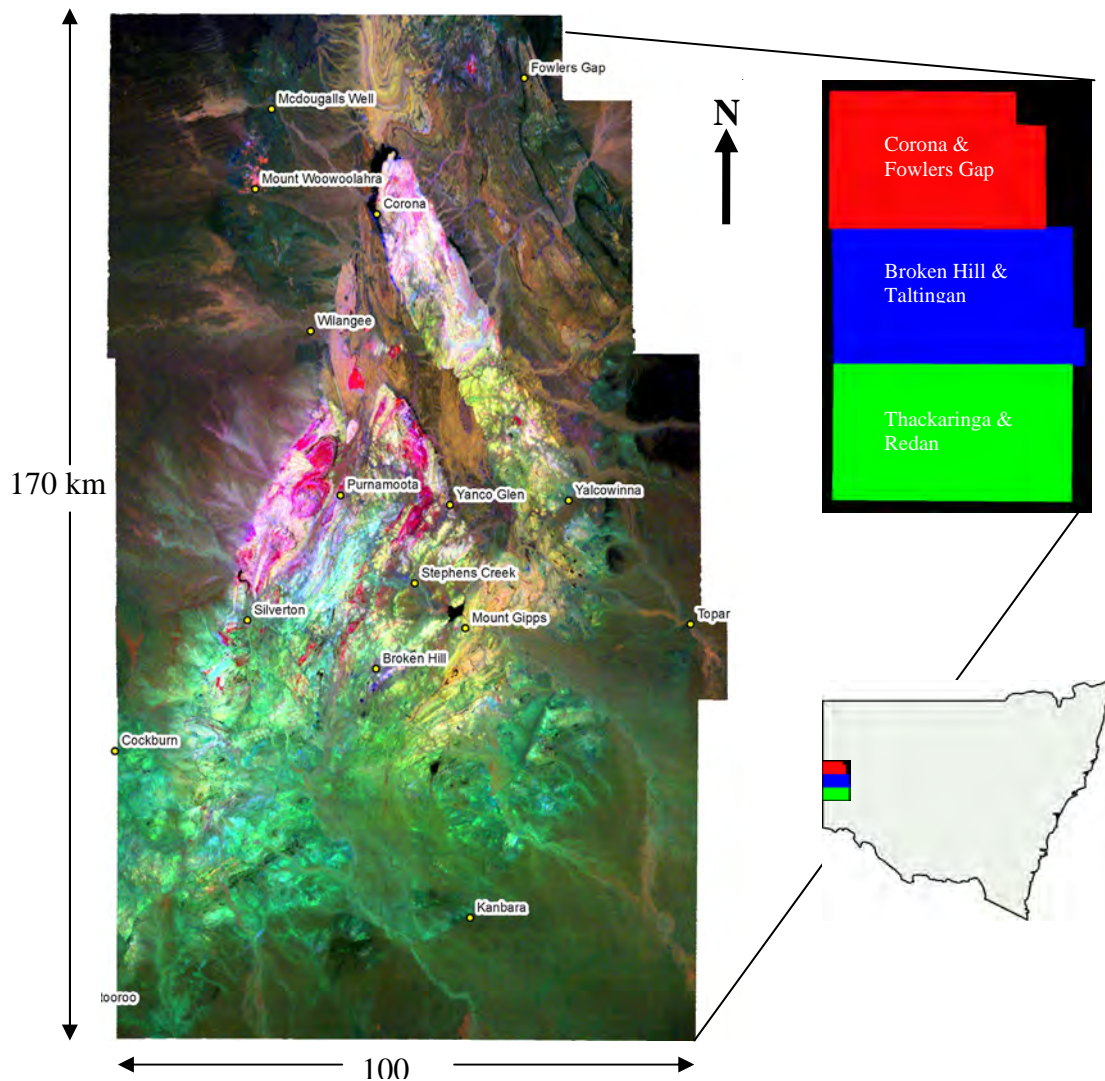


Figure 1. Ternary red-green-blue (RGB) image of the reprocessed radioelement data, with project survey legend shown in red (Corona-Fowlers Gap), blue (Broken Hill-Talingan), and green (Thackaringa-Redan) colours.

Processing

The three data sets were imported into a database where the flight paths were verified. At the time of acquisition and to adhere to the survey specifications, the survey data required many small reflights, which resulted in numerous infill lines and overlapping line segments.

The 256-channel, gamma-ray spectrum data, acquired in 1995, were used for data reprocessing in order to utilise spectral smoothing. The data processing steps included:

- Positional data editing and verification. As line overlaps often cause gridding artefacts, overlapping lines and infill lines were either trimmed by editing the spatial extents, or overlapping data values were set to null to remove them from the gridding process. The data were examined prior to editing to determine which data were the best quality to retain. Data extents were trimmed to straight boundaries.

- A parallax correction of 1.5 seconds was applied to the radar altimeter data (see below for a detailed discussion of parallax corrections).
- Radar altimeter data were checked for spikes and edited.
- Statistical noise reduction of the 256-channel data was performed using the Noise Adjusted Singular Variable Decomposition (NASVD) method (Hovgaard and Grasty, 1997). The spectral shapes output by the NASVD process were examined to determine the dominant spectral shapes. The first eight NASVD components were selected for the spectral reconstruction process.
- Smoothed 256-channel data were corrected for system dead-time.
- The full spectrum data were not initially recorded in the standard energy/channel positions, so energy recalibration was performed, in order to place the spectra in the standard energy/channel positions prior to further processing. The energy positions of thorium and potassium were used to recalibrate the smoothed spectra.
- Aircraft and cosmic backgrounds were removed from the data using full spectrum backgrounds. As the full spectrum backgrounds were not available from the survey data, good backgrounds obtained previously from another Aero Commander airborne geophysical system, carrying a GR820 spectrometer and 33.6 litres of NaI crystal, were used. It was considered that the aircraft spectrometer, body size and body composition would provide very similar background data.
- Atmospheric radon background was removed from the K-Th-U windowed data, using the method described by Minty (1992, 1996).
- STP height-corrected, spectral stripping was applied. Data were height corrected to a maximum of 250 m. Where terrain clearance exceeded 250 m, gamma-ray spectrometric data were corrected to only 250 m. Table 2 defines the stripping coefficients.
- STP height correction was applied to the K-Th-U windowed data, to the specified survey height (60 m). Table 3 defines the height attenuation coefficients.
- Tie line levelling (see below for detailed description).
- Micro-levelling (see below for detailed description).
- Radioelement data were converted from counts per second to ground concentrations, using the conversion coefficients defined in Table 1.

Radiometric Correction and Conversion Coefficients

Radiometric coefficients used for data reduction were supplied in the original survey logistics reports by Geoscience Australia (Table 2 and Table 3).

Table 1. Conversion to ground concentration coefficients.

Radiometric Window	Ground Concentration Conversion factors
Total Count	45 cps/nGy
Potassium	139.4 cps/pct eK
Thorium	7.3 cps/ppm eTh
Uranium	14.19/ppm eU

Table 2. Stripping coefficients.

Alpha	0.3047
Beta	0.3923
Gamma	0.8295

Stripping coefficients were corrected for height using the following formulae:

$$A = 0.3047 + 0.000388 * \text{height}$$

$$B = 0.3923 + 0.000911 * \text{height}$$

$$G = 0.8295 + 0.001365 * \text{height}$$

Table 3. Height attenuation coefficients.

	Total Count	Potassium	Uranium	Thorium
Height attenuation coefficients	-0.006323	-0.009365	-0.006248	-0.006156

Source of Data Errors

Data files supplied for the Broken Hill-Taltingan and Thackaringa-Redan surveys had the live-time to 10 ms interval, instead of a 1 ms precision. Thus, the live-time corrections were only corrected to 10 ms accuracy for those survey lines.

Additionally, some survey data contained live-time errors. The live-time data were spiky, and did not reflect the activity of radiometric data. In these cases, the live-time data showed unrealistically low values, thereby introducing a false high radioelement response, after live-time correction. Fortunately, these errors were not common, and did not adversely affect the quality of the gridded data. Where such errors introduced anomalous values, the affected data were reset to a value similar to that of surrounding good data values.

Most surveys exhibited some level of residual radon striping after radon removal. As micro-levelling wide bands of radon striping can lead to long wavelength ripples in the gridded data, tie-line levelling was used to remove the radon stripes before micro-levelling.

Parallax Corrections

The survey operation reports documented that the GPS antenna was positioned on the roof of the aircraft, but there was no documentation for the displacement between the GPS antenna and the gamma-ray spectrometer. As the spectrometer is contained within the body of the aircraft, it was assumed that the displacement of the position data and the gamma-ray data would be less than 2 m. Consequently, no parallax would be observable when a minimum grid cell size of 25 m was applied to the data.

There also was no documentation relating to any temporal or physical displacement of the radar altimeter data from the gamma-ray data. After correcting the gamma-ray data, flight line busts were especially evident over areas where the aircraft terrain clearance was large, and where the radiometric anomalies were large. These flight line busts are usually due to parallax effects.

When the flight line data crossed sharp linear features normal to the flight line direction, parallax effects in the gridded data also appeared as herring-bone effects in the gridded processed data. This herring-bone effect is due to the displacement (or lag effect) of an anomaly when flown in opposite flight directions. These are easily visualised through image processing, by applying a sun-angle filter parallel to the flight line direction.

The two common ways for correcting parallax effects are due either to position lag, or to altimeter lag effects. Lag effects can be due to physical displacement of measuring devices from each other, or through inherent system processing and recording time delays.

The initial investigation targeted positional lag effects. Lag was applied to the positional data in increments, in both the forward and backward directions. While some improvements occurred in some areas, other areas showed greater distortions in the data set. After testing many different

lag values, it appeared that the problem was not due to positional data, as no overall improvement was observed in the gridded data. The same testing process was then applied to the radar altimeter data.

After numerous incremental tests, it was determined that when 1.5 seconds of lag was applied to the radar altimeter data, there was an overall improvement in the resolution of the anomalies. This lag value was then applied to the radar altimeter data.

Tie Line Levelling

Tie line levelling was applied to the data by least squares minimisation, using a polynomial fit (Order 0) of the differences in data values at the crossover points of the survey traverse and tie-line data.

The least squares tie line levelling process employs a two pass Gauss-Seidel iterative scheme. In the first pass, the tie lines are first adjusted to minimise, in the least squares sense, the crossover values, with the traverse line values being held constant. In the second pass, it holds the levelled tie line values constant, and minimises, in the least squares sense, the crossover values with traverse data. The calculated DC correction values are then applied to the traverse lines and to the tie line data.

To reduce the effects of terrain-induced variations, the recorded data at the crossover points, which have a greater than specified radar altimeter difference, or a gradient exceeding a stated value on the traverse, or tie lines, are excluded from the tie line levelling process.

Microlevelling

Microlevelling was performed using an iterative process. The object of each microlevelling iteration is to produce a smooth control surface to which the traverse lines are levelled. This control surface was provided through the use of pseudo-ties.

Selective microlevelling provides greater control over the:

- intensity of microlevelling,
- wavelength of the data errors being targeted, and
- regions where microlevelling is applied.

Areas with more severe problems can be targeted with more intensive levelling, whereas trouble-free areas can be left untouched. Each levelling iteration may use parameter settings designed to target specific data errors. This microlevelling method has increased the sharpness and clarity of the boundaries within the ternary image, and has better defined geological boundaries. Such a process avoids smearing of boundaries, which often occurs in routine levelling of the entire dataset.

Selective microlevelling proceeded on the Broken Hill data sets using the following steps:

- Areas of interest that require microlevelling are identified through the use of image processing visualisation.
- Polygons are used to define areas requiring microlevelling.
- Pseudo-ties are constructed from the gridded data, by extracting traverses from the grid normal to the flight direction, at a designated interval.
- Line dependent artefacts are removed from the pseudo lines using custom filters.
- Crossover values are calculated between traverse lines and pseudo-tie lines.
- The traverse lines are adjusted in the predefined sections to minimise the crossover values.
- The above steps are repeated in order to remove various wavelength line dependent artefacts from the pseudo-ties until all flight line dependant blemishes are removed.

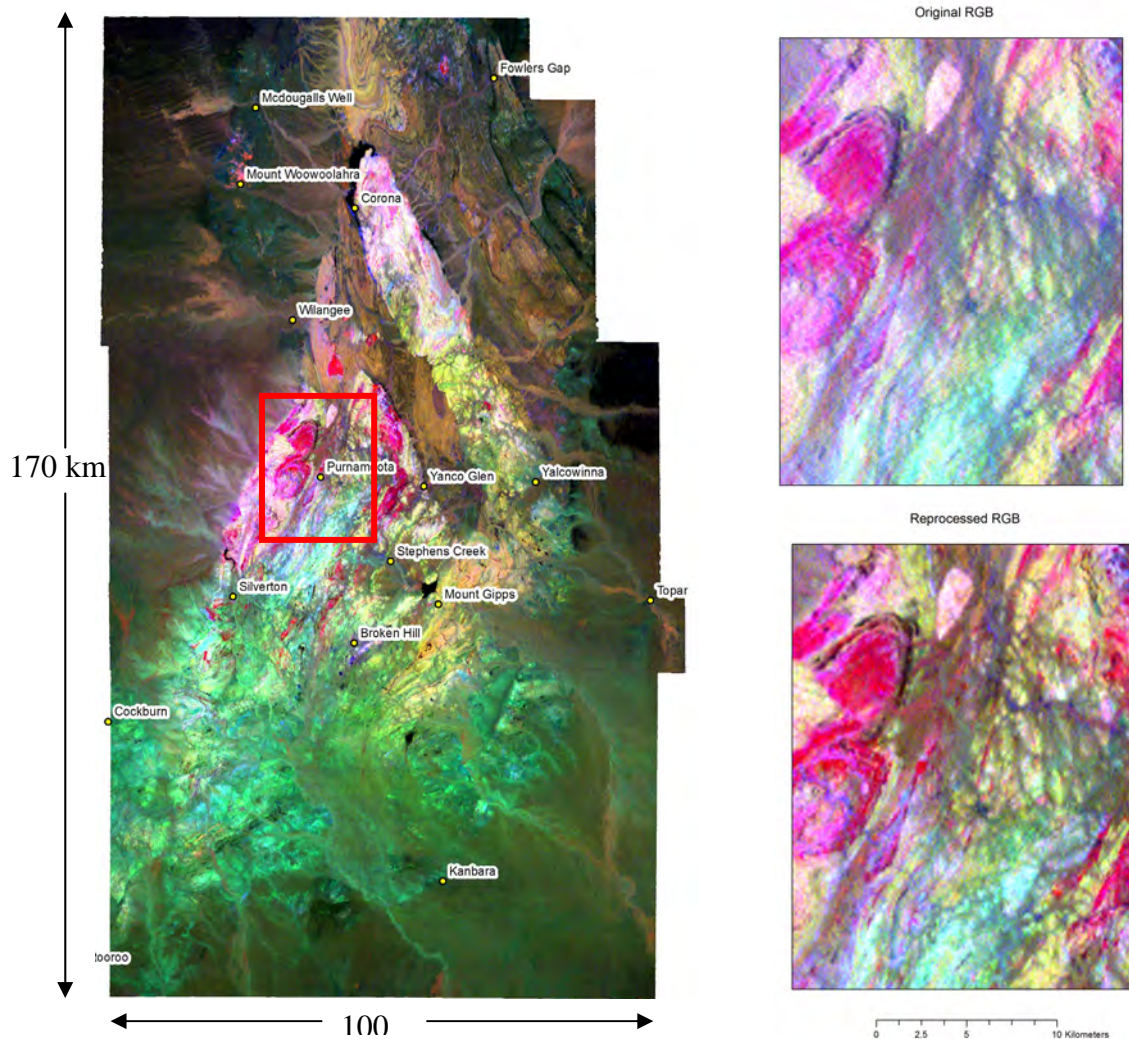


Figure 2. Extract of the ternary RGB radioelement image over the Purnamoota area (red outline). Image at top right shows the extract before reprocessing (original RGB) and the image at bottom right shows the corresponding extract after reprocessing the radioelement data.

Gridding

Final data were gridded using minimum curvature gridding, and supplied as ER Mapper grids at 50 m and 25 m grid cell sizes. The three surveys were then merged into overall grids of 25 m and 50 m. The data were supplied in GDA94, UTM Zone 54 spatial coordinates.

Reprocessing of the Broken Hill radiometric data greatly improved the gridded data quality, due to the reduction of noise in the data, and also by careful levelling techniques, such as selective microlevelling.

Results

The reprocessed airborne gamma-ray spectrometer data are displayed in Figure 1 as a ternary red-green-blue (RGB) radioelement image where concentrations of potassium (K40) are shown as red colour, thorium (Th232) as green colour, and uranium (U238) as blue colour. The brightness of a colour equates to its relative abundance. For instance, a dark red colour

indicates a low level of potassium, with little or no thorium or uranium. Bright red indicates a

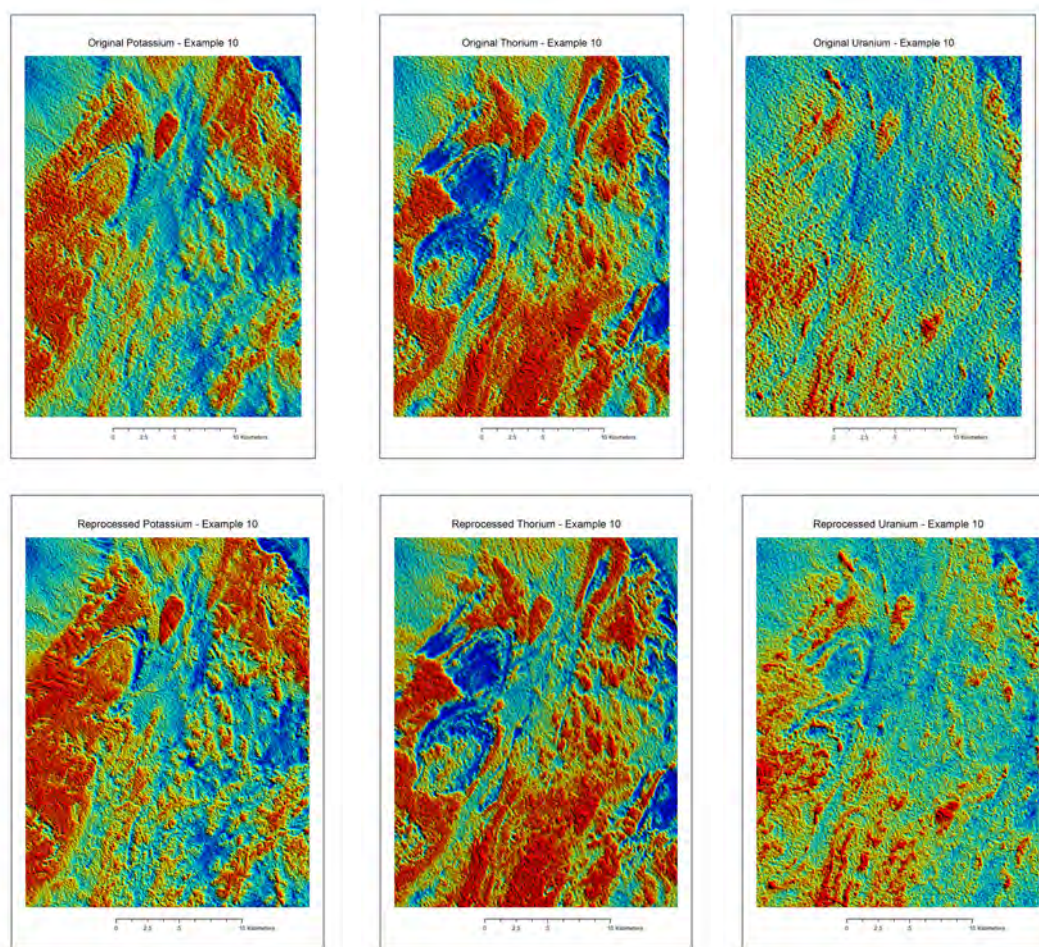


Figure 3. Extract over the Purnamoota area showing pseudocolour images of individual potassium, thorium and uranium radioelement data before (top row) and after reprocessing (bottom row) the data.

high level of potassium, with little or no thorium or uranium. The same pattern applies for the green and blue colours that, respectively, represent the thorium and uranium concentrations. When two high levels of different radioelement concentrations overlap on the same pixel of the image, the mixture of additive primaries (RGB) can produce cyan, magenta, or yellow. When all three concentrations are present in relatively high concentrations, white is produced. Conversely, when no radioelement concentrations are present, black is produced.

The mapping geologists have found the image of the ternary radioelement data useful for distinguishing outcrop from cover successions. Contrasts in and between rock units were also better identified using this imagery.

To display visually the improvement in data quality with the reprocessing, Figure 2 shows an extract over the Purnamoota area before (original) and after reprocessing the radiometric data. To help understand the improvements in the reprocessing, Figure 3 shows the same extract as in Figure 2, but with the individual channels of potassium, thorium and uranium of the before (top row) and after (bottom row) reprocessed data. In conjunction with Figure 3, Table 4 tabulates the statistics associated with each of potassium, thorium and uranium for that extract area. The reprocessed data clearly show a greater range of data, with an increase of more than

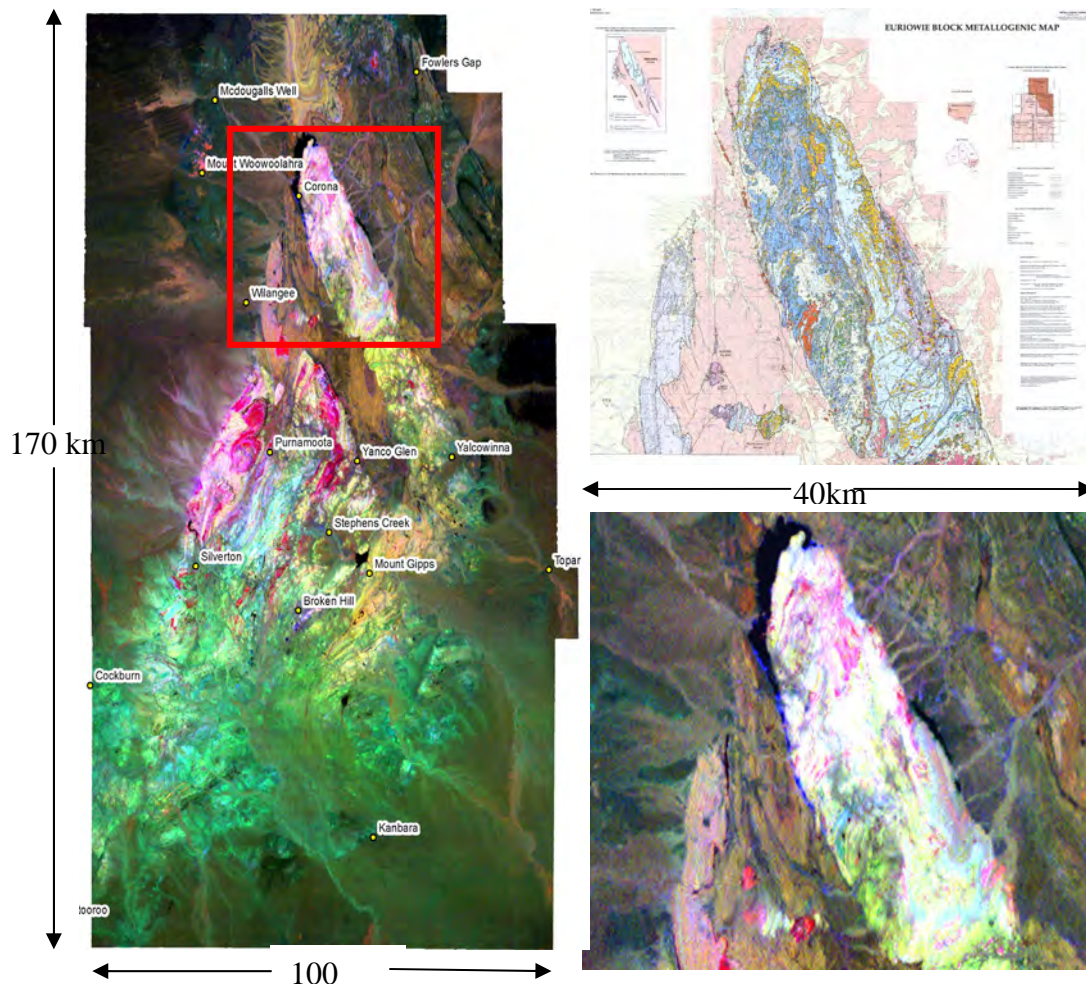


Figure 4. Euriowie Block. An extract of the northern part of the Euriowie Block (red outline on left hand figure) showing the geology map (top right) with the corresponding reprocessed ternary RGB radioelement image (bottom right).

10% (especially thorium and uranium) in overall concentrations, which were previously not defined as they were hidden within the noise of the data set. These statistics only tell part of the story of reprocessing as the improved clarity in the images is also due to spectral smoothing and judicious microlevelling, so that more of the finer features in the data are now observed.

As shown in Figure 2, the extract of the ternary RGB radioelement image over the Purnamoota area, highlights areas of bright red colour, which are indicative of areas of relatively high levels of potassium concentration, with corresponding low concentrations of both thorium and uranium. In the northwest part of the image over the Purnamoota area, the semicircular bright red zone, with a faulted southwest boundary, corresponds to the pegmatites of the Mount Robe Synform and the brown-coloured rim around the pegmatite is due to amphibolites. Northeast of the Mount Robe Synform shows a distinct rain-drop shaped white-mottled zone indicative of relatively high concentrations of potassium, thorium and uranium, which corresponds to the Mesoproterozoic Cusin Creek Granite. At the bottom left-hand side of the Purnamoota area, a dark-blue and brown coloured north-northeast trending zone corresponds to the Apollyon Valley Shear Zone and the Dalnit Bore Metasediments.

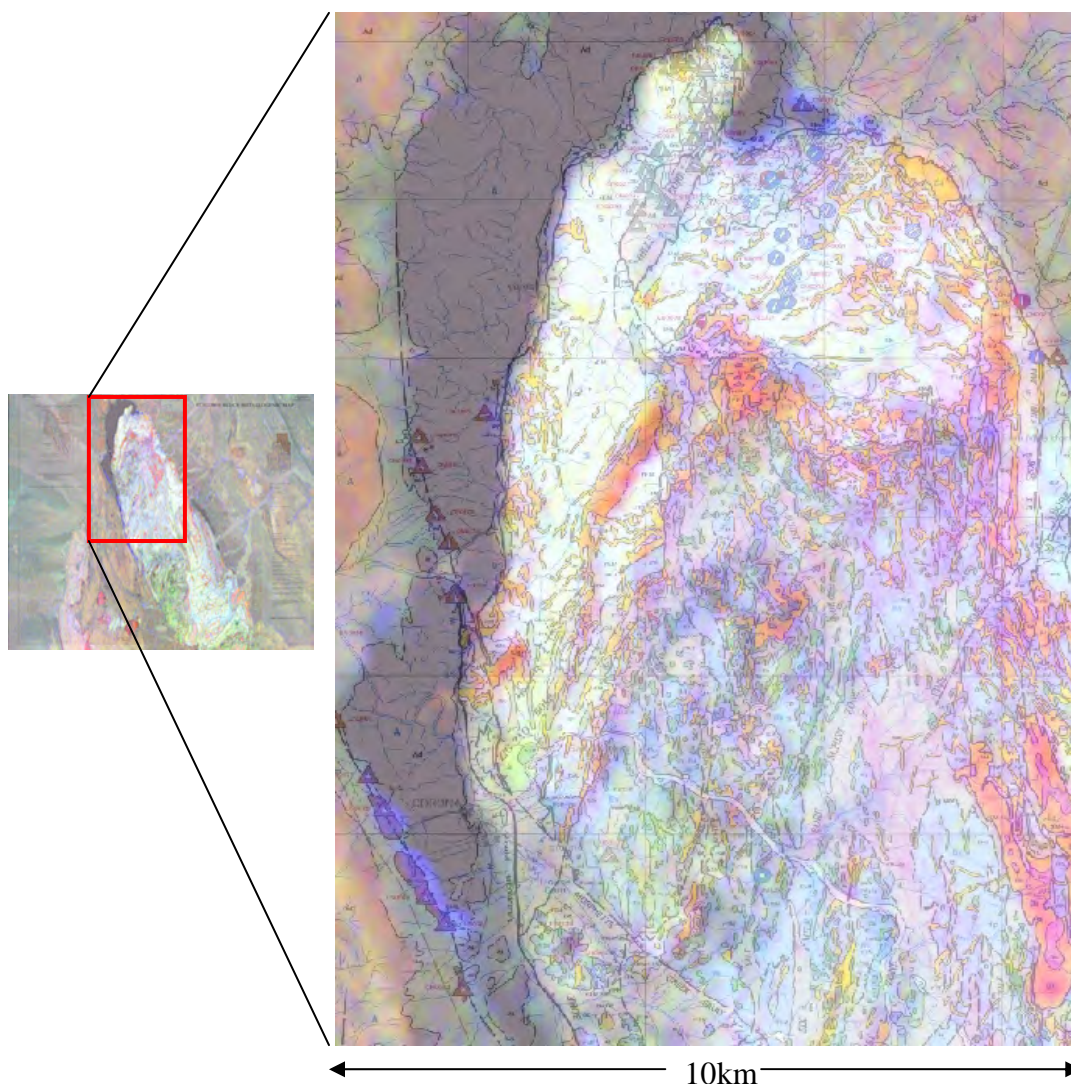


Figure 5 Euriowie Block. Most northern part of the extract of the image shown in Figure 4, showing the geology map overlain with a 50% transparent ternary RGB image of the reprocessed radioelement data.

Table 4. Extract over the Purnamoota area showing statistics of the potassium, thorium and uranium concentrations before and after reprocessing of the radioelement data.

	K% before	K% - after	Th ppm-before	Th ppm-after	U ppm-before	U ppm-after
Minimum	0.592	0.605	2.812	0.402	1.664	1.006
Maximum	4.104	4.201	34.975	39.684	12.405	15.678
Mean	2.391	2.409	16.397	15.895	3.911	3.905
Median	2.362	2.375	16.256	15.747	3.761	3./700
Std. Dev.	0.508	0.521	4.092	4.660	0.846	1.071

Figures 4 and 5 illustrate another example of the reprocessed radioelement data, by showing extracts of the northern part of the Euriowie Block with the mapped geology; Figure 5 shows a larger scale version of the northern part of the extract as shown in Figure 4. The sillimanite-muscovite-biotite grade Euriowie Block lies to the north of the Broken Hill Block, and is

straddled to the east and west by Adelaidean rocks. Overall, the metamorphic rocks within the outcrop-subcrop of the Euriowie Block, exhibit relative high and unique radioelement expressions due to differing weathering (Wilford et al., 1997; Wilford and Creasy, 2003). For instance, the leucocratic quartzofeldspathic rich pegmatite/leucocratic rocks show an identifiable red colour, implying thorium- and uranium-poor, but potassic-rich rocks. The areas around these pegmatite and leucogneisses exhibit a white colour, indicative of relatively high concentrations in potassium, thorium and uranium these correspond to mapped metasedimentary rocks and are possibly due to higher concentrations of micas. In the southwest corner of the extracts on Figure 5, the north-northwest trending, bright-blue, linear trend maps the Corona Fault, demonstrating that the fault zone is depleted in potassium and thorium, but relatively enriched in uranium. On the western and northwestern edge of the Euriowie Block, a distinctive, black-coloured zone implies low concentrations in all three radioelements; this is mapped as the Corona Dolomite.

Conclusions

In 1995, when the GA airborne radiometric surveys over Broken Hill were acquired and processed, the Noise Adjusted Singular Variable Decomposition method for processing 256-channel radiometric spectrum had not been fully developed, and thus not applied to these data sets. Thus, modern reprocessing of the Broken Hill radiometric data, with this method, has greatly reduced the noise and improved the gridded data quality. The data were then further processed with levelling techniques, such as selective microlevelling, and the resultant reprocessed radioelement data have significantly improved the sharpness and clarity of geological boundaries and units.

Acknowledgement

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Broken Hill and the Kidd Creek VHMS deposit: A comparison of giants

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Introduction

The Kidd Creek Cu-Zn-Ag deposit, in Canada, with current resources of 29.7 Mt @ 2.1 % Cu, 5.4 % Zn, 61 gpt Ag (Xstrata, 2009), combined with past production in excess of 135 Mt is, by any definition, a giant among ore deposits. Also undeniable is the origin of the orebody as volcanic-hosted massive sulfide (VHMS)-type mineralisation. At >250 Mt, the iconic Broken Hill Pb-Zn-Ag orebody is one of the few that surpass Kidd Creek in size. Despite obvious differences in the immediate geological setting of the two deposits, several distinctive characteristics of the Broken Hill orebody identified by past workers bear a striking resemblance to the Kidd Creek deposit. These similarities illustrate less about the categorisation of the deposits into comparable geological models as they do factors contributing to the formation of giant orebodies.

The Kidd Creek Deposit

The Kidd Creek deposit is located approximately 21 km north of the city of Timmins, Ontario, Canada (Figure 1). The orebody was discovered by Texasgulf Sulfur in 1963 through diamond drilling of an airborne EM anomaly in proximity to an exposure of brecciated, felsic volcanic rock (Barrie and Hester, 1999). Production from the open-cut began in 1966, with underground operations commencing in 1973. Ore is shipped directly by rail to the concentrator and smelter-refinery complex approximately 27 km to the southeast. Mineralisation extends from the surface in a pipe-like fashion to a depth of >3.1 km, with the bottom of the deposit still not defined. Mining currently is occurring at a rate of ~2.6 Mtpy, to a depth of 2.8 km, making it the deepest mine in the western hemisphere, the deepest base metal mine in the world and at the forefront of deep mining technology and innovation.

The deposit occurs in the prolific Abitibi Greenstone Belt (Figure 1), a volcano-sedimentary terrain within the Superior Province of the Canadian Shield (Jackson and Fyon, 1991; Thurston et al., 2008). In addition to copper, zinc and silver the deposit has also produced significant amounts of lead, tin, indium and cadmium. Mineralisation consists of a series of stacked, massive sulfide lenses dominated by sphalerite, pyrite and pyrrhotite (\pm chalcopyrite-galena) mineralogy (Figure 2). The sulfide lenses are underlain by an extensive stockwork of chalcopyrite-pyrrhotite stringer mineralisation (Hannington et al., 1999). Host rocks are felsic volcanoclastic fragmental and tuffaceous rocks overlying a succession of vent-proximal, high-silica, tholeiitic rhyolites (Prior, 1996). Footwall rocks consist of a thick accumulation of talc-carbonate-rich ultramafic units of likely extrusive origin, with the hangingwall consisting of a succession of massive to pillow textured mafic volcanic flows and associated intrusive rocks. The north- to northwest-trending package has been slightly overturned to the west, and plunges

steeply to the northeast (Walker et al., 1975). Its southern limit is truncated by a structural discontinuity, the “Greywacke Contact”, where the entire volcanic pile has been thrust over younger clastic sedimentary rocks. Hydrothermal alteration around the deposit is dominated by a zone of strong pervasive silicification grading laterally into a quartz-sericite (\pm pyrite-sphalerite) assemblage at its margins. Fe-rich chlorite alteration is restricted to selvages immediately surrounding Cu-stringers, although a strong Mg-rich chlorite (\pm F-rich sericite) alteration occurs within the host volcanoclastic and tuffaceous units (Koopman et al., 1999).

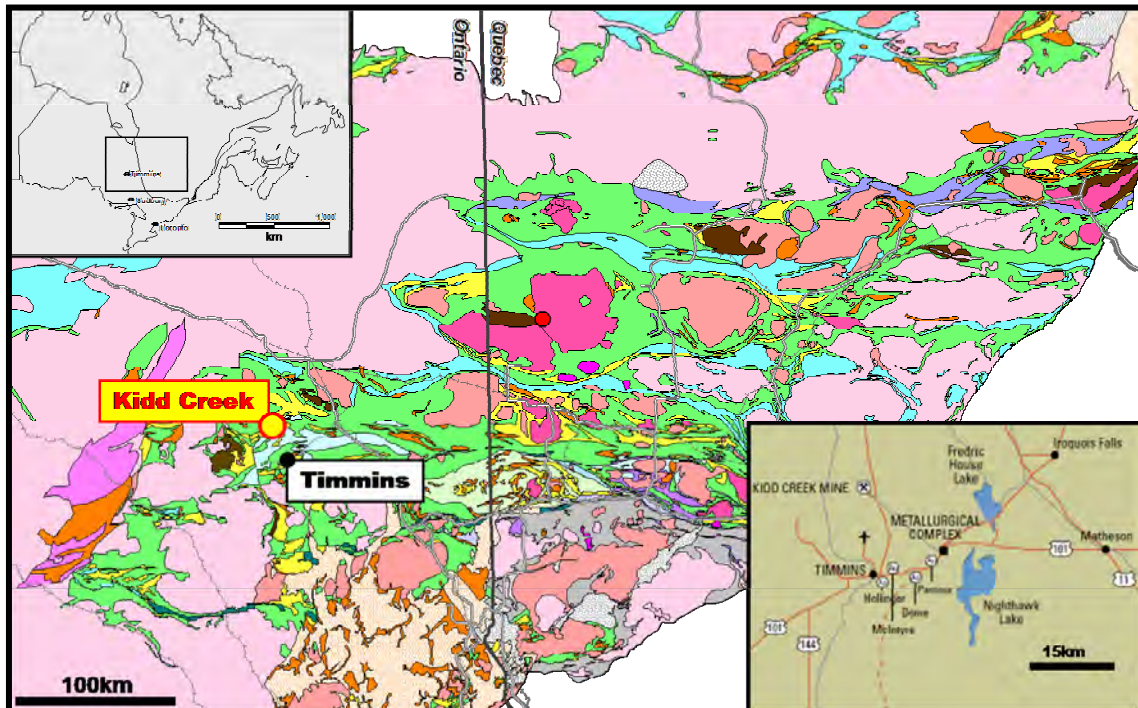


Figure 1. The Abitibi Greenstone Belt, Canada, and location of the Kidd Creek deposit.

Kidd Creek and the Broken Hill Line of Lode

Several distinctive features common to both the Broken Hill Line of Lode and the Kidd Creek deposits at both local and regional scales are interpreted to be contributing factors to their freakishly large size. These characteristics are listed below:

Sub-seafloor emplacement mechanism for the mineralisation

This is proposed at both Kidd Creek (Hannington et al., 1999; Gibson et al., 2003) and Broken Hill (Stevens, 2003; Parr et al., 2004). Although it is more contentious at Broken Hill, due to the high degree of metamorphism and deformation, the process likely allowed for a more efficient trap for the accumulating sulfide minerals with minimal loss to the overlying water column.

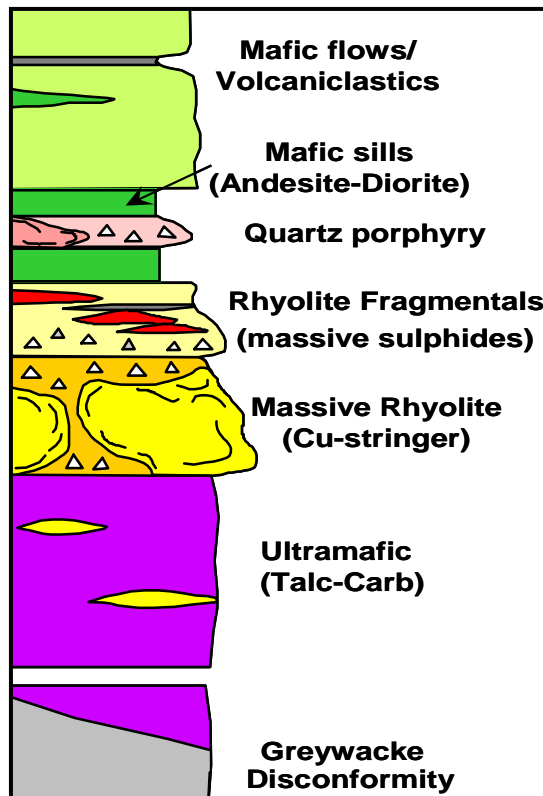


Figure 2. Idealised stratigraphic section at Kidd Creek (after Prior et al., 1999).

Strong but laterally restricted alteration around and below the deposits

This most notably involved intense silicification of the footwall rhyolites at Kidd Creek (Gibson et al., 1983; Richardson, 1998) and a quartz-gahnite and quartz-garnet envelope surrounding the interpreted mineralising feeder at Broken Hill (Groves et al., 2008). The strong silicification would serve to both insulate and isolate the hydrothermal upflow zone, allowing for sustained and focused discharge.

Apparent mantle contribution to the mineralising systems

This is evidenced by an enigmatic, ultramafic footwall at Kidd Creek (Barrie et al., 1999; Wyman, 1999) and by trace element and isotopic signatures at Broken Hill (Both and Smith, 1975; Gulson et al., 1983; Plimer, 1985; Laing, 1996). Although neither deposit displays any obvious candidate for a subsurface heat source for generation of a hydrothermal system, the mantle associations do suggest formation within a crustal scale thermal anomaly.

Igneous lithogeochemistry suggesting a geotectonic setting dominated by rapid crustal extension

This is most strikingly illustrated by the identification of low-Ti tholeiite of boninitic affinity at the Kidd Creek ore horizon (Kerrich et al., 1998; Wyman, 1999), suggestive of a subduction-related protoarc setting. At Broken Hill, highly Fe-Ti mafic rocks have been used to interpret an intracratonic rift environment the Broken Hill Block (Crawford, 2006; Raveggi et al., 2007). Although different geotectonic environments, both locations are indicative of areas of high-heat flow, deep-seated crustal structures, and generation of significant volumes of mafic magmas.

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Delamerian reworking in the southern Curnamona Province

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Constraining the thermobarometric evolution of a metamorphic event requires the identification of related mineral parageneses and distinguishing them from those that formed during prior or subsequent events. Previous studies on the metamorphic evolution of the Willyama Supergroup interpreted an anticlockwise P-T path for the Olarian Orogeny (ca. 1600 Ma), based on the replacement of andalusite- and sillimanite-bearing assemblages by staurolite- and kyanite-bearing assemblages. Studying of the metamorphic evolution of many Proterozoic terrains, however, occurred prior to the advent of *in situ* geochronological techniques which constrain the different stages of mineral parageneses. In this study, two independent geochronological techniques targeting postkinematic or late-stage growth of kyanite, staurolite and garnet were utilised. Monazite occluded by kyanite and staurolite was analysed using the chemical U-Th-Pb EPMA technique and garnet was analysed using the Sm-Nd technique. It has been shown that the development of secondary mineral assemblages previously associated with retrograde Olarian metamorphism, namely the overprinting staurolite- and kyanite-bearing assemblages, retrograde reaction textures containing garnet, and garnet overgrowths, occurred during the Delamerian Orogeny (ca. 530-500 Ma). The extent and causes of Delamerian metamorphism on the Willyama Supergroup remains unknown. Several studies have identified Delamerian-aged shear zone reactivation, implying that increased strain rates did exist during this time. Conversely, static growth of staurolite, kyanite and garnet distal to the shear zones implies that the effects of deformation may not have been as great. One possible explanation for the growth of the secondary mineral assemblages is that the basement rocks experienced prolonged heating due to the insulating effects of the overlying Adelaidean successions. This has implications for the remobilisation of mineralisation within the southern Curnamona Province during the Delamerian, as temperatures were likely well in excess of that required to remobilise metals.

Exhalative systems in the Olary Domain, Curnamona Province

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An exhalative origin has been suggested for the Broken Hill Pb-Zn-Ag deposit very early on (King, 1970; Stelzner, 1894, cited in King, 1970) and has been supported by numerous following studies (e.g. Plimer, 1983), and recent results by Spry et al. (2007) support an input from hydrothermal vent fluids, characterised by positive Eu-anomalies (Mitra et al., 1994; Cornell and Schuette, 1995). Whereas other genetic models are still discussed, the consensus at this time appears to support an exhalative or inhalative (Haydon and McConachy, 1987; Parr et al., 2004) origin of the Broken Hill ore body. Lottermoser (1989) demonstrated a distinct Eu enrichment for the sulfides at Broken Hill as well as for exhalites identified in the country rocks of the deposit, and demonstrated a decreasing positive Eu anomaly with distance to the deposit. In the Olary Domain exhalites have been identified by Cook and Ashley (1992) and were further characterised geochemically by Lottermoser and Ashley (1996). Bierlein (1995) demonstrated similar REE patterns in the Olary Domain for a quartz-barite-magnetite rock suite broadly contemporaneous with the Broken Hill Group. Our project tested whether the geochemical (REE) signature of the exhalative system can be used as a vector to the source of exhalative brines.

Samples of exhalative units from the Cathedral Rock Formation, and stratigraphic equivalents, were collected along strike over distances of 100s to 1000s of metres at Mount Mulga, Ameroo Hill and Meningie Well in the Olary Block to:

- determine the spatial variation of geochemical signatures related to the exhalative input into the Palaeoproterozoic water body
- characterise the source of the fluids and dissolved components, and
- reconstruct the depositional environment.

To achieve this, samples were analysed for whole rock major, trace and rare earth element composition, initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios and $\delta^{34}\text{S}$.

The most significant chemical signature detected is the REE patterns (Figure 1). The overall REE content resembles that of crustal rock types, with an overall abundance of REE <2800 ppm, and a slight enrichment of LREE over HREE. The most pronounced feature is a distinct enrichment of Eu ($\text{Eu}/\text{Eu}^* \leq 64$) and at the same time a slight negative Ce anomaly ($\text{Ce}/\text{Ce}^* \geq 0.75$).

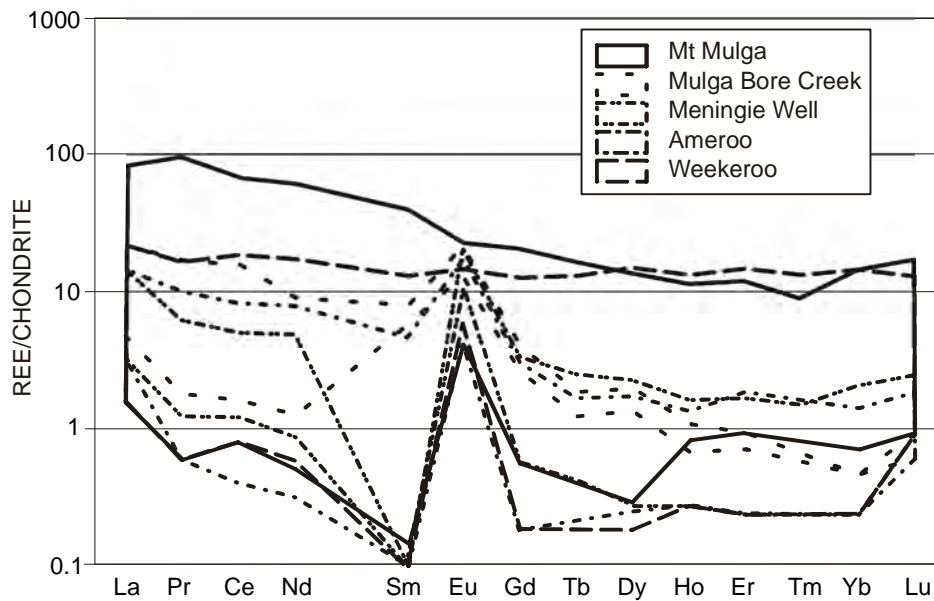


Figure 1. Summary diagram of REE patterns from exhalite-containing strata in the Olary Province.

Initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of selected samples of stratiform barite range from 0.708364 to 0.725991, with a distinct peak at 0.709 to 0.7095, and a trail of data to higher values (Figure 2). $\delta^{34}\text{S}$ ratios of barites range from 13.8 to 15.5 ‰ and correlate reasonably well ($\rho = 0.9876$) with the $^{87}\text{Sr}/^{86}\text{Sr}$ data.

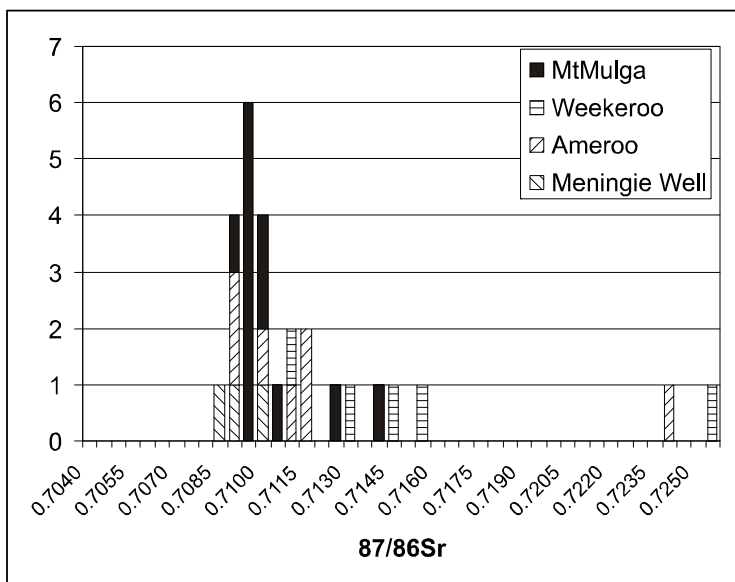


Figure 2. $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of rocks from the exhalite bearing units

The recorded GPS coordinates of samples were used to investigate the geochemical data set for systematic spatial relationships. Since the Eu/Eu^* was identified as an indicator value for the exhalative input, we tested this value for its spatial relationship to an inferred source point defined by the most pronounced occurrence of barite (e.g. the Mount Mulga barite deposit), or

the occurrence of massive quartz-magnetite bodies. The plot of the Eu/Eu^* values against the calculated distance from the source shows a distinct systematic variation (Figure 3). This is most prominently expressed in the sample sets from profiles along strike of the barite bearing units of the Mount Mulga barite (solid square) to the southeast (solid triangle) and northwest (solid diamond). A similar trend is seen in the spatial variation of the Ce/Ce^* ratios, where proximal samples have a distinct negative ratio, gradually changing to a distal positive ratio (Figure 4).

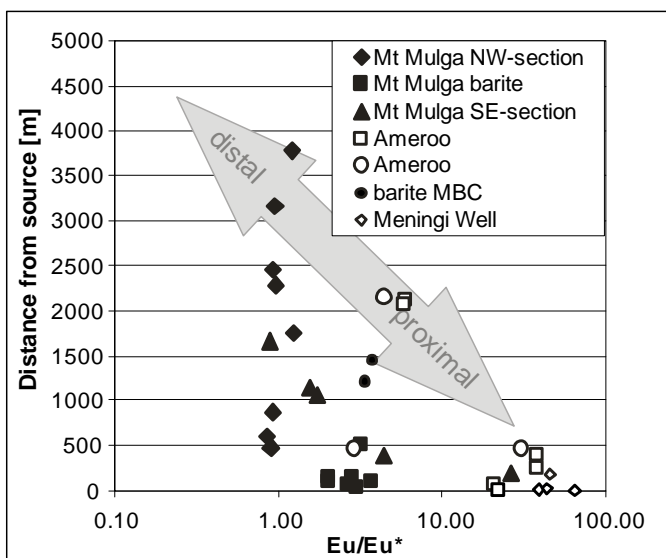


Figure 3. Spatial variation of Eu anomalism

These variations cannot be ascribed to the barite content in the units, as Ba content does not correlate with the Eu/Eu^* or Ce/Ce^* values ($\rho_{\text{Ba}/\text{Eu}} = 0.1370$ and $\rho_{\text{Ba}/\text{Ce}} = -0.5595$). In fact, at the Mount Mulga southeast section, the Eu/Eu^* point to a source with higher values than those of the barite deposit.

Similar procedures applied to the Ce/Ce^* values produce comparable results, which more prominently demonstrate the environment in which the mineral precipitation occurred due to the redox sensitivity of Ce mobility.

The data allow an environmental reconstruction for the conditions of mineral deposition. We can confidently assume that the ambient seawater was oxidised, as evident from the common presence of stratiform barite in the investigated units, and is well reflected in the heavy sulphur isotope ratios of the barite. The $^{87}\text{Sr}/^{86}\text{Sr}$ are in agreement with earlier data (Lottermoser and Ashley, 1996) and are markedly above average sea water at the time (Veizer, 1989), and thus a purely marine source can be excluded and a crustal influence (lower Willyama Supergroup?) is inferred. The mineralising fluid is thus suggested to have been derived from the underlying Lower Willyama Supergroup. Mineral-forming fluids were reduced and enriched in Ba^{2+} and Eu^{2+} , resulting in barite precipitation and the pronounced positive Eu anomaly upon mixing with the ambient, oxidised waters. Similarly, variation of the Ce anomaly can be ascribed to the proximal influence of reduced hydrothermal fluids producing slightly negative Ce anomalism, whereas distal precipitation shows no or slightly positive Ce anomalism as expected from an environment dominated by oxidised water (Kuhn et al., 1998).

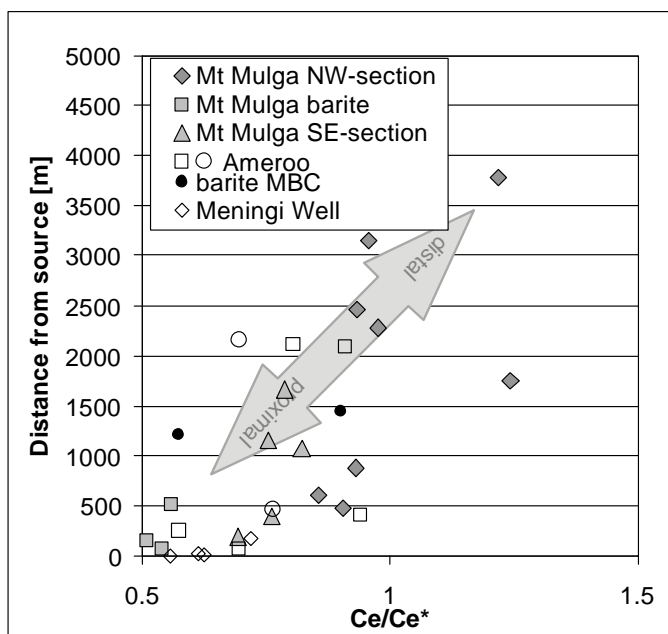


Figure 4. Spatial variation of Ce anomalism

The systematic spatial variation of these geochemical signatures can be used to generate vectors to the source of the mineralising fluids.

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CALLABONNA 1:250 000 scale area: maps and report

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The CALLABONNA 1:250 000 scale area in northeast South Australia remained one of the few Atlas Series regions not covered by first pass, ground-checked, geological mapping until 1989. Over the next decade, mapping involved two primary geologists with assistance from several colleagues. Crystalline basement (Curnamona Province: Mount Painter and Mount Babbage Inliers) and metasedimentary rocks of the Adelaide Geosyncline form the northeast Flinders Ranges. Those rocks were mapped at 1:20 000 scale to produce two detailed special issue maps: Moolawatana 6838-III (1:50 000 scale digital geology; Sheard, 1994) and Northern Flinders Ranges Geology (1:75 000 scale digital geology; Sheard et al., 1996). Elsewhere was mapped at 1:87 000 to produce six 1:100 000 scale digital geological maps (Figure 1); together, these provided a base for the CALLABONNA 1:250 000 scale Geological Atlas map (Sheard and Callen, 2000). Staff redeployment and retirements in late 1996 brought a halt to further work. A synthesis recommenced in late 2008, however, leading to the completion of the Explanatory Notes (Sheard, 2009).

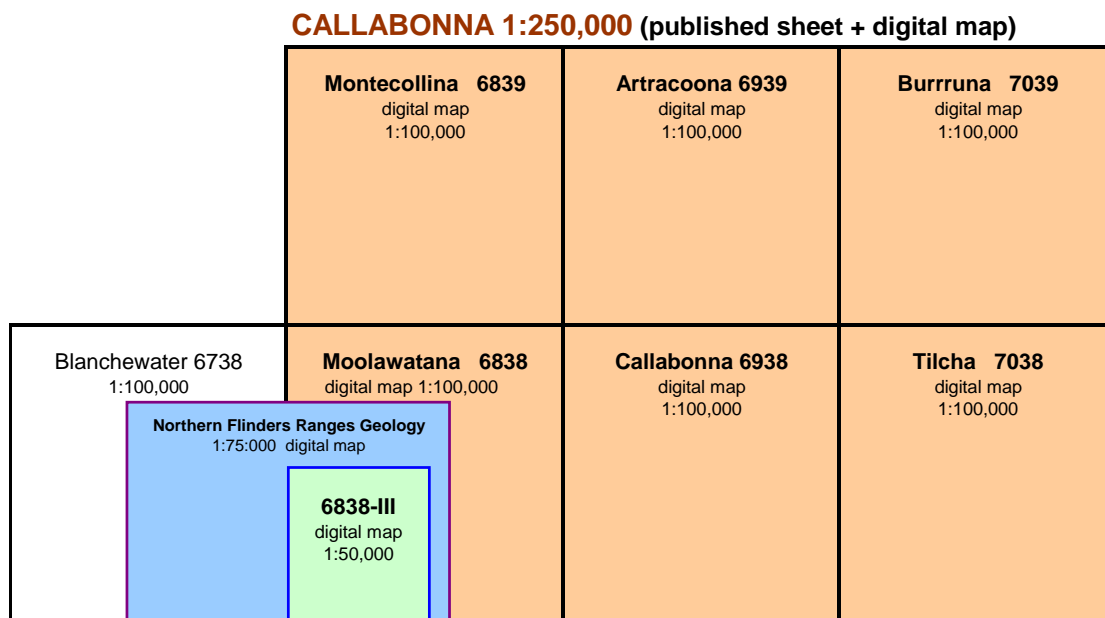


Figure 1. Map products released as part of the CALLABONNA mapping project.

The CALLABONNA map includes the southern end of Strzelecki Desert and northeast Flinders Ranges between latitudes 29° to 30° S and longitudes 139° 30' to 141° E. Its eastern boundary adjoins New South Wales and the northeast corner adjoins Queensland. This region is broadly flat and predominantly covered by longitudinal northeast- to north-trending seif dunes. The Flinders Ranges form highlands within the southwest corner of this region. The Ranges consist of highly-deformed, Paleoproterozoic metasedimentary rocks, variably deformed Mesoproterozoic granitoids and volcanics (Mount Painter and Mount Babbage Inliers); and folded Neoproterozoic metasedimentary rocks of the Adelaide Geosyncline. Surrounding the ranges are plains, underlain by sedimentary rocks of the Cambrian Arrowie Basin, Cambro-Ordovician Warburton Basin, Carboniferous-Permian Cooper Basin, Mesozoic Eromanga Basin and Cenozoic Lake Eyre Basin.

Fossils include Neoproterozoic stromatolites, Cambro-Ordovician trace fossils, Permian shelly fauna and trace fossils, carbonaceous flora and coal (Cooper Basin), Mesozoic shelly fauna and animal burrows, calcified wood and coal (Eromanga Basin), Cenozoic animal burrows, bones and teeth, leaf impressions and lignite, and spectacular bones from the once abundant Quaternary Australian Megafauna (marsupial *Diprotodon* sp. and tall flightless bird *Genyornis newtoni*).

Exploration since 1870 has located As, Co, Cu, Pb, Mo, REEs, Sn, U, W and Zn mineralisation, along with trace Au, Ag and Nb. Nonmetallic extractive minerals include: talc, dolomite, magnesite, muscovite, celestite and fluorite. From those, mining has extracted copper, talc, dolomite and muscovite.

More recently, mineral exploration in this area has involved a number of companies searching for hard rock sourced and sedimentary uranium (Beverley and Four Mile deposits to the south on COPLEY), Cu-Au and Cu-Mo (Parabarana Hill and areas south), and tin at Prospect Hill.

Geothermal energy in this area has potential for exploitation, because of locally and regionally high thermal fluxes, and buried crystalline basement containing unusually abundant REEs. The drilling of a geothermal exploration well by Petrotherm Limited, east of Arkaroola on the adjoining COPLEY map sheet area, is currently underway. Other geothermal exploration wells in this area are planned.

Groundwater is a valuable commodity and is exploited by pastoralists, mineral explorers and miners, and wildlife.

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Crocker Well Uranium Project

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Project History

The Crocker Well Uranium Project is located on Plumbago Station approximately fifty kilometres north of Manna Hill in the northeastern Olary Domain. Crocker Well was originally discovered by the South Australian Department of Mines and Energy (SADME) following up regional radiometric anomalies from a survey flown in 1951. In the 1950's, drilling and exploratory shafts identified an anomalous area of 4 x 1 km (Campana and King, 1958). In the 1970's, Esso Australia Ltd. undertook further exploration work and defined four principal deposits (Original, Junction, Central and East) within this area.

In 2005, PepinNini Minerals Ltd applied for the then vacant Bimbowrie exploration licence primarily for copper-gold and base metals, but which also covered the Crocker Well and Mt. Victoria uranium deposits. In September 2005, Hellman Schofield completed an inferred JORC compliant resource for Crocker Well based upon the historical drilling data estimating 12.4 Mt at 0.05 % U₃O₈ resulting in 6293 tons of contained U₃O₈. In April 2007, PepinNini entered into a strategic alliance with Sinosteel Corporation to jointly develop the Crocker Well resource. Under the terms of the Joint Venture, Sinosteel acquired a 60% stake of the project and a Joint Venture company SPCM Pty Ltd. was set up for the ongoing management of the project. The joint venture's plan is to commence commercial production in 2011 subject to regulatory approvals.

Geology

The local geology, which has >40 % outcrop, consists of sodic, peraluminous granites and high-grade sodic-felsic gneisses, interpreted to have originated as alkaline volcano-sedimentary rocks, which maybe correlated with the lower suites of the Willyama Supergroup. The host granites, which have restricted SiO₂ and contain high Na₂O, U, Th, Nb, Ce, Y and F with low K₂O, CaO, Rb, Ba, Sr and ferromagnesian elements, are considered to have been derived by anatexis during high-grade metamorphism (Ashley, 1984). The typical mineralogy is opalescent blue quartz, albite, and biotite with accessory apatite, monazite, zircon, galena, pyrite, magnetite, rutile and sphene. The timing of granite emplacement has been calculated at ~1580Ma (Ludwig and Cooper, 1984; Cook et al., 1994).

The dominant uranium mineralisation phase is coarse-grained thorian-brannerite, with minor coffinite and uraninite. Uranium-thorium mineralisation is closely associated with an elongate complex of white, massive F-rich phlogopite-bearing trondhjemite grading to sodic-alaskite, which extends in east-west orientation within a geological setting of more potassic regional granitoids and subordinate sodic-felsic gneiss. The alaskite phases appear as distinctly separate late stage dykes, veins and irregular sheets which fill fractures and steeply dipping veins. In addition, there are localised areas of phlogopite breccias containing clasts of both trondhjemite and alaskite. Within the trondhjemite body are large xenoliths consisting of

migmatitic gneiss and earlier intrusions of granodiorite composition. Pervasive hydrothermal alteration has not occurred aside from minor localised, structurally controlled rehydration during subsequent low-grade events.

Ashley (1984) proposed that, as the granite was crystallising, there was a separation of F-rich fluid phases containing certain high-field strength ions, which invaded fractures in the apical region of the intrusion. The thorium-brannerite was thus deposited contemporaneously as the granite cooled, and the HF fugacity decreased in mechanically induced fractures and breccia bodies in the sub-solidus state. Higher grades of U-Th mineralisation formed in intensely developed fractures zones and in breccia bodies. Ashley (1984) considered that this process has affinities with porphyry copper and stock-work Mo deposits, although the relatively deep (~7-10 km) depth of crystallisation would have subdued the commonly associated effects of pervasive hydrothermal alteration.

Bankable Feasibility Study

The Crocker Well Project is currently in the final stages of a Bankable Feasibility Study which is being undertaken by Bateman. During the last two years, a total of 19 core holes (1938 m) and 294 RC holes (29,658 m) have infilled and validated the Crocker Well deposits such that sufficient inferred resources can be converted to higher level JORC-complaint categories, with the aim of sustaining an initial mining phase of approximately seven years at 300-400 tons U₃O₈ per annum. The final JORC compliant report by Hellman Schofield, which incorporates this new information, is anticipated shortly.

Brannerite is well known as a difficult mineral to process. Substantial metallurgical test-work has been undertaken by Amdel and ANSTO, which have succeeded in obtaining recoveries of 80%. The proposed mining process will extract ore from six shallow open-cut pits of less than 100m depth. The ore will be milled to 106 microns before beneficiation using flotation, which rejects 80% of the mass but which retains 90% of the uranium. The retained mass will be subsequently ground to 40 microns before hot sulphuric acid leaching at atmospheric pressure. After filter-press separation of liquids from solids, solvent extraction will be undertaken using Bateman Pulsed Column and mixer-settler strip circuit technologies to produce yellowcake slurry ready for drying and packaging on site.

In August 2008, a Referral was lodged under the Australian Government Environment Protection and Biodiversity Conservation Act for the development of Crocker Well and a Mining Lease application was submitted to the South Australian Government in September 2008. Regulatory approvals and Environmental Impacts Studies are currently being prepared under the guidance of the regulatory bodies and consultants at URS and KBR.

Exploration

Since the 1970's, there has been no new uranium exploration in the Crocker Well region, although the prospectivity of discovering additional similar styled resources is considered high, and numerous untested anomalies have been identified within close proximity to the proposed mining operation. Recent geophysical surveys have been acquired, including infill gravity (1 km x 1 km) and high resolution magnetics-radiometrics collected on 50 m traverses regionally and 25 m traverses over the immediate Crocker Well area. Rock chip results at a number of radiometric anomalies have returned high uranium values (e.g. Becaroo Prospect up to 2.6 % U₃O₈). The aim of these surveys was not only to identify additional radiometric anomalies but to discern the structural architecture and geological model of the region, to enable potential discoveries where radiometrics are masked by shallow cover. The geochemical signature associated with the exotic sodic-fluorine-rich host also has potential application as an exploration tool to discover additional mineralisation beneath shallow cover. Drill testing of these new targets is scheduled for later this year. The 2008 infill drilling did discover additional

mineralisation extending at depth beneath the Junction Deposit. The economic viability of this mineralisation requires further assessment.

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New interpretation maps of the Willyama Supergroup, Broken Hill, NSW

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Introduction

An interpretation map of the Precambrian of far western New South Wales has been constructed, and will be available in digital form at two scales: 1:25 000 and 1:100 000. The author prepared the Early Proterozoic Willyama Supergroup section of this map (Figure 1).

Map Concept

The most recent, previous maps of the Early Proterozoic areas are 1:25 000 lithological maps that show rock types, rather than stratigraphy, and the 1:100 000 Broken Hill Stratigraphy Map (Willis et al., 1989), which only shows stratigraphic units and ignores many intrusive rocks, notably masses of pegmatite. The new map is constructed in the same manner as a standard map from a Paleozoic area, in that it shows stratigraphic units and intrusive rocks. Where it differs from a standard map, however, is that it attempts to remove the alluvial cover and shows solid geology.

New Stratigraphic Interpretation

An important input into the new map is the updated stratigraphic interpretation, resulting from zircon geochronology, geochemical and petrological studies into the origins of Broken Hill rock types (Figure 2). This has resulted in significant changes from the Willis et al. (1983) and Stevens et al. (1983) stratigraphy, notably:

- The granite gneisses are now interpreted as granite sills emplaced, at high levels, during deposition of the sedimentary succession. Thus, they are now part of the Silver City Suite of intrusives, and are no longer a part of the Thackaringa Group (Stevens et al., 2008).
- The basic gneisses (amphibolites and hornblende granulites) are now interpreted as very high level sills and related feeder dykes, emplaced at around 1690 Ma, during deposition of the sedimentary succession. As such, they can no longer be used in the definition of stratigraphic units, although sills may assist locally in identifying particular stratigraphic levels.

The resulting changes in nomenclature have been difficult for the users of previous nomenclature to digest. Changes in the way that these rock types are interpreted, however, may present new opportunities for exploration. Specifically, the emplacement of relatively hot granite magma at high levels in the sedimentary pile, and emplacement of very hot, fractionated tholeiitic magma into probable wet sediments provides an interesting combination of heat sources and fluids. Change is inevitable – get used to it.

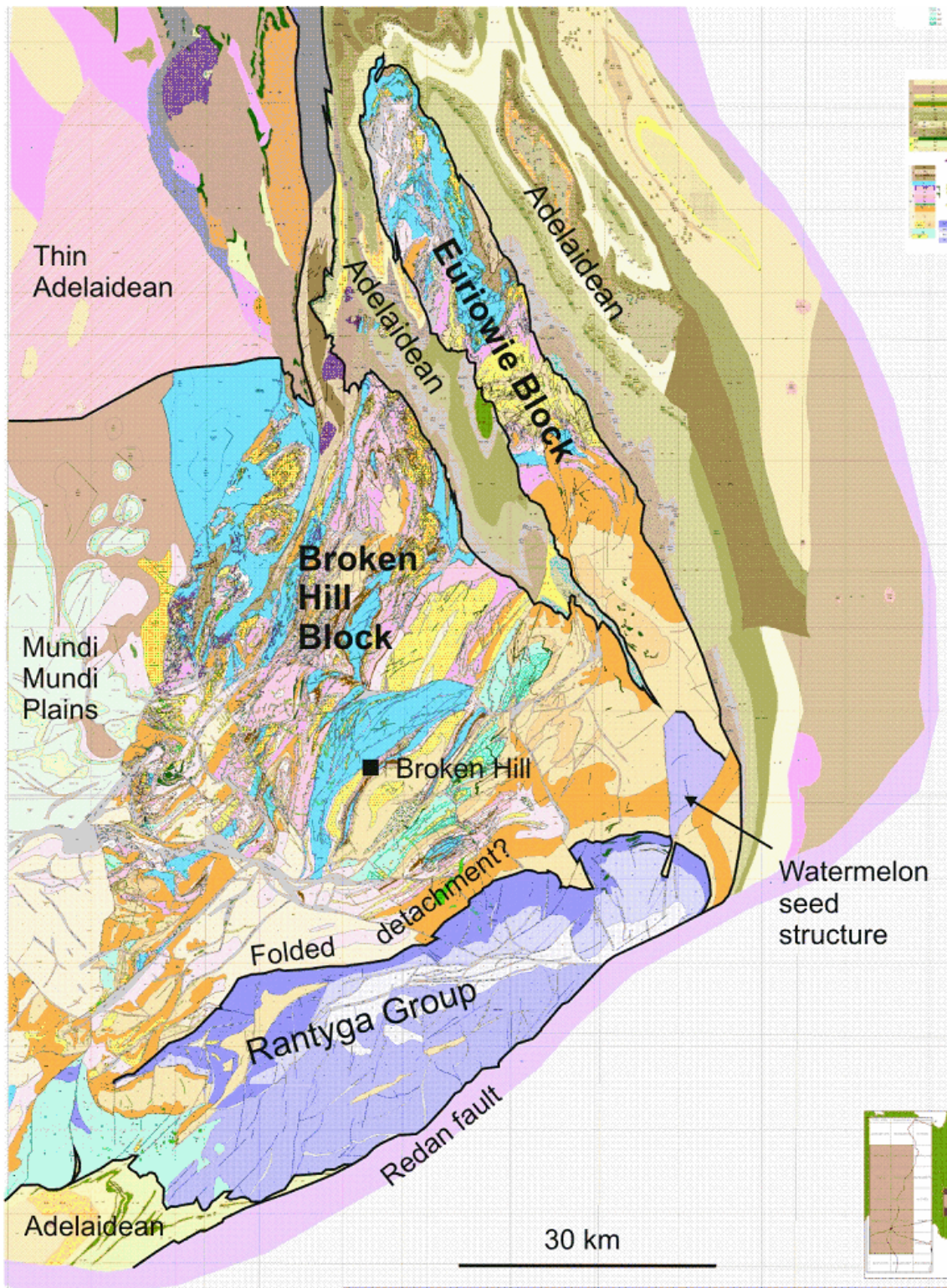


Figure 1. Southern half of the far western NSW Precambrian interpretation map.

BROKEN HILL BLOCK- EURIOWIE BLOCK

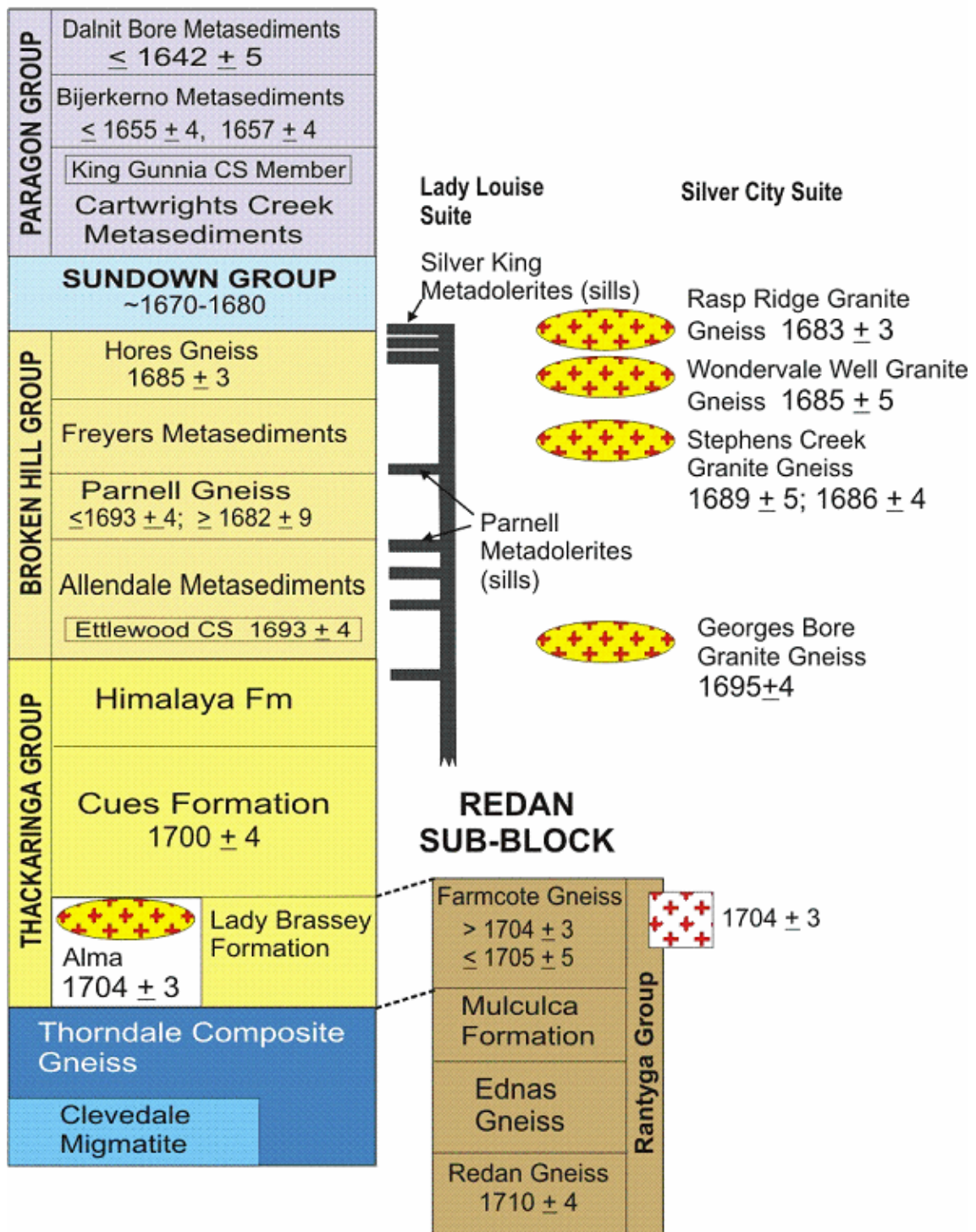


Figure 2. Stratigraphic column for Broken Hill and Euriewie Blocks, but not including the Curnamona Group under Mundi Mundi Plains.

New Igneous Stratigraphic Nomenclature

Following Geoscience Australia guidelines, the metaigneous rocks in the succession are dealt with in the following manner.

The Potosi Supersuite (Wyborn et al., 1997) includes all of the S-type granitic rocks and acidic volcanic rocks emplaced in the interval ~1705-1680 Ma. The Silver City Suite (Stevens et al., 2008) contains all of the granite gneisses, and the Barrier Suite contains the metavolcanic rocks, that is, the Potosi-type gneiss and leucogneiss in Cues Formation, the Hores Gneiss in Broken Hill Group, and possibly the Parnell Gneiss, if it is found to be volcanic in origin.

The metavolcanic units, Hores Gneiss and possibly Parnell Gneiss, have dual roles, being part of the igneous suite, but retaining their stratigraphic names.

The basic gneisses (amphibolites and hornblende granulites), interpreted as metamorphosed tholeiitic intrusions, constitute the Lady Louise Suite (named after a location in the Olary Domain). Two individual groups of sills within the Lady Louise Suite have unit names: the Parnell Metadolerites (immediately below and above the Parnell Gneiss), and the Silver King Metadolerites (intruding uppermost Broken Hill Group). It is not clear whether the Lady Louise Suite should also be included in the Potosi Supersuite.

Map Construction Process

The main building blocks for the interpretation maps of the Willyama Supergroup were the mapped geology and specially prepared aeromagnetic images. The most useful presentation of the aeromagnetic data was found to be a combination of the following:

- Total Magnetic Intensity, in colour, most useful for delineating different domains.
- Second vertical derivative in greyscale, depicting near-surface features in great detail.
- Second vertical derivative contours, helping to pinpoint the near-surface features.
- Flight lines, allowing the distinction between magnetometer fact and computer-gridding fiction.

In addition, gravity data were useful in places. Drilling data were used sparingly, since examination of all such data would have greatly increased compilation time.

Reliability

Reliability of the map varies from place to place. In the most reliable areas, the stratigraphy has been interpreted from detailed mapping of exposed geology, supported by zircon geochronology (Page et al., 2005; Stevens et al., 2008). In the most unreliable areas, there is little or no outcrop and the stratigraphy has been interpreted from the aeromagnetic images. In a number of places, there is insufficient information to make an informed judgement, and the interpretation can be considered a slightly informed guess.

In some local areas, where there is little outcrop and considerable drilling (e.g. the North Tank prospect), the interpretation might be considerably improved by consulting the drill data.

Difficulties: The Parnell Gneiss

The Parnell Gneiss is a very significant stratigraphic marker horizon, but tends to be very thin and discontinuous, and difficult to portray at 1:100 000 scale. In its type area, it is sandwiched between two amphibolite units, here named the Parnell Metadolerites. On the interpretation maps, the Gneiss and the enclosing Metadolerites are shown as a single unit (Bp). Where the

Parnell Gneiss is absent, its position can be inferred by the presence of metadolerites, interpreted to be the Parnell Metadolerites. In such areas, the package is given the letter symbol aBp (with amphibolites representing the Bp package).

So What is New?

Comparison is made with the 1989 map. The 1989 map was a stop-gap one, incomplete, and out of date, before it was printed. Continuing mapping led to reinterpretation of local areas, even before the stratigraphy was revised.

The depiction of the new stratigraphy is a new element over the whole of the map. In some areas, the depiction of the stratigraphy is quite similar to that on the 1989 map, except that the new map shows the interaction between stratigraphy and pegmatite masses. These masses are largely confined to the Thackaringa and Broken Hill Groups.

The much greater extent of the Rantya Group (Redan Gneiss to Farmcote Gneiss) (Figure 1) is indicated by the aeromagnetics. Geophysical modelling (Tucker 1983) indicates that the magnetic Rantya Group dips northward below the main part of the Broken Hill Block. Stevens and Corbett (1993) observed a conformable relationship between the Rantya Group (their Redan Geophysical Zone) and the remainder of the Willyama Supergroup. The new map, however, suggests an acute angle discordance in the northern part, and intermingling or feathering-out in the southwest. The above features might be explained if the boundary acted as a detachment during the 1705-1685 Ma crustal extension, which created the depositional space for the Thackaringa and Broken Hill Groups. Crustal extension led to mantle melting, resulting in emplacement of tholeiitic magma.

The watermelon seed structure (Figure 1) at the northeastern end of the Redan Geophysical Zone (Rantya Group), may result from a Paleozoic collision, which wrapped the Koonenberry Belt around the Precambrian promontory, or it may be a horst block left behind after 1705-1685 Ma extension.

The northern part of the Euriowie Block was blank on the 1989 map, but now shows interpretation.

There is no outcrop on the Mundi Mundi Plains, but aeromagnetics and drilling have permitted interpretation, partly after CRA Exploration Pty Ltd (Figure 3).

Similarly, aeromagnetics and drilling have allowed interpretation of covered areas of the Stephens Creek 1:25 000 Sheet. The eastern part of the Mount Gipps 1:25 000 Sheet is interpreted from aeromagnetics, with little assistance from mapped geology.

Many shear zones that crop out poorly, can be seen in their full glory on the aeromagnetic images (e.g. Pinnacles 1:25 000 Sheets, Figure 4). The new interpretation map allows for an analysis of the shear zones, something apparently not attempted before.

The depiction of the tholeiitic and alkaline basic dykes provides valuable information on relatively young (post-dyke) shear zone off-sets (e.g. Figure 5).

There is some clarification of the geology to the south and southwest of the Broken Hill orebody. It has long been interpreted that the Globe-Vauxhall Shear, which cuts the Broken Hill orebody, extends southwest to join the Hillston Fault. Clearly, this is false.

The behaviour of the Broken Hill Mine Sequence, where it is cut by the Thackaringa-Pinnacles shear system, is of interest. The Balaclava Silver mine area may be the offset and rotated continuation of the Mine Sequence, and hence is an important exploration target.

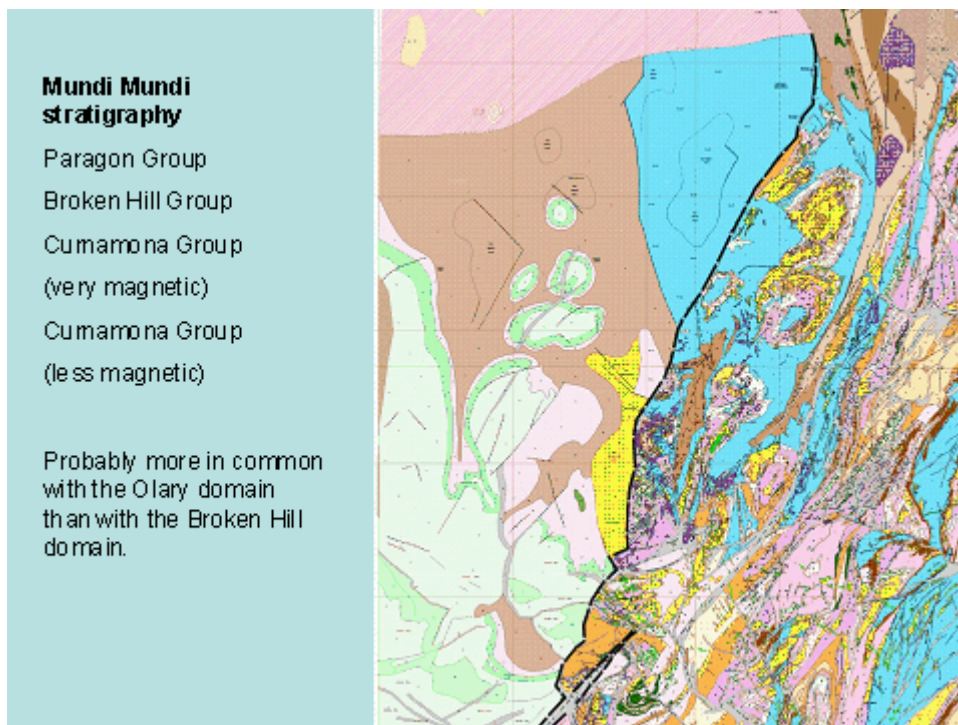


Figure 3. General geology under Mundi Mundi Plains, to the left of the heavy dashed line, which is the Mundi Mundi Fault.

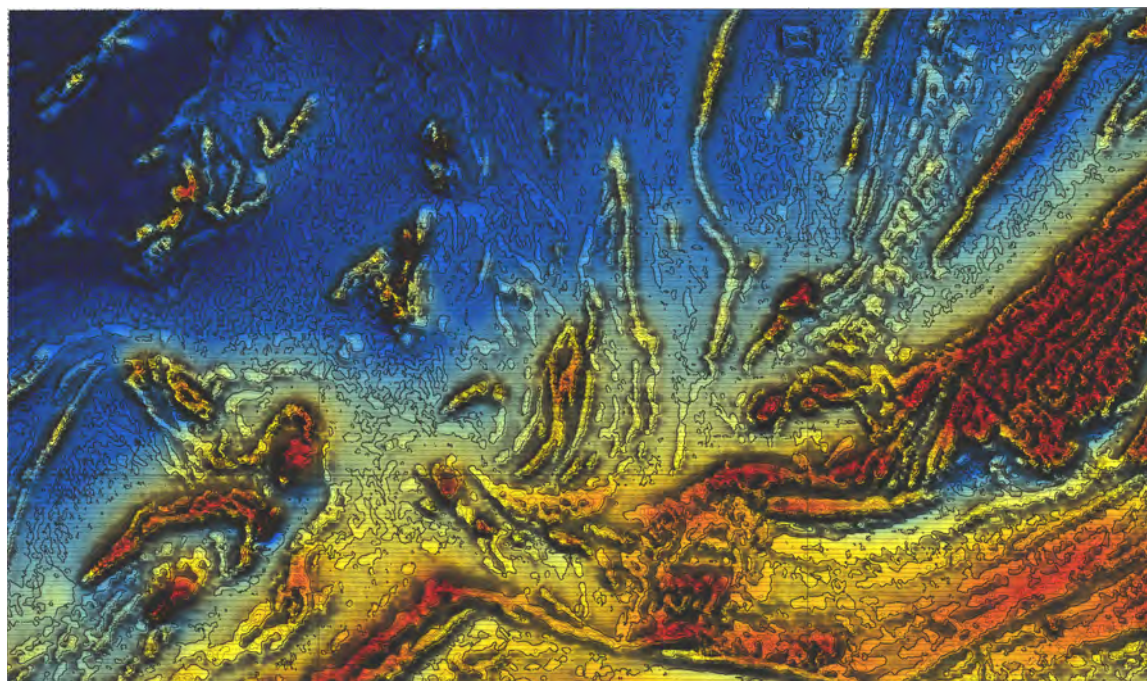


Figure 4. Aeromagnetic image of the Pinnacles 1:25 000 sheet.

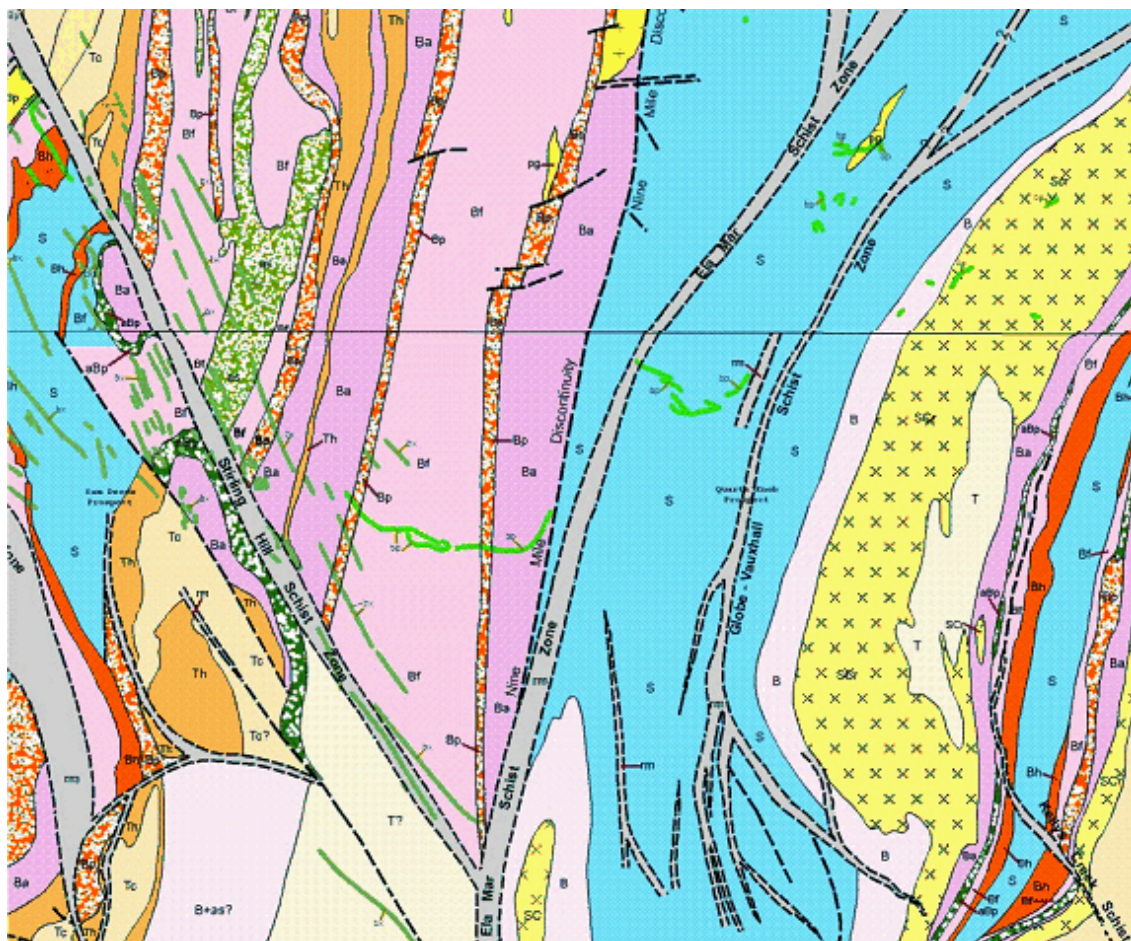


Figure 5. Offset of dolerite dyke (Bp) by Nine Mile Discontinuity and/or Ela Mar Schist Zone. This demonstrates post-dyke displacement, probably Delamerian in age.

Acknowledgements

The project was financed by the Geological Survey of New South Wales, Industry and Investment New South Wales. Aeromagnetic data were provided by Geoscience Australia, and images prepared by consultants to the GSNSW. Most of the map drafting was carried out by Andrew Valja and Karen McLaughlin. Interpretation of the Neoproterozoic rocks was carried out by Bill Reid of the GSNSW. The geology of the Willyama Supergroup is the result of mapping by the dedicated group of GSNSW geologists, with which I had the pleasure of working: Ian Willis, Jim Stroud, Graham Bradley, Bob Brown, Gary Burton, with Rob Barnes on mineral deposits, and with valuable input from industry geologists.

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Tectonic linkages between the Curnamona Province and Gawler Craton

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The Proterozoic of southern Australia is dominated by two domains: the Gawler Craton and the Curnamona Province. Both these regions are of proven economic significance in that they host some of the largest base metal ore bodies ever found, and have therefore been the focus of mineral exploration efforts for a number of years. In addition, these regions also contain the record of how the southern Australian Proterozoic system was assembled. Whilst there has been considerable focus on the tectonic evolution of the Curnamona Province, along with a growing focus on the development of the Gawler Craton, there has been little attempt to systematically explore tectonic linkages between the Curnamona Province and the Gawler Craton. Tectonic models describing the relationship between the now contiguous Gawler Craton and the Curnamona Province, have been described as either an amalgamation of individual Cratons, for example, Betts and Giles (2006) and Wade et al. (2006), or the development of younger Proterozoic basins on a single Archaean craton, for example, Glen et al. (1977).

We present new isotopic and geochemical data from a series of east-west bounded, inverted Palaeoproterozoic basin successions which geographically link the eastern margin of the Gawler Craton to the Curnamona Province. The data indicate a progressive development of Palaeoproterozoic basins with similar provenance of relatively evolved initial ϵNd values of ~ -3 to -6 @1740 Ma, and enriched sources with steep, light to heavy REE patterns compared with the average of Australian Post-Archaean Shales (PAAS). The data also indicate the basin system progressively youngs from the eastern side of the Gawler Craton at ~ 1790 Ma through to the Curnamona Province at ~ 1710 Ma, implying spatial and temporal linkages between the eastern Gawler Craton and Curnamona Province from as early as 1710 Ma. A younger, ~ 1590 Ma granulite facies tectonothermal event, similar in timing to the Olarian Orogeny in the Curnamona Province has also been identified within the Barossa Complex. The timing of this event is younger than the aforementioned ~ 1710 Ma link between the Gawler Craton and Curnamona Province and therefore does not appear to be related to the joining of the domains.

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Tin and base metal mineralisation associated with highly fractionated Mesoproterozoic volcanics and intrusives, northwest Curnamona Province, South Australia

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Introduction

The Prospect Hill area is situated in the northwestern region of the Curnamona Province in the Mount Babbage Inlier, which forms part of the Mount Painter Province. Tin was discovered in the early 1980's within deformed east-west trending Mesoproterozoic volcanics. Rock chip sampling recorded anomalous tin (200 ppm-500 ppm Sn) and this was followed up by stream sediment sampling. A number of small drilling programs were undertaken in 1986, 1994 and 1996, and more extensive programs were undertaken in 2007 and 2008. Currently, the Southern Ridge tin resource stands at 302,000 tonnes @ 0.64 % Sn to 90 vertical metres. The deposit is open to the east and west and at depth. A detailed soil sampling program in mid 2009 indicates that the tin mineralisation continues undercover for a further 2000 m to the west, and is as yet untested.

Regional geology

The Mount Painter Province contains a succession of multiply deformed, high temperature and low pressure metamorphic rocks which are stratigraphically overlain by a series of predominantly quartzites and metavolcanics. The latter have undergone lower temperature P-T conditions. Teale (1993) divided the basement rock-types into three successions, mainly on structural grounds. Paul (1998) also noted that, on structural grounds, the basement could be subdivided into an older Paleoproterozoic and a younger Mesoproterozoic succession. Coats and Blissett (1971) and Elburg et al. (2001) considered the entire basement to be a single succession. Fanning et al. (2003) undertook a SHRIMP U-Pb zircon investigation on detrital zircon from the numerous quartzite units within the Mount Painter Province. This study showed that the time of deposition of the pre-Adelaidean basement succession of the Mount Painter Province was younger than 1630 Ma, most probably in the age range of 1580-1590 Ma.

Volcanics and granitoid intrusives of the Mount Painter Province are in the age range of ~1585 Ma to ~1550 Ma (Sheard et al., 1992; Teale, 1993; Elburg et al., 2001; Teale and Fanning, unpub. data). Younger Paleozoic granitic to tonalitic intrusives are also present. The Mesoproterozoic volcanic and intrusive rocks exhibit A-type characteristics (c.f. Whalen et al., 1987) and generally exhibit low concentrations of Mg, Ca and Sr, and moderate to extreme concentrations of LREE, Y, Zr, U, Zn, Pb and Nb.

Geology of the Prospect Hill Region

The Prospect Hill area is composed of strongly foliated felsic volcanics, named the Petermorra Volcanics by Sheard et al. (1992). These are intruded by the White Well Granite and the Prospect Hill Granite (Teale et al., 1989; Sheard et al., 1992) with the latter being high level and porphyritic. Minor meta-epiclastic rocks are intercalated with the felsic volcanics, as are rare quartzitic metasedimentary rocks. The Mesoproterozoic succession is overlain by Adelaidean metasedimentary rocks with a basal conglomerate present. The metavolcanics, dated by Sheard et al. (1992) at 1560 ± 2 Ma, and the associated intrusives are some of the youngest Mesoproterozoic igneous rocks in the Curnamona Province. The volcanic succession was altered close to its depositional age. Fluids causing this alteration, and associated deposition of tin and base metals, were generated most likely from nearby high level, sub-volcanic, porphyritic intrusives.

The metavolcanics are siliceous and contain the assemblage quartz-K-feldspar-plagioclase-biotite-muscovite. The muscovite is fabric-forming and developed during the Delamerian tectonothermal event via the destruction of original phenocrystic and groundmass K-feldspar. Magmatic biotite has been deformed and recrystallised. The White Well Granite is porphyritic and contains large (~1.5 cm) subhedral phenocrysts of K-feldspar, which can be partially mantled by a thin rim of calcic oligoclase. Plagioclase phenocrysts can be up to 1 cm in size, and the groundmass is dominated by finer-grained quartz, K-feldspar, plagioclase and biotite. Plagioclase can be replaced by sericitic white mica. Many samples exhibit a granophyric intergrowth of quartz and K-feldspar within the matrix.

The Prospect Hill Granite contains scattered ovoidal phenocrysts of K-feldspar which can be up to 3 cm in diameter, as well as smaller, rounded, corroded and embayed quartz and lesser euhedral plagioclase. Biotite occurs interstitial to matrix feldspar and quartz, and is now represented by decussate biotite aggregates. It is Fe-rich (~29 % FeO) and averages 0.83 % F. Abundant fluorite is present as well as trace allanite, zircon, apatite, tourmaline, pyrite, magnetite and very rare cassiterite.

The intrusives are enriched in LREE and have an extreme negative europium anomaly. High concentrations of Y (~120 ppm), Nb (~40 ppm), U (8-55 ppm), Sn (8-18 ppm), Pb (55-65 ppm) and Th (55-175 ppm) are present. The Prospect Hill succession is separated from the rest of the Mount Babbage Inlier by a major east-northeast trending structure. The White Well and Prospect Hill Granites and the associated felsic volcanics are not present to the south of the structure.

Mineralisation

The Southern Ridge Prospect is situated within the metavolcanics and hosts the only known tin resource in the Prospect Hill area. Other anomalous chip and stream sediment samples remain largely untested. The Southern Ridge prospect "lode" has been drill tested over approximately 350 m and can be up to 14 m in thickness. The metavolcanics within the structural hangingwall become more muscovite-rich, and develop fine-grained garnet, as mineralisation is approached. The increase in muscovite here is due to pre-metamorphic K-alteration, which has been affected subsequently by the Delamerian tectonothermal event. The structural footwall metavolcanics are more garnet and magnetite-rich, and can also contain gahnite, fluorite and sphalerite.

The tin mineralisation is contained within siliceous and/or fluoritic rocks, which can also contain gahnite, biotite, tourmaline, garnet, muscovite, F-margarite, epidote, magnetite and sulfides. Trace scheelite, uraninite and xenotime can also be present. The garnet is Mn-rich, and is distinct from the almandine-rich hangingwall and footwall garnet. Gahnite is almost end member composition within mineralisation, and is ferroan gahnite in composition outside of the mineralisation.

The mineralisation is sulfur-poor, with trace pyrrhotite (or secondary pyrite) associated with sphalerite, chalcopyrite, galena and Ag-rich sulphosalts. Tin can be found in biotite (up to 0.17 %), epidote (up to 0.24 %), spinel (up to 0.10 %) and garnet (up to 0.04 %). Zinc is present in spinel, biotite (up to 7 % ZnO), magnetite (up to 1.2 % ZnO), and Pb can be found in epidote. The cassiterite is generally in the 0.01 mm to 0.5 mm size range, and is pure SnO₂ with no contained Nb, Ta or Mn. No stannite or tin-bearing sphene (malayaite) is present.

Concluding remarks

- Tin mineralisation is contained within siliceous metavolcanics which are dated at 1560 ± 2 Ma. The mineralisation exhibits a Pb isotopic composition which shows that it shares similar characteristics to Mesoproterozoic mineralisation elsewhere in the Curnamona Province. It is totally distinct from the Pb isotopic composition of known Delamerian mineralisation in the northern Flinders Ranges. The Prospect Hill mineralisation has not been introduced during the Delamerian tectonothermal event.
- The tin mineralisation can also contain minor Pb-Zn-Ag sulfides which contain anomalous Bi, Sb, In, Se, Cu, Te, As, U, Cd and W. The mineralisation is considered to be skarn-like, emanating from late, fluorine-rich fluids generated at the top of adjacent subvolcanic intrusives. The anomalous In, Se and Te may support this.
- Mineralisation is sulfur-poor, with trace pyrrhotite and more common sphalerite, galena and chalcopyrite. Trace tin can be contained within epidote, biotite, spinel and garnet, and abundant zinc can be contained within spinel, biotite, chlorite and magnetite.
- Mineralisation away from the Southern Ridge Prospect has not been adequately tested. Alluvial/eluvial tin potential and U potential in the adjacent Cenozoic-Cretaceous sediments has not been tested.
- It is considered that the Prospect Hill succession continues to the northeast around the northwest margin of the Curnamona Province. Tin and base metal mineralisation would be associated.

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The Mundi Mundi clinopyroxenite mass, Silverton

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Introduction

A significant magnetic anomaly has long been known on the Mundi Mundi Plain. Seltrust drilled a vertical hole in 1966 through 50 metres of overburden. Pre-collar drilling to 177.1 metres was followed by BQ core to 344.43 metres. Geophysical data suggest that the Mundi Mundi clinopyroxenite has intruded rocks of the Willyama Supergroup. However, the contact rocks neither crop out nor have been intersected in drilling.

On the basis of 20 specimens, the mineralogy, texture and geochemistry (i.e. major, trace elements, REE and PGE) of the rocks were studied in detail, in order to understand the genesis and age of this pyroxenite body, and to evaluate whether the body has potential for economic Ni-Cu-sulfide and PGE concentrations. Microanalytical data were derived from microprobe analyses using a JEOL JXA 8200 superprobe, and geochemical analyses were carried out using XRF and ICP-MS techniques.

Geology and Mineralogy

The rock sequence is represented by magnetite, magnetite-ilmenite bearing clinopyroxenites showing, in most cases, an ad-cumulate texture. This texture is defined by clinopyroxene cumulus with magnetite and magnetite-ilmenite intercumulus, which clearly indicates that the rock sequence represents an ultramafic intrusion. The clinopyroxenites are generally homogeneous; the only distinct features are defined by two types of clinopyroxenes. These are

- *Coarse grained* with laths up to 8 mm in size which are rarely zoned, rarely simply twinned and rarely euhedral, and
- *Fine grained* with anhedral grains up to 3 mm in size. In both textural variants, the abundance of magnetite, magnetite-ilmenite varies from about < 5 modal % to up to 20 modal % (i.e. at 614 feet). The clinopyroxenite mass is cut by several shear zones wherein the retrograde assemblage is characterised by zoned coarse-grained garnets and abundant green amphibole, Mg-chlorite, epidote, sphene and calcite with remnant clinopyroxenes. The clinopyroxenites in close vicinity to the shear zones are moderately to strongly deformed and altered, where alteration starts at grain boundaries and leads to replacement of clinopyroxenes by green Ca-amphiboles and epidote.

Microprobe analyses show that the clinopyroxene is a Cr-poor diopside of uniform composition (Mg# from 80 to 87, the latter predominantly in shear zones). Zoned clinopyroxenes are characterised by a core with slightly less Al than the rim. This indicates increase in pressure, most likely induced by metamorphic overprint, because the variation in Al-content from core to rim is not consistent.

Two types of spinel occur:

- *Interstitial* pure magnetite and magnetite-ilmenite as a typical intercumulus mineral. Where ilmenite is present, it forms oriented exsolution lamellae in magnetite. In many places, the ilmenite is altered, up to complete replacement by a Ti-Fe-Ca-containing mineral phase.
- *Subordinate* Ti-Mn-Mg-Al-rich magnetite inclusions in clinopyroxene. These show a typical oval, occasionally euhedral shape. Sphene, calcite and apatite have been observed as accessory mineral constituents. Apatite forms inclusions in clinopyroxene, sphene, and calcite most commonly occurs in, and close to, shear zones.

Sulfides (i.e. chalcopyrite, pyrite, bornite and digenite) are very rare. They occur as accessories, finely distributed in the interstitial space. They become slightly more abundant in shear zones, closely associated with mineral phases such as sphene, calcite, chlorite and amphibole. No Ni or PGE minerals were observed.

Geochemistry

The rocks show a uniform chemical composition with respect to major and trace elements. Cr varies between 24 and 113 ppm, Ni lies in the range of 145 and 243 ppm and Cu concentrations lie in the range of 114 to 579 ppm with two samples up to 1660 ppm. The alkalis (Na₂O and K₂O) are below 0.5 wt. %, thereby differentiating the Mundi Mundi clinopyroxenite from other alkali clinopyroxenites and jacupirangites elsewhere in the Broken Hill and Olary Domains (Binns, 1966; Bell, 1979; Binns and Barron, 1983).

The chondrite-normalised REE patterns show a slight LREE enrichment (up to 10 times chondrite) and rather smoothly shaped patterns with respect to the HREE at 1-6 times chondrite value. REE patterns from the shear zones show a pronounced positive Eu anomaly, which indicates remobilisation of some of the REE during shear deformation.

The PGE concentration is, in general, very low. The IPGE (Os, Ir, Ru) are less than 1.2 ppb. The PPGE (Rh, Pd, Pt) are also very low. Rh is less than 0.6 ppb, Pd ranges between 7 and 53 ppb, Pt is in the range of 2 to 38 ppb. The Os model ages suggest an intrusion age of ~700 Ma. In and around shear zones, Pd and Pt are slightly enriched, suggesting some PPGE remobilisation during retrogression. The PGE concentrations, however, are very low and there is no horizon or zone with PGE enrichment, despite the possibility that intrusion may have been through sulfur-rich rocks, thereby producing late stage sulphur saturation of the melt.

Conclusions

The Mundi Mundi clinopyroxenite intrusion beneath the Mundi Mundi Plain is a homogeneously layered clinopyroxenite intrusion. The abundance of magnetite and magnetite-ilmenite is the characteristic feature of the intrusion, hence the prominent magnetic anomaly. Furthermore, the rocks contain accessory mineral phases such as calcite, sphene and apatite, which are typical for highly alkaline rock sequences, despite the low (Na₂O+K₂O) content. Sulfides are very rare, except sometimes in shear zones. This assumes a S-poor system for the intrusion, also rather typical for alkaline settings. The fact that no Cr-spinel has been identified, also indicates a Cr-poor environment, commensurate with an alkaline rock sequence.

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Curnamona Province: Exploration review and mineral systems

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Uranium has been a focus of mineral exploration and mining in the western, South Australian part, of the Curnamona Province since the early prospecting activity at Radium Hill in 1906 and Mount Painter in 1910. Larger scale mining and exploration began after the Second World War, with extraction of radium and uranium from the Radium Hill mine between 1954 and 1961. Regional exploration during this period also led to the discovery of significant uranium prospects in the Crocker Well district. Following renewed interest in uranium in the late 1960's, uranium exploration switched to the search for sedimentary deposits in the Cenozoic palaeochannels of the Frome Embayment. The Petromin group discovered the Beverley deposit in the northwest Frome Embayment in 1969 and the Minad Teton Joint Venture discovered the Honeymoon, East Kalkaroo and Goulds Dam deposits in the southern Frome Embayment between 1972 and 1974. Sedimentary uranium exploration has dominated mineral exploration expenditure in the Curnamona Province since that time. Uranium is being mined currently by *in situ* extraction methods at the Beverley and Honeymoon deposits, and resources are under development at the Four Mile uranium project, 11 km northwest of the Beverley mine, and at the Oban uranium project, 60 km north of Honeymoon mine. A low-grade, bulk minable, bedrock uranium resource is also under development at Crocker Well uranium project.

The presence of the giant Broken Hill Pb-Ag-Zn orebody in the eastern Curnamona Province in New South Wales, a stratabound deposit hosted by Paleoproterozoic metasedimentary rocks, has prompted speculation about the potential for similar deposits in South Australia. Exploration for this style of deposit was boosted in the late 1970s, when Esso Exploration recognised the importance to mineralisation of a package of rocks they named informally the Bimba Suite, which they concluded was stratigraphically equivalent to the rocks containing the lode horizon at Broken Hill. The Bimba Suite marks a regional redox boundary, which is readily traced under cover using magnetic imagery, and has since been a major guide in the search for stratigraphically-controlled base and precious metals. Major exploration programs in the southern Curnamona Province, between ~1980 and ~2000, produced many encouraging discoveries, without matching the size or tenor expected of Broken Hill-type deposits. Copper, zinc and gold tend to dominate deposits in South Australia, whereas silver-lead-zinc mineralisation appears to be more prominent to the east in New South Wales. Potentially economic resources are under development at White Dam Au project and Kalkaroo Cu-Au project.

IOCG deposits have been an exploration target in the Curnamona Province since the discovery of the giant Olympic Dam deposit in the eastern Gawler Craton in 1975. Close similarities were recognised between the related Gawler Range Volcanics and the then newly discovered Benagerie Volcanics of the central Curnamona Province. Recent studies suggest that the Curnamona Province was once continuous with the Gawler Craton, and the central region of the Benagerie Ridge shares important features of geological setting with the major IOCG deposits of the Olympic Domain in the eastern Gawler Craton. These features include:

- a significant basement high, the Benagerie Ridge, preserved beneath Neoproterozoic and Phanerozoic cover sediments;
- the presence of bimodal Mesoproterozoic volcanics similar to the Gawler Range Volcanics;
- preservation of a shallow igneous environment, beneath and adjacent to the Benagerie Volcanics; and,
- evidence that the Willyama Supergroup of the underlying basement once contained evaporitic sediments, a potential source of saline fluids for the formation of hybrid IOCG systems.

Since the 1990's, explorers have recognised the potential of the Curnamona Province to discover types of IOCG deposit types other than the Olympic Dam style, generally adopting exploration models based on the range of examples found in the Cloncurry district in Queensland and the Tennant Creek field in the Northern Territory. These include magmatic, non-magmatic and hybrid styles of IOCG deposits, but tend to have a stratigraphic component, so that deposit types tend to overlap with the stratabound styles associated with the oxidised zone beneath the Bimba Suite. Prospects such as White Dam (Au), Kalkaroo (Cu-Au) and North Portia (Cu-Au-Mo) reflect aspects of both stratabound deposits and IOCG-related mineralisation.

Gold mineralisation in the southern Curnamona Province tends to be associated with copper in stratabound deposits of the oxidised zone beneath the Bimba Suite, although, in deposits such as those mentioned above, IOCG-style alteration is also present. Secondary eluvial gold at Portia prospect, apparently derived from this style of mineralisation nearby, accumulated at the interface between the weathered basement rocks and the overlying Cenozoic sediments. Delamerian shear zones crosscutting the Proterozoic basement contain fracture-controlled gold deposits in places.

Uranium in the Frome Embayment: Recent results from Geoscience Australia's Onshore Energy Security Program

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Introduction

Sandstone-hosted uranium systems account for a third of the production of uranium in the world (OECD Nuclear Energy Agency, 2008). In Australia, only 7% percent of production is sourced from sandstone-hosted uranium mineralisation, all of which is produced from the Lake Frome region (McKay, 2008). Due to the uranium policies of previous governments, and historic low uranium prices, Australian Phanerozoic basins have been under-explored for uranium. Recently Geoscience Australia has been conducting studies of uranium systems in the Lake Frome region, with the aim of developing a series of models and exploration techniques to assist uranium exploration in this and other basins (Skirrow, 2009).

Methodology

To better understand mineral systems and the spatial and temporal controls on mineralisation, Geoscience Australia conducts studies using the Five Questions framework developed by the Predictive Mineral Discovery Cooperative Research Centre (*pmd*CR*C) (Walshe et al., 2005; Barnicoat, 2007). The Five Questions framework is an holistic approach towards understanding the entire mineral system, rather than simply characterising the deposit. The Five Questions are:

- What are the geodynamic and pressure-temperature histories of the system?
- What is the architecture of the mineral system?
- What and where are the fluid reservoirs for the system?
- What are the fluid flow drivers and pathways?
- What are the metal transport and deposition mechanisms?

Conceptual Model

Two models have been proposed for the formation of sandstone-hosted uranium deposits (Figure 2): a single-fluid model (Finch, 1985) and a two-fluid model (e.g., Jaireth et al., 2008). In the single-fluid model, oxidised meteoric water migrates through a confined, reduced sandstone aquifer, progressively oxidising and remobilising uranium in the sandstone. The uranium is subsequently deposited and concentrated at the redox 'roll' front (Figure 2a). In the two-fluid model (Figure 2b), oxidised meteoric water migrates through a clean, oxidised sandstone aquifer. A reduced basinal fluid (hydrocarbon and/or H₂S bearing), from underlying hydrocarbon

reservoirs, migrates upwards along faults, and mixes with the oxidised fluid, resulting in the precipitation of uranium adjacent to the fault. The two-fluid model requires that there is little to no *in situ* reductants, so that uranium-bearing oxidised fluids can migrate much deeper into the basin, where there is greater opportunity of interaction with a reduced, hydrocarbon bearing fluid. These concepts underpin a study utilising numerical modelling techniques to simulate fluid flow in uranium mineral systems of the Lake Frome region (see below).

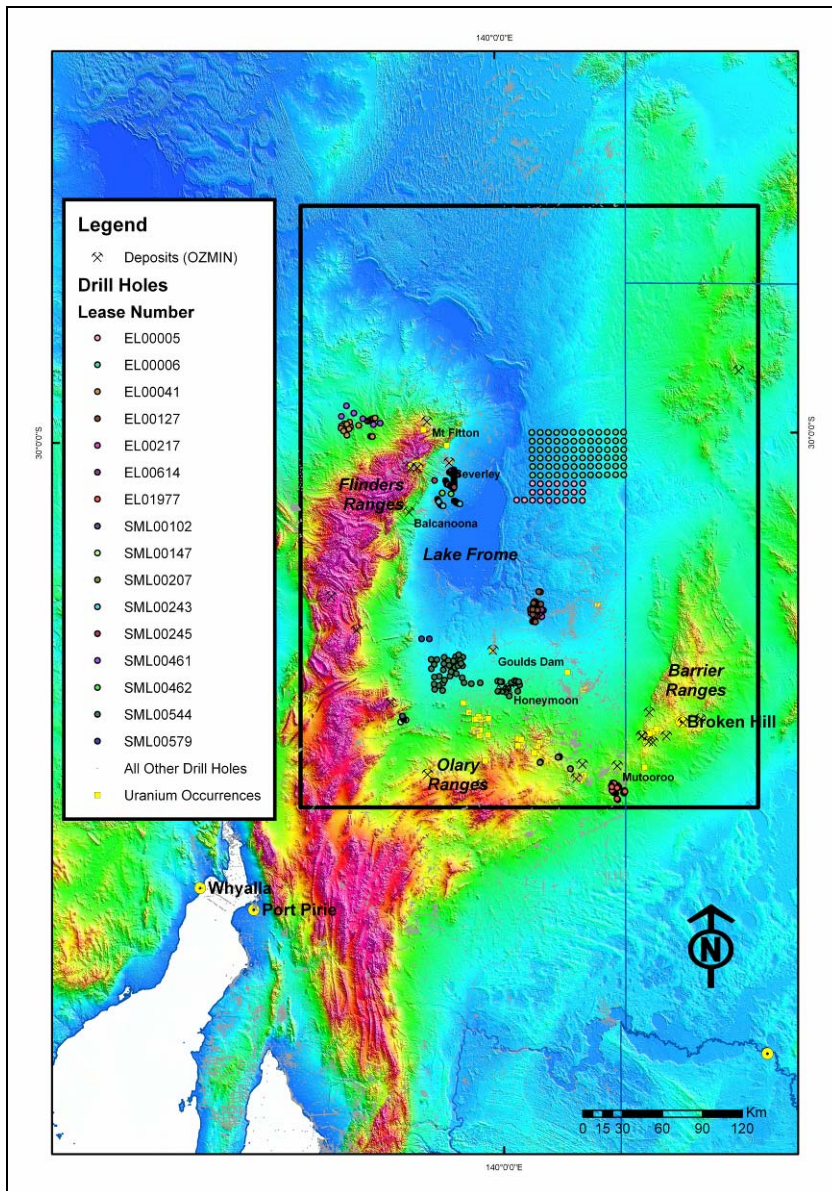


Figure 1. Locality map showing the study area (black rectangle), deposits, uranium occurrences, all exploration drilling and drill holes used to identify redox conditions of sediments (coloured by exploration lease).

Question 1: What are geodynamic and pressure-temperature histories of the system?

The Lake Frome region has a long and complex geodynamic history with multiple subsidence (basin forming) and deformation events. A summary of the geodynamic history with specific relation to uranium mineralisation is presented below.

Neoproterozoic-Paleozoic

The Moorowie Sub-basin, in the west, and the Yalkalpo Sub-basin, in the east, are separated by the north-south-striking Benagerie Ridge. This Paleoproterozoic-Mesoproterozoic basement ridge is covered by younger sediments. The Proterozoic complexes of the Curnamona Province form the southern boundaries of both the Moorowie and Yalkalpo Sub-basins, the latter of which is bound to its east by the Barrier Ranges. The Adelaidean strata of the northern Flinders Ranges form the western boundary of the Moorowie Sub-basin. These basement rocks are locally anomalous in uranium.

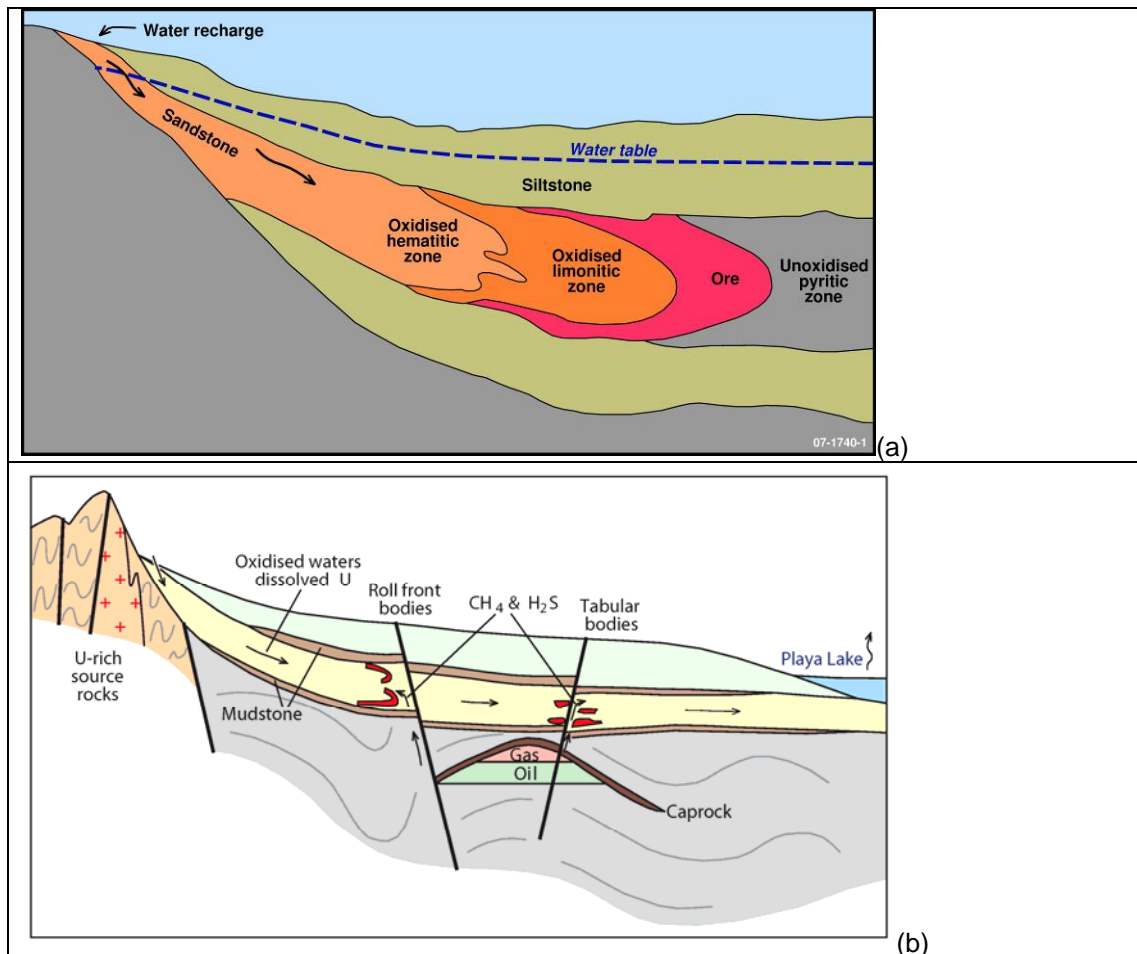


Figure 2. Two conceptual models have been proposed for sandstone-hosted uranium systems: (a) a single fluid model (Finch, 1985) and (b) a two fluid model (Jaireth et al., 2008).

Mesozoic

The Mesozoic Eromanga Basin is an intracratonic basin covering some one million square kilometres of east central Australia (Gravestock et al., 1986). Sediments of the Eromanga Basin unconformably overly those of the Moorowie and Yalkalpo Sub-basins, they drape over the Benagerie Ridge and, locally, onlap the Proterozoic rocks of the Flinders and Olary Ranges. Earlier workers (Gravestock et al., 1986; Hill and Gravestock, 1995; Krieg, 1995; Radke et al., 2000) have compiled a detailed stratigraphic framework for the Eromanga and adjacent basins. The Eromanga Basin has been subdivided into three main stratigraphic successions: a lower

non-marine succession (Early Jurassic to earliest Cretaceous), a middle marine succession (Early Cretaceous) and an upper non-marine succession (Late Cretaceous).

Cenozoic

The Lake Eyre Basin was created by subsidence commencing in the late Paleocene, with episodic fluvial and lacustrine sedimentation occurring in the basin until the present day (Alley and Benbow, 1995). The Eyre Formation is the basal unit of the Lake Eyre Basin and unconformably overlies the Eromanga Basin. Sedimentation spanned the latest Paleocene to the Middle Eocene. The Eyre Formation consists of pyritic, carbonaceous sand of varying grain size ranging from silt to gravel with occasional small cobbles, and was deposited by braided streams (Alley and Benbow, 1995).

There is little evidence for further sedimentation in the Lake Eyre Basin until the late Oligocene, when widespread gentle folding and uplift rejuvenated the Birdsville Track Ridge some 200 km to the north of the Frome Embayment. This activity split the Lake Eyre Basin into the Tirari and Callabonna Sub-basins, and revived sedimentation, which continued to the Pliocene. The new sediments form the Namba Formation (host of the Beverley deposit) which disconformably overlies the Eyre Formation. Sediments of the Namba Formation are described by Alley and Benbow (1995) as grey, green and white clay, fine-grained sand and carbonate, and minor conglomerate. They were deposited in a fluvial-lacustrine environment, with meandering streams and billabongs. They average 90 m in thickness, thin over the Benagerie Ridge, and thicken to 170 m towards the Barrier and Flinders Ranges. Drillhole logs from the Frome Embayment typically record unconsolidated, very fine- to fine-grained angular sand, black carbonaceous clay, green and grey clay, dolomitic ooze and, in places, lignite.

Quaternary

Quaternary processes have created the present-day alluvial fans, claypans, playas, dunes and ephemeral streams of the Callabonna Sub-basin. The oldest Quaternary unit, the Willawortina Formation, formed as alluvial fans built up around the Flinders and Olary Ranges. Deposition of these fans actually began in the late Cenozoic, continued until the Plio-Pleistocene, and consists of two facies: one fine-grained and one coarse-grained (Callen et al., 1995). The fine-grained unit is an upwardly fining, cyclical succession of sandy mud and silty dolomite, with distal fan, mudflow and playa-lacustrine complexes represented by outcrops of green clay, and thick, calcareous paleosols also occur (Callen et al., 1995). The coarse-grained facies is seen in the drillholes around the Beverley uranium deposit. Braided alluvial fans deposited coarse-grained, framework-supported gravels, and debris flows resulted in poorly-sorted, matrix-supported gravels (Callen et al., 1995).

The Coomb Spring and Millyera Formations were deposited from the mid to late Pleistocene (Callen and Benbow, 1995). The beach deposits of the Coomb Spring Formation are found around Lake Frome, and consist of white to yellow, often coarse-grained, well-sorted sand (Callen and Benbow, 1995). Present-day topographic contours suggest that it was deposited when lake levels were higher, and when Lakes Frome and Eyre were possibly joined (Callen and Benbow, 1995). The Coomb Spring Formation intertongues with the flood-plain and lacustrine deposits of the Millyera Formation, which consists of greenish clay, thin algal limestone, and fine-grained, white to greenish sand (Callen and Benbow, 1995).

Late Pleistocene sedimentation also resulted in the deposition of the Eurinilla Formation, found in the northern Callabonna Sub-basin and near Lake Frome. It also intertongues with the Millyera Formation, and was partly deposited in paleovalleys formed within the Willawortina Formation (Callen and Benbow, 1995). The Eurinilla Formation consists of bright red-brown to yellow-brown sand and gravel of intermittent streams and their overbank deposits (Callen and Benbow, 1995).

The youngest unit in the Callabonna Sub-basin is the late Pleistocene to Holocene Coonarbine Formation, consisting of aeolian sands of red-coated, frosted quartz grains, yellow to orange grains, clay pellets and gypsum flakes, with aeolian cross-bedding (Callen and Benbow, 1995). The sands form a striking pattern of longitudinal dunes, with wind-eroded claypans aligned obliquely. The dunes are typically 15 m high (Callen and Benbow, 1995) and trend northwards in the northern part of the study area. With Lake Frome as an axis, their orientation progressively rotates to an east-northeasterly trend in the southern part of the sub-basin (Callen and Benbow, 1995; Randell, 1973). Older dunes contain calcareous paleosols, and a greater proportion of clay, compared to the younger phases of dune formation (Callen and Benbow, 1995). Large transverse dunes also formed along the downwind margins of playas and claypans and, on the bed of Lake Frome, gypsum dunes have been built upon clay dunes indicating deflation of the lake floor clay, followed by exposure and deflation of the groundwater gypsum horizon (Callen and Benbow, 1995).

Timing of mineralisation and tectonics

A review of published information has resulted in three hypothetical timing scenarios for the formation of basin-hosted uranium system(s) in the Lake Frome area (Skirrow, 2009):

- Mineralisation hosted by both the Namba Formation and Eyre Formation is of the same age and part of the same hydrogeological system. The maximum age of mineralisation is that of the host Beverley Sands (Miocene).
- Mineralisation is of the same age across the basin but the systems are hydrogeologically different.
- Mineralisation hosted by the Namba Formation and Eyre Formation is of different age (maximum Eocene age for uranium in Eyre Formation; maximum Miocene age for Namba-hosted mineralisation).

The uplift histories on the eastern margin of the Flinders Ranges could have played an important role in the deposition and preservation of both Mesozoic and Cenozoic sediments in the area and, as a result, the formation and preservation of uranium mineralisation. Geoscience Australia is currently undertaking studies to better constrain the timing of mineralisation within a regional context.

Question 2: What is the architecture of the mineral system?

Variations in permeability and porosity are one of the major factors in controlling the location of a mineral system and, as a result, understanding the 3D fault and lithological distribution is crucial in being able to predict the likely location of mineralisation. To this end, a 3D map (Figure 3) of fault and geological architecture was constructed in gOcad using publicly available datasets, such as drilling, seismic, radiometrics, DEMs and surface geology (Skirrow, 2009).

Question 3: What and where are the fluid reservoirs for the system?

Fluid reservoirs for sandstone-hosted uranium systems are relatively well known, as described in the conceptual model section above. In the case of Beverley and Four Mile, oxidised meteoric waters are assumed to have dissolved uranium from Proterozoic granites in upland areas of the Mount Painter Inlier and Olary region, or from sediments derived from these sources. Uranium was deposited along redox fronts in the Cenozoic sediments (Figure 4). Numerical simulation was undertaken to address both Question 3 (fluid reservoirs) and Question 4 (fluid flow drivers and pathways).

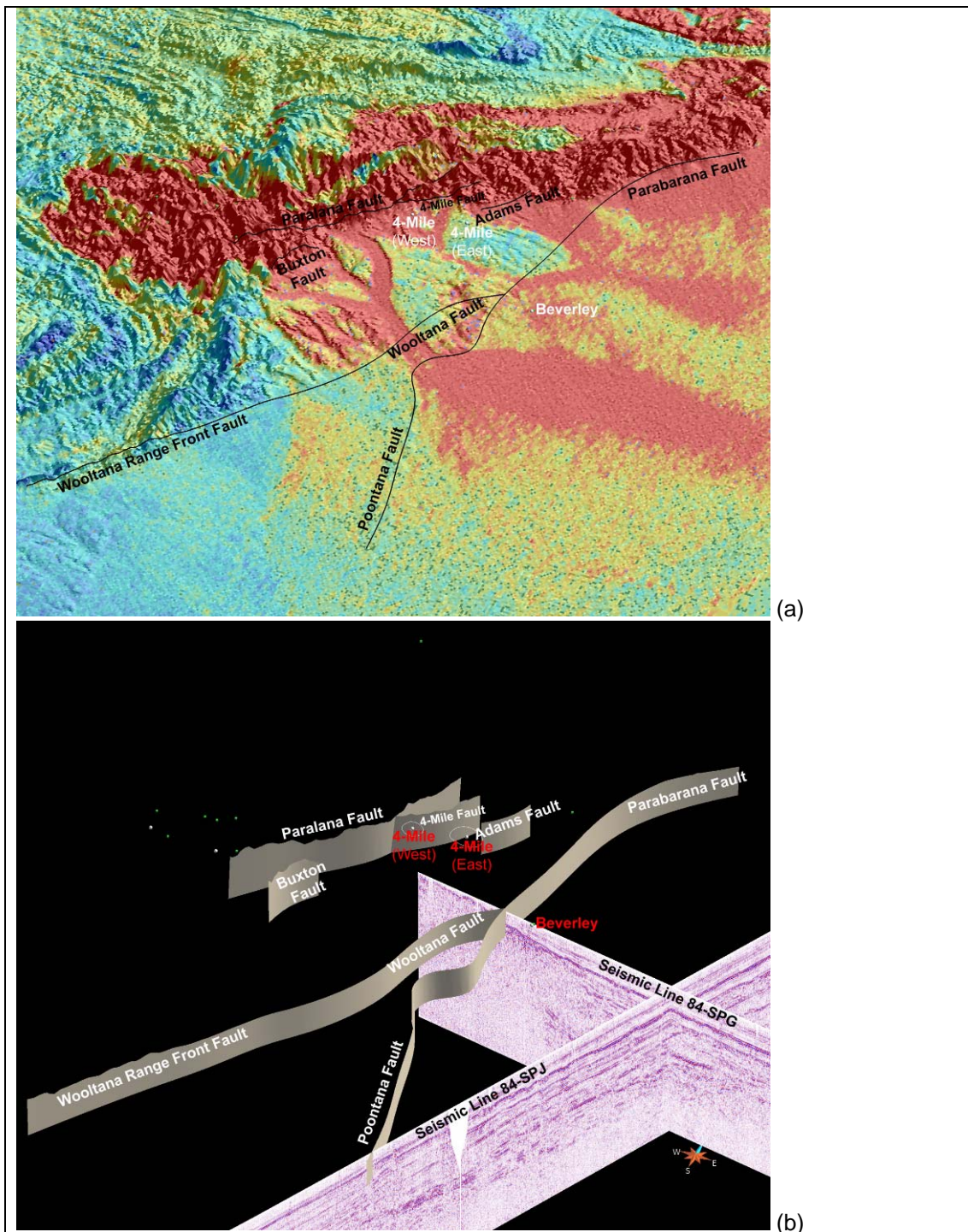


Figure 3. Screen captures of an oblique view of the 3D map, showing the faults within the vicinity of the Beverley and Four Mile uranium deposits, at ten times vertical exaggeration, looking north-northwest. (a) Uranium-band radiometrics draped onto the DEM; note the surface expression of some faults. (b) 3D fault surfaces and adjacent seismic lines, for the same area as in (a). In this oblique view scale is not linear; the distance between Beverley and Four Mile East deposit is ~8 km.

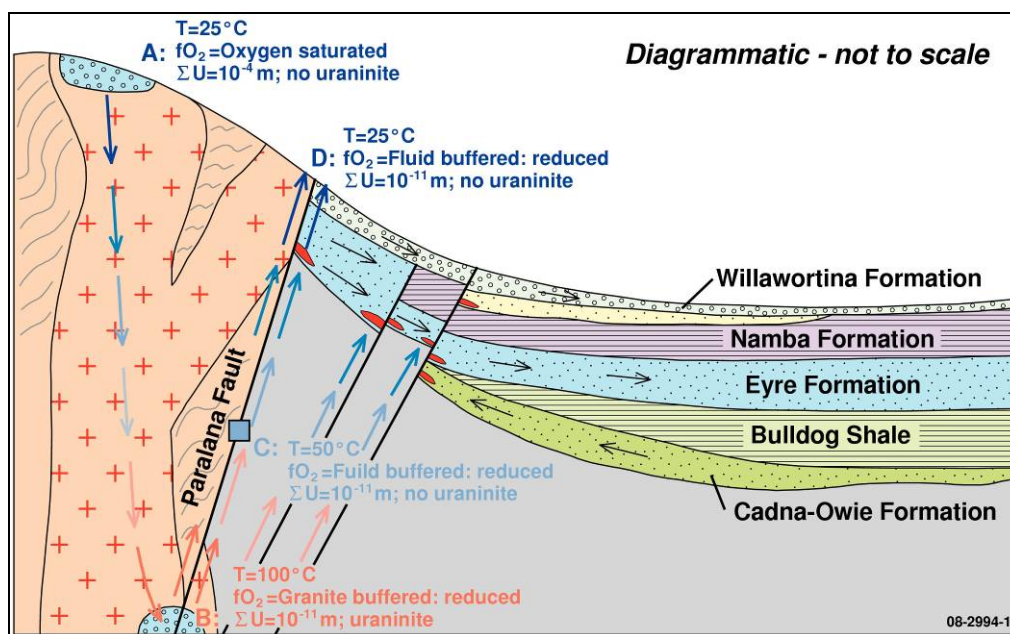


Figure 4. Schematic cross section of the conceptual geological model used for geochemical and fluid flow modelling of the Paralana Hot Spring and basin-hosted uranium mineralisation in the Lake Frome region. The blue to red arrows show the heating and cooling cycle of fluid related to the Paralana Hot Spring; the black arrows show the fluid flow in the present-day aquifers; the red zones show hypothetical zones of uranium mineralisation.

Question 4: What are the fluid flow drivers and pathways?

Numerical modelling, using the Desktop Modelling Kit (DMT) and the PmdPyRT code developed by the Computational Geoscience Group at CSIRO Exploration and Mining Division (Cleverley and Oliver, 2005), has been used to test various hypothetical regional fluid flow scenarios relevant to both current and past geological periods in the Lake Frome region (Skirrow, 2009). Detailed site-specific data for the deposits have not been used in the modelling, and we have utilised only public domain regional data. Geochemical modelling also has been carried out. In one scenario, the single-fluid conceptual model summarised in Figure 4 (which is based on published models), the numerical modelling simulates uranium mineralisation resulting from fluids driven by the topography of the Flinders Range interacting with the Cenozoic sediments of the Callabonna Sub-basin and Frome Embayment. For each numerical modelling scenario, plots of the distribution of permeability, instantaneous Darcy flux, tracer distribution, as well as fluid flow lines, are drawn for the same time slice (i.e. 10,000 years). An example of the numerical modelling results is shown in Figure 5.

In relation to fluid flow drivers and pathways, some of the conclusions from the numerical modelling of the scenario shown above are:

- The Eyre Formation, with its high permeability, shows maximum fluid flux, and direct recharge by oxidised surficial fluids.
- Fluids that discharged at the top of the Paralana Fault (i.e. Paralana Hot Springs) are heated to temperatures of 50° to 200°C in the simulation, and penetrated to considerable depths. They are unlikely to carry significant concentrations of uranium on the upflow path, as they would be efficiently buffered (i.e. reduced) by wall rock reactions with fresh granite and/or gneiss.
- The numerical modelling suggests that fluid mixing could be a potential depositional mechanism in the modelled scenario. In this model, oxidised, uranium-rich groundwater may have interacted with reduced fluids moving up the Paralana Fault system and/or derived from the underlying sedimentary basins (e.g., Arrowie Basin).

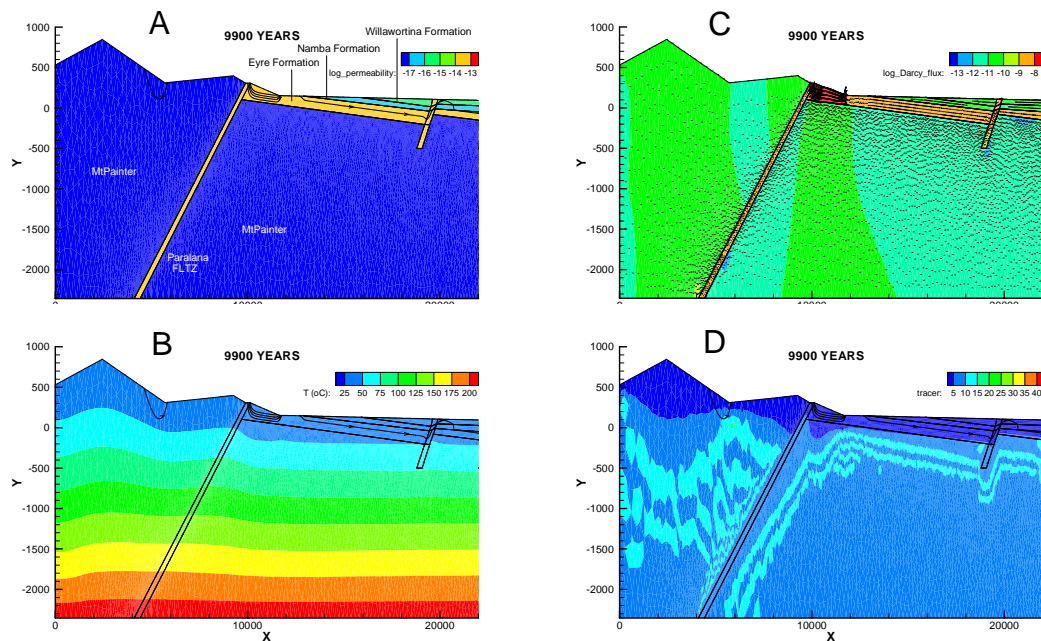


Figure 5. Example of numerical modelling results for an hypothetical regional geological scenario based on interpretation of seismic and other public domain data for the Lake Frome region. The geometry represents a scenario post-dating the existence of the Paralana Fault zone (PLFZ), for a particular time step in the modelling (9900 years). A: Distribution of the assigned permeabilities; B: Distribution of temperature; C: Darcy fluid fluxes and vectors; D: Distribution of a geochemical tracer component. A, B, and D show fluid flowlines in the hypothetical model. The X and Y axes are in metres in this simulation.

Question 5: What are the metal transport and deposition mechanisms?

As discussed in the conceptual model above, the transport and depositional mechanisms are relatively well understood for sandstone-hosted uranium deposits. Uranium is transported by oxidised meteoric waters or groundwaters and precipitated either by an *in situ* reductant, or by mixing with a reduced fluid (e.g., Finch, 1985; Jaireth et al., 2008). Using the concept that an oxidised fluid will progressively oxidise the rock that it passes through and, in turn, the fluid will be reduced by wall-rock interactions, we can use drill hole logs to identify and map the redox state of the rocks and hence identify potential uranium depositional sites.

As part of company reporting requirements, the results of mineral and other exploration activities are submitted to various state government geoscience agencies. The large open file archives of drilling results include geological logs, geochemical analyses and geophysical logs. Although not widely used by the research community, these reports are a valuable source of geoscientific information.

A pilot study was undertaken to determine whether the open file geological logs could be used to map the redox state of basin sediments. A list of oxidised and reduced words was identified from the logs (Table 1). Logs were digitised, and oxidised words were given a value of one and reduced words given a value of negative one. Where there was a combination of oxidised and reduced words, zero was used to designate the intermediate redox state. Where redox state could not be determined from the logs, a null data value (i.e. -99999) was used. The redox values were imported into gOcad and gridded using DSI and IDW for comparison purposes (Figures 6 to 9).

Table 1: A list of oxidised and reduced words that were used to identify redox state of sediments in geological logs.

Oxidised Words			
Red	Ferruginous	Manganese	Gypsum
Pink	Ferric	Mn	Blown
Maroon	Laterite	Iron	Dune
Orange	Lateritic	Fe	Duricrust
Yellow	Limonite	FeO	Ferricrete
Saffron	Hematite	Fe ₂ O ₃	
Purple	Goethite	Oxide	
Ochre	Martite	FeOx	
Mustard	Maghemite		
Mottled	Specularite		
Reduced Words			
Green	Pyrite	Glaucanite	Lignite
Blue	Mundic	Chlorite	Coal
Black	Chalcopyrite	Biotite	Organic
Olive	Chalcocite	Garnet	Carbonaceous
Khaki	Marcasite	Olivine	Graphite
Dark Grey	Galena	Peridotite	Bitumen
Fresh	Sphalerite	Actinolite	Creosote
Gley	Pyrrhotite	Pyroxene	Petrol
	Magnetite	Amphibole	Kerosene
	Sulphur, Sulphur	Hornblende	Hydrocarbons
	Sulphides, Sulphides		H ₂ S
			Odour

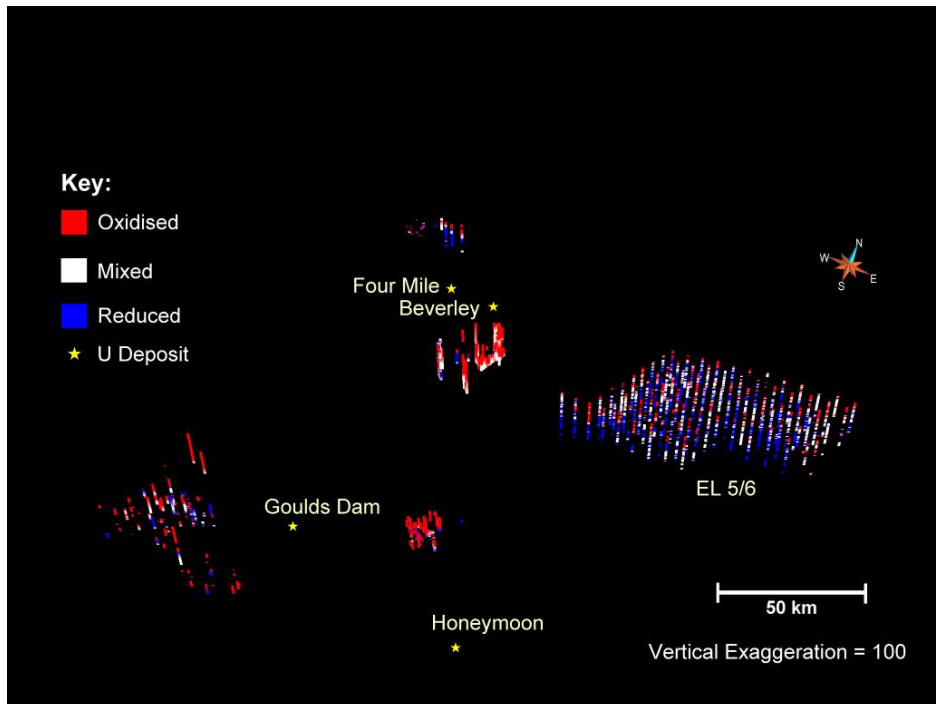


Figure 6. Oblique view (from south) of 3D map of the Lake Frome region showing redox characteristics of selected drill holes. Locations of uranium deposits are indicated.

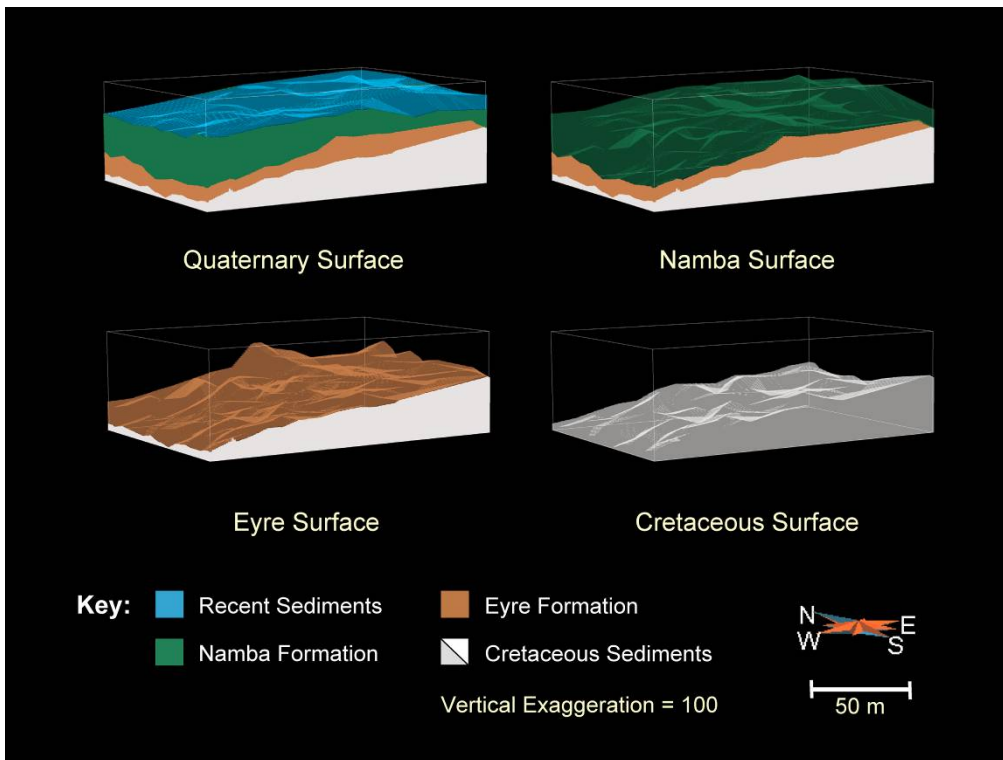


Figure 7. Voxet model of stratigraphic units and topography of the upper surfaces of each unit in the EL 5/6 area, east of Lake Frome.

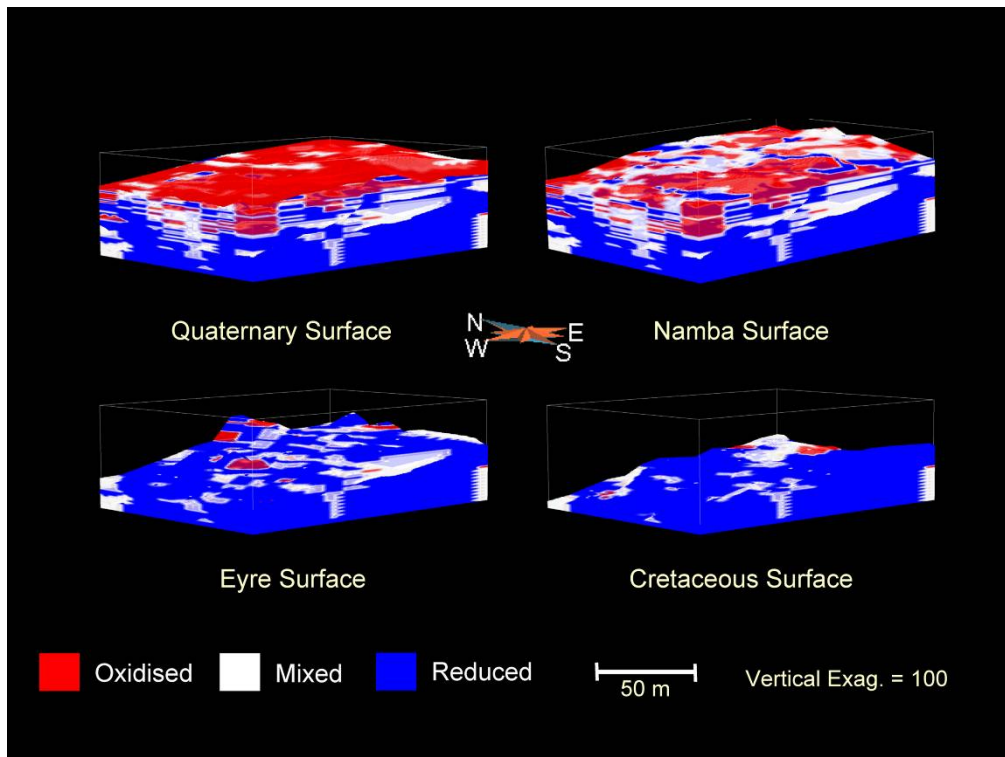


Figure 8. Voxet model of redox in the EL 5/6 area, showing variations on the upper surface of each unit as well as cross sections at the sides of the 3D model.

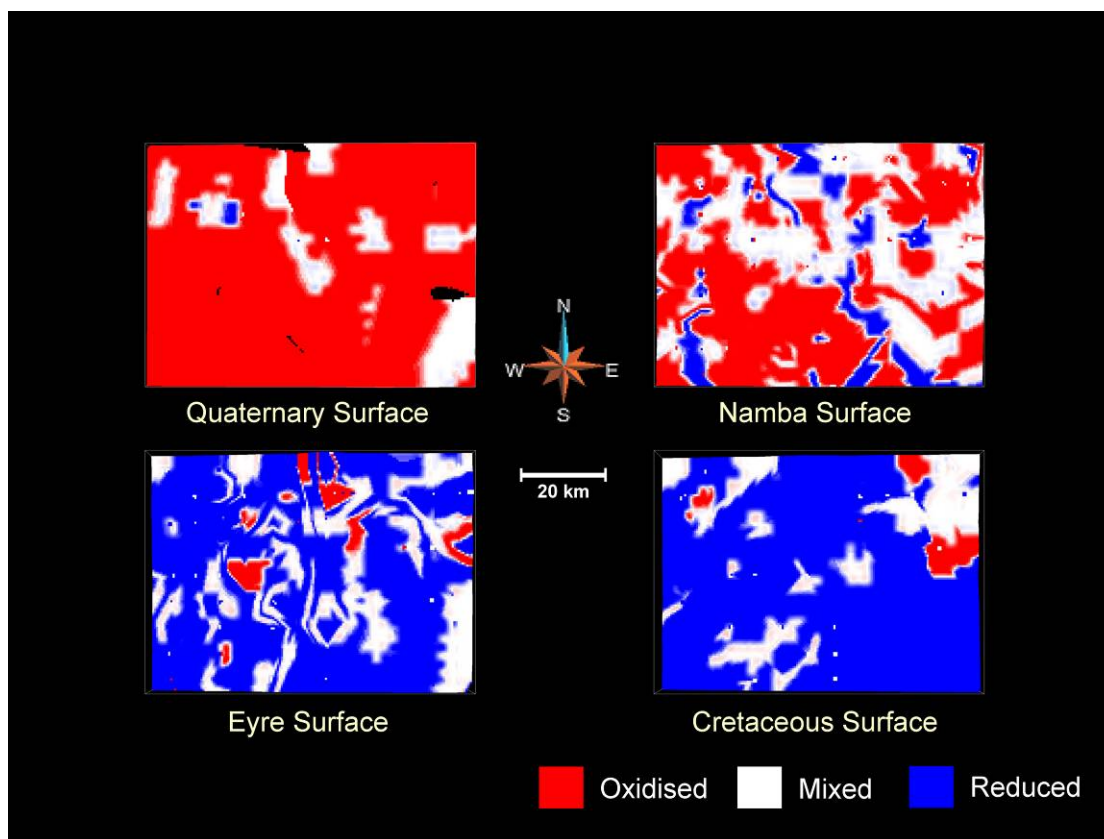


Figure 9. Plan view of the voxel model showing the redox variations on the upper surface of each stratigraphic unit in the EL 5/6 area.

Conclusion

The application of a mineral systems approach in the Lake Frome region has provided new insights into the controls on known uranium mineralisation, aimed at benefiting exploration in the region. The main highlights of the work reported here include:

- Creation of a 3D fault and lithological architecture map for the Lake Frome region.
- Application of numerical modelling to test various regional fluid flow and chemical scenarios, based on open file data.
- Development of a new technique to map in 3D the redox characteristics of sediments, using open file drill hole logs.

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The stratigraphic history of the Murray Basin and its industrial mineral deposits in New South Wales

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Introduction

The Murray Basin in southeastern Australia is an intracratonic sedimentary basin of Cenozoic age, with a diverse range of continental and marine sediments, which extends across the states of New South Wales, Victoria and South Australia. The upper successions of the Murray Basin, principally the mostly Pliocene Loxton-Parilla Sands, Calivil Formation and Shepparton Formation, contain economic occurrences of mineral sands, bentonite, kaolin and gypsum. These deposits formed in a large geological province in which critical interactions of depositional, eustatic, climatic and tectonic processes featured in their development.

The mineral sands deposits, which in New South Wales are the most significant commodities owing to their large resources of premium grade rutile, zircon and ilmenite, are mined west of Pooncarie by Bemax Resources Limited at their Ginkgo mine and their nearby recently commissioned Snapper mine. Gypsum is mined at various places, mainly near Balranald, bentonite is obtained from deposits at Arumpo, and kaolin is mined near Oaklands, which is situated in the eastern side of the Murray Basin. Quartz sand amenable to construction applications occurs in many places, primarily as aeolian dune deposits, alluvial successions associated with modern drainage courses, and ancient stream channels. Since mineral sands production at the Ginkgo mine began in late 2005, over 600 000 tonnes of rutile, zircon and ilmenite (and leucoxene) have been produced. These commodities are largely destined for export markets, principally China. Bentonite and gypsum, which are used in domestic markets, mainly New South Wales and Victoria, have individual production rates at present in the order of 30 000-40 000 tonnes per annum. Gypsum production, which has decreased in recent years owing to drought conditions, is currently about 85 000 tonnes per annum.

Mineral Resources of the Murray Basin

The Murray Basin is a remarkable geological province, which is characterised by an extremely well preserved succession of regressive Pliocene barriers extending over a distance of about 500 km inland from the present shoreline. This barrier succession provides an extraordinary, almost unbroken history of sea level changes going back some 6 Ma. The mineral resources of the Murray Basin are equally impressive in their diversity and origin, as illustrated by the following examples. Kaolin deposits of inferred Cenozoic (?Miocene) age that accumulated in lacustrine-floodplain settings on the Riverine Plain, eastern Murray Basin, are believed to have been derived from the weathering of adjacent basement rocks. Near Oaklands, kaolin deposits, mined for their high quality clays, occur in a distinctive north-south trending plateau that might

have developed in response to the erosion of neighbouring sediments or, alternately, consist of alluvial successions that were locally tectonically uplifted above the Riverine Plain.

The diverse styles of beach placers in the Loxton-Parilla Sands, their host succession, indicate that complex variations of several broad entrapment mechanisms were probably involved in their formation. Thick deposits of mineral sands that formed in early Pliocene successions in the northern Murray Basin are believed to represent coastal barrier stacking (composite barriers) that involved sea level fluctuations of at least 40 m. This is in contrast to single beach placer deposits elsewhere in the Murray Basin, which appear to have mainly accumulated during prolonged periods of stable (highstand) sea level. There is, however, a group of single deposit, extremely high grade beach placers in the northern Murray Basin that might represent multiple erosive events linked to variations in coastal sediment supply in turn related to localised tectonic activity that formed mineral sands-rich condensed sections on the shoreface. Regional analysis of their location, in relation to relict barrier trends on DEM imagery, implies that some of the condensed section deposits and composite barrier deposits formed at the same time, though on different parts of the same shoreline.

The Murray Basin has been subject to intermittent tectonic activity, particularly since the beginning of the Miocene, which has primarily been related to the reactivation of older basement faults. Cenozoic successions, notably in the central Murray Basin, are disrupted in many places, mostly as largely concealed, typically northeast to southwest, extensively faulted and uplifted basement ridges. Tectonic activity is also believed to have played a major role in the formation of mineral sands deposits, through the formation of uplifted fault blocks upon which beach placers preferentially formed. Bentonite deposits scattered across the southern and central Murray Basin were probably derived from volcanic ash emitted from inferred eruptive centres, now concealed by younger sediment, in the late Pliocene. At Arumpo, northeast of Mildura, distinctive successions of Na-Mg bentonite developed in response to the alteration of volcanic ash that was deposited in brackish and saline waters, in turn related to variations in the local depositional and structural environment.

During the last 0.5 Ma, large quantities of marine salts from the Southern Ocean have been deposited over much of southern Australia. These salts leached into shallow Pliocene aquifers, resulting in their typically saline groundwater, from which salt is produced in the Mourquong Swamps northeast of Mildura by the use of solar evaporation technology. Production of evaporated salt, mainly sodium chloride and magnesium chloride, at this location in recent years has been in the order of 15 000 tonnes per annum. In numerous locations, favourable structural or stratigraphic pathways allowed this groundwater to migrate to the surface to form hypersaline lakes that subsequently dried out leaving numerous scattered deposits of gypsum.

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