



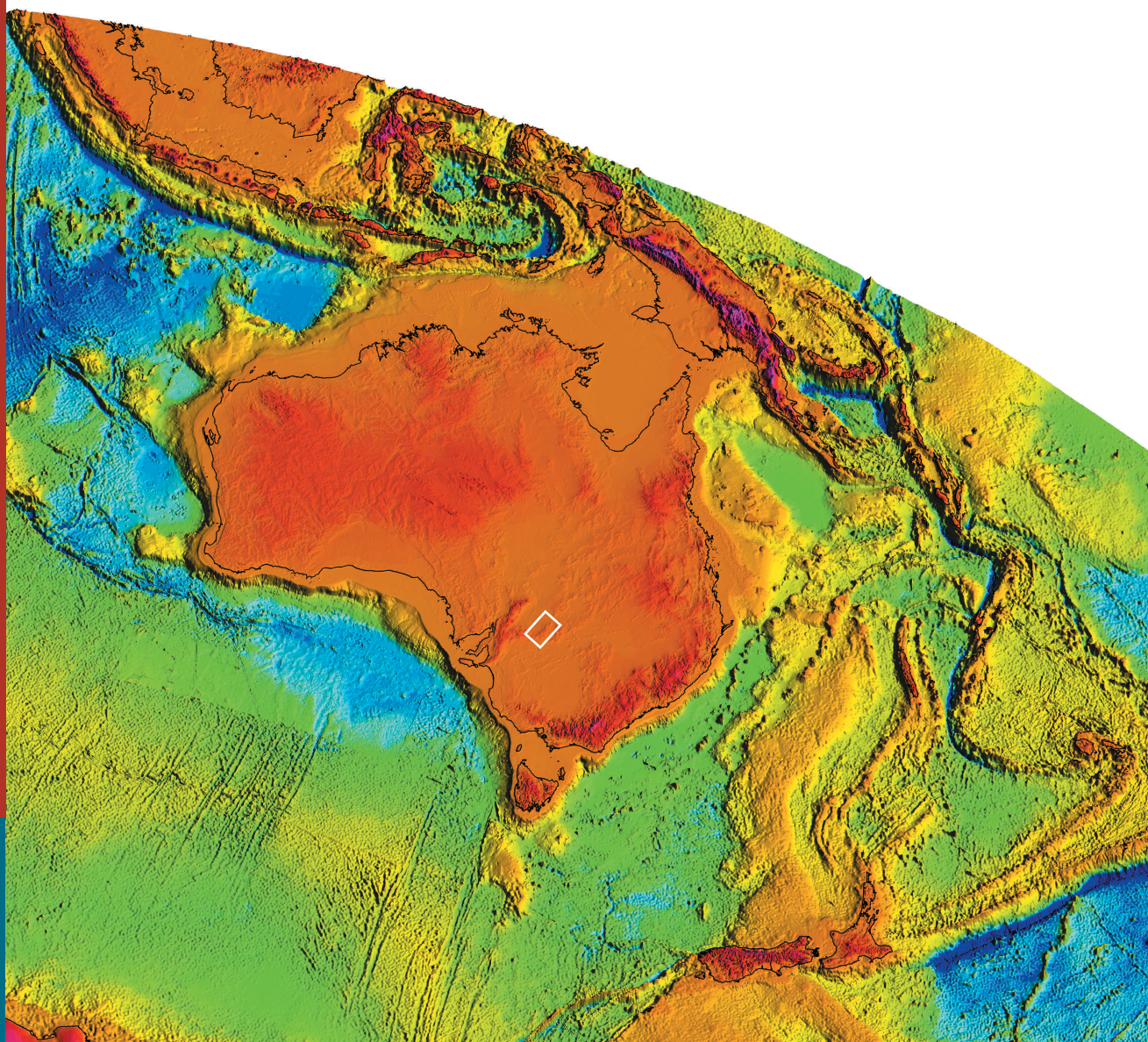
G E O S C I E N C E   A U S T R A L I A

Record 2003/13

# Broken Hill Exploration Initiative

Abstracts from the July 2003 Conference

*Compiled By Matt Peljo*



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**Broken Hill Exploration Initiative:**  
Abstracts of papers presented at the July 2003 conference in  
Broken Hill

**Geoscience Australia Record: 2003/13**

**Compiled by M. Peljo**

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**ISSN: 1448-2177**

**ISBN: 0 642 46771 4**

**GeoCat no. 47786**

Bibliographic reference: Peljo M., comp., 2003. Broken Hill Exploration Initiative: Abstracts from the July 2003 conference. <i>Geoscience Australia Record</i> 2003/13.
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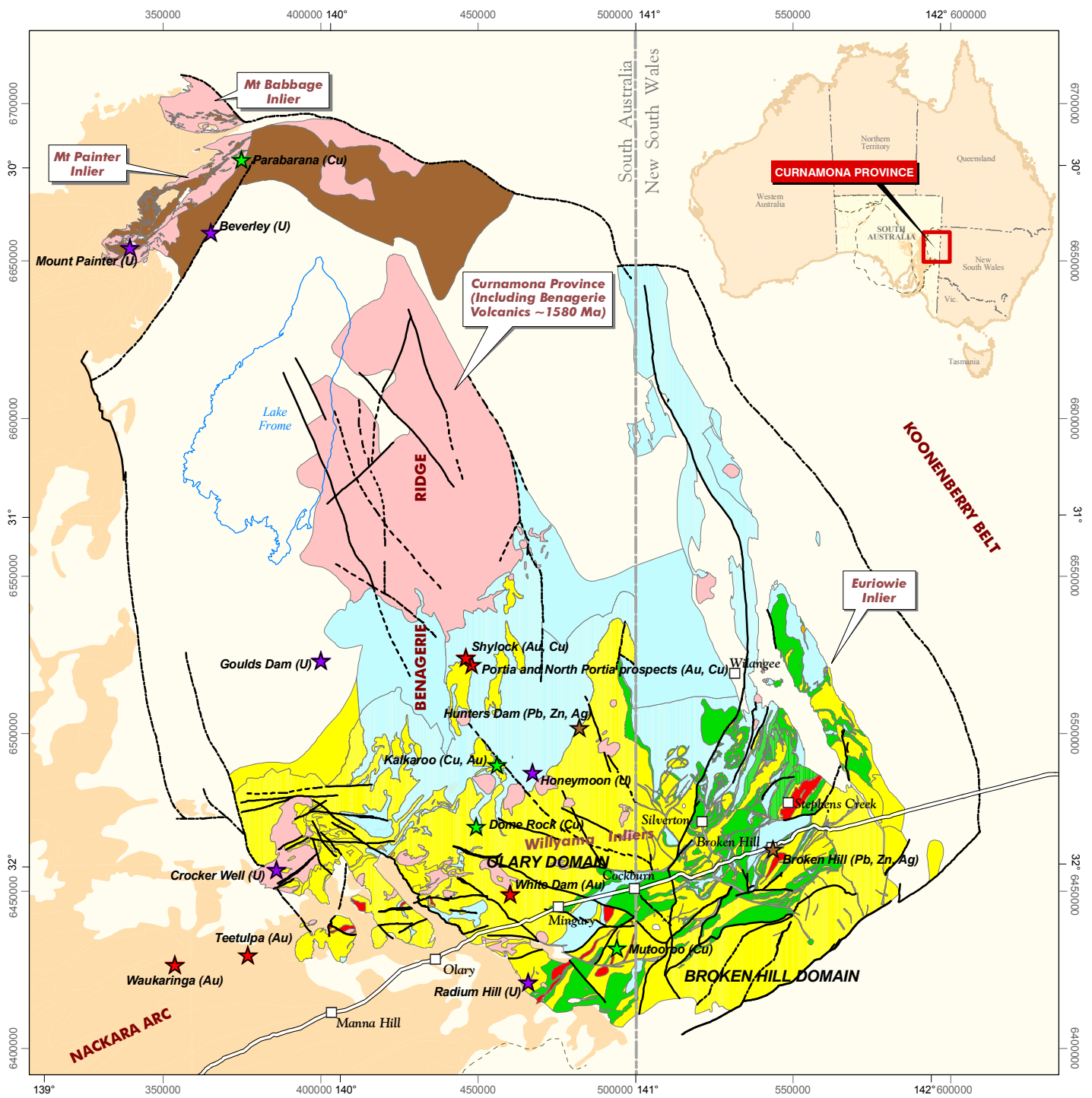
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# Curnamona Province

## GEOLOGY AND MINERALISATION

### OUTCROP AND INTERPRETED SUBSURFACE GEOLOGY



- Mesoproterozoic - granites and volcanics
- L-M - Undifferentiated
- Lg - Poodla Hill Suite ~1630 Ma
- Lga - Basso Suite ~710 Ma
- Upper Willyama Super group
- Lwb - Broken Hill Group
- Lower Willyama Super group
- Neoproterozoic

- Fault
  - Fault - approximate
  - Fault - inferred
- Selected mineral deposits
- Gold
  - Uranium
  - Copper
  - Zinc



0 30 60 Kilometres  
Grid Reference: MGA Zone 54



MINERALS  
PETROLEUM  
& ENERGY



PRIMARY INDUSTRIES  
AND RESOURCES SA





# COPPER GOLD POTENTIAL IN THE WILLYAMA IN NSW: “NAILS IN BALES”

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Although no current copper-gold production exists in the Broken Hill district, other than by-product Au from the Broken Hill Pb-Zn-Ag operations, recent research has continued to confirm similarities in regional structure, stratigraphy, hydrothermal alteration and metallogeny within the district, when compared with other Proterozoic Cu-Au provinces throughout the world.

Many questions still remain regarding absolute timing of sedimentation, magmatic intrusive events and mineralisation processes, but geochronology evidence continues to support the regional stratigraphic, intrusive and metamorphic similarities between the Broken Hill Block in NSW, Olary Block in SA and Palaeo-Mesoproterozoic sequences of Northern Australia.

Formation processes for important Cu and Cu-Au deposits within the Proterozoic period are believed to be closely linked to magmatic and tectonic processes accompanying continental scale orogenic processes. Arguably these deposits include the “sediment hosted” Cu ore body at Mount Isa, and the family of Fe-oxide Cu-Au deposits (Hitzman et al., 1992; Williams, 1998), represented by Ernest Henry and Osborne in the Cloncurry District, and Olympic Dam in South Australia. Although the role of magmatic fluids in the formation of these deposits is not necessarily clear, granite emplacement and associated periods of peak metamorphism are widely inferred to control fluid migration and associated ore deposition processes (Williams, op.cit.).

Comprehensive radiometric age data correlate the timing of felsic magmatism with granulite facies metamorphism in the Broken Hill Block at 1600-1570 Ma (Creaser and Cooper, 1993; Page and Laing, 1992). High precision age dating however also suggests peak metamorphism and syn-post tectonic magmatic activity were diachronous through the orogenic belt. In the Mount Isa Inlier peak metamorphism is now dated at 1532±7 Ma, and the collapse-related Williams and Narku Batholiths at 1510-1480Ma (Page and Sun, 1998). New chronostratigraphic subdivisions for Palaeo-Mesoproterozoic rocks of northern Australia (Page et al., 2000a) and recent geochronological data for the SE Curnamona (Page et al., 2000b) also support a direct correlation between elements of basin stratigraphy in each area. Reduced shale sequences, represented by the Urquhart Shale (Mount Isa), the Lawn Hill Formation (Century), and the Sundown/Paragon Groups (Broken Hill) are an important component for “sediment hosted” deposits, providing both physical and chemical trap sites for mineralising fluids.

An empirical assessment of available exploration data is presented for the Broken Hill Block, with an outline of conceptual models for Cu-Au ore formation. Exploration criteria considered to be relevant to further exploration are applied to existing data to firstly review remaining potential in the vicinity of known Cu-Au occurrences and, secondly, outline any priority target areas that may not have been recognised previously.

Regional aeromagnetic and gravity data are interpreted to indicate patterns of granite distribution and penetrative structures active at the time of granite emplacement that are key elements of the proposed fluid flow mechanisms for ore formation. Quantitative modelling of regional magnetic “base level” shifts indicates that weak to moderately magnetic intrusive bodies (granites) can account for the observed regional magnetic characteristics.

Existing exploration data define five specific “exploration elements” that deliver a province-wide system of ranking of possible Cu-Au target areas.

- *Interpreted Proterozoic granites:* thermal and/or mineralised fluid source for Fe-oxide Cu-Au deposits.
- *Mapped and interpreted regional structures and/or shear zones:* focus for fluid flow from intrusives or basin de-watering.
- *Metasediments of Sundown/Paragon Groups:* favourable reductant “trap” sequence for fluid flow.
- *Cu-Au mineral occurrences and defined geochemical anomalies.*
- *High gradient aeromagnetic features:* limited extent magnetite distributions compatible with alteration by metasomatic Fe-rich fluid.

Based on these exploration elements, a limited number of priority magnetic and geochemical anomalies are delineated. Target areas are further classified into likely deposit “types”, based on three working models for economic mineralisation and exploration elements that characterise them:

- *Fe-oxide Cu-Au*: regional structure, peak metamorphic oxidised granites, and positive local magnetic anomalies.
- *Sediment hosted Cu*: regional structure, clastic to shale transitional stratigraphy, carbonate (silica-dolomite) alteration, and extensive geochemical anomalies.
- *Shear controlled Au-Cu*: regional structure, linear zones of low order positive or negative magnetic relief, gold geochemistry.

Open file exploration drill hole locations are shown to be concentrated in a relatively small number of areas, which do not show any correlation with defined Cu-Au target areas. This is not an unexpected result, given that the great majority of historical exploration drilling within the Broken Hill Block has been concentrated in areas of known Broken Hill-style Pb-Zn-Ag mineralisation. Selected examples for each of the three principal Cu-Au ore model types illustrate the approach taken to target selection and prospectivity determination, as applied to the Broken Hill Block. These example areas appear to have received little exploration focus, as indicated by low levels of assessment drilling.

Broadening the commodity focus should shorten the exploration odds for the elusive next ore-body in the Willyama sequence, from “needle in a haystack” to “nail in a bale”.

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# **GEOCHEMICAL AND Nd ISOTOPIC EVIDENCE FOR SEDIMENTARY SOURCE CHANGES IN THE WILLYAMA BASIN, CURNAMONA PROVINCE**

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## **SUMMARY**

This contribution presents geochemical and Nd isotope data for sedimentary rocks from the Willyama Supergroup across the Curnamona Province. Firstly, the data corroborate earlier suggestions that the Arunta Inlier is a likely source terrane for the lower Willyama sediments (Barovich et al., 2002). Secondly, the data demonstrate a marked change in source provenance of the upper part Willyama Supergroup stratigraphy, the Paragon Group of the Broken Hill Domain and the Mt. Howden Subgroup of the Olary Domain. Page et al. (2000) documented an age discontinuity between the substantially younger detrital zircon population of ca 1648 Ma in the Mt. Howden Subgroup and Paragon Group, and the 1692 Ma graphitic ‘tuffs’ at the base of the Saltbush Subgroup (OD) and Broken Hill Group (BHD). Our data shows this structural or sedimentary disconformity of about 40 Ma is also marked by a change in source terrane.

## **BACKGROUND**

The Curnamona Province contains the world’s largest known Pb-Zn-Ag deposit at Broken Hill, hosted by the Broken Hill Group of the Willyama Supergroup. The Willyama Supergroup is an early Proterozoic sequence of metamorphosed quartzofeldspathic and pelitic sedimentary rocks, calcsilicates and minor volcanic and subvolcanic rocks, and is basement to the Province. The sequence extends across the Curnamona Province into the Olary Domain, SA, but questions remain about the extent of the stratigraphic coherence across the package. It is important to identify similarities in depositional age and source provenance across the Province, which will highlight the prospectivity for similar Pb-Zn mineralisation in the OD. Age and geochemical similarities have also been drawn between Broken Hill type mineralisation and stratiform/stratabound Pb-Zn-Ag mineralisation at Georgetown and in the Eastern Fold Belt (Page and Sun, 1998 and refs. therein). Additionally, linked tectonic evolutionary paths have been drawn between the Mount Isa Inlier and the Curnamona Province, based on similar depositional and tectonic evolutions (Laing and Beardsmore, 1986; Giles and Betts, 2000).

## **METHODS AND RESULTS**

U-Pb detrital zircon age data from sedimentary rocks can give us the spectrum of zircon-bearing source rocks, in addition to defining the maximum depositional age of the sedimentary rock. Page et al (1998; 2000) have demonstrated, through SHRIMP U-Pb zircon techniques, a solid temporal correlation between OD and BHD sediment deposition. In particular, they have determined contemporaneous depositional ages of ca 1690 Ma that link the economically significant Broken Hill Group to the Saltbush Subgroup of the OD. But disadvantages of detrital zircon dating include the fact that fine zircons, often derived from volcanic sources, may be lost in separation, and also, zircon-free mafic components are unidentified.

Geochemical and Nd isotope data are effective in establishing both an average provenance age and broad tectonic setting of sediments. Trace element distributions in fine-grained clastic sedimentary rocks are used widely to characterise both sediment source and constrain tectonic setting (McLennan et al. 1993). The most useful geochemical tracers are the rare earth elements (REE), Th, Sc and the high field strength elements (HFSE). The distribution patterns of these elements seem to be transferred effectively from source to sediment by way of the terrigenous component. Additionally, they are relatively robust during post-depositional alteration and metamorphism.

Th geochemistry of the BHD lower Willyama sedimentary rocks are unusual in their high HFSE, REE, U and Th contents, enriched by up to a factor of three or more compared to average upper crust. Nd isotopic compositions of sedimentary rocks from the lower part of the BHD Willyama Supergroup, the Thackaringa Group through the Sundown Group, match well with correlative units in the OD (from the Wiperaminga Subgroup through the Saltbush Subgroup). Using an average deposition age of 1700 Ma, Initial  $\epsilon_{Nd}$  values range from  $-4.0$  to  $-6.8$  across the Curnamona, and show no systematic variation vertically.

Conversely, the geochemistry of upper Willyama sediments, including the BHD Paragon Group and the OD Mt. Howden Subgroup, are much more typical of average upper continental crust. Initial  $\epsilon_{Nd}$  values are significantly less negative ( $-0.2$  to  $-1.4$ ).

## DISCUSSION

The highly enriched character of the lower Willyama sediments was probably inherited from their source. The similarity of the geochemical signature across the Curnamona strengthens our previous suggestion (Barovich et al., 2002) of the felsic highly enriched Arunta terrane as a likely dominant source region. This conclusion supports the reconstruction of Proterozoic Australia by Betts and Giles (2000), which places the Curnamona Province adjacent to the Mt. Isa terrane, and east of the Arunta. The Nd isotope compositions of the lower Willyama sediments are too negative to allow derivation solely from an Arunta source, and combined with consideration of the complex detrital zircon patterns (Page et al., 1998; 2000) may require some contribution from a Late Archaean terrane, possibly the Gawler Craton, or whatever lay to the present-day east of the Curnamona basin.

The shift in trace element geochemistry from enriched to typical crustal abundances and Nd isotope composition of the uppermost Willyama sediments requires detrital input from a source with a far more typical upper crustal composition, and a slightly younger mantle extraction age. Neither Th/Sc or Sm/Nd ratios suggest involvement of any mafic material. The change in the geochemical signature from enriched to normal upper crustal compositions could be explained by an absence of Arunta input, but such a change in provenance would still have to be accompanied by a new source input to explain the rise in initial  $\epsilon_{Nd}$  values. Based on stratigraphic considerations, Conor (2002) has suggested a present-day southeasterly source for upper Willyama sediments, but that terrane is currently unidentified. It is interesting to note that Page et al. (2002) have suggested a correlation of upper Paragon Group/Mt. Howden Subgroup sediments with tuff ages in the mineralised Mount Isa Urquhart Shale. Sparse sedimentary geochemical data from Mt. Isa sedimentary sequences suggests typical upper crustal sources, similar in composition to an upper Willyama sediment source.



## ACKNOWLEDGEMENTS

Work in the Curnamona Province has been supported financially by PIRSA and an ARC Linkage Grant to Hand, Barovich and Foden. GA kindly supplied samples and geochemical data for the Broken Hill area. Important contributions have come from discussions with Colin Connor and Rod Page.

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# **COPPER/GOLD, GOLD PROSPECTS IN THE BROKEN HILL DOMAIN**

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## **INTRODUCTION**

The Broken Hill domain (BHD) includes the outcropping Broken Hill and Euriovie Blocks and surrounding areas of shallow cover. It has been a focus for explorers seeking Broken Hill type Silver Lead Zinc deposits for well over a century, since the discovery in the domain of the giant deposit that defines that type. Although Cu and Au were found early in the domain's mining history and major deposits have been discovered elsewhere in Proterozoic domains, the BHD has remained relatively unexplored using modern methods. In the 1880s-90s, an association of Au with sulphides was frequently reported (eg in newspapers) as a reason for abandonment of Au prospects. Most regional soil, stream sediment, rock chip geochemical and metallogenic surveys were completed before 1980, when Au was not assayed. Large, tight ground holdings by companies with a narrow Pb-Zn-Ag focus and the cost of Au analysis limited exploration for these commodities. Changes in technology, a better understanding of regolith processes and sampling media, the exit of some major players and the formation of new strategic alliances, largely as a result of difficult economic times in the industry is now contributing to increased interest in the domain for these commodities.

## **EXPANDING Cu/Au INTEREST**

The NSW DMR has commissioned studies by Willis (2000) and Anderson and McConachy (2001) to evaluate the potential for Cu/Au and Au in the BHD. Reports from both studies are available from the NSWGS, as internet downloads or on CD. A summary of the first study and its findings was presented at the 2000 BHEI conference and those from the second study are being presented here. I will not, therefore, review them in detail.

The first study emphasised marked similarities between the stratigraphic, thermal and magmatic histories in the BHB and western parts of the Curnamona Province where Cu/Au exploration activity has been more intense. Similarities between alteration and mineralisation in the Curnamona Province and in other Eastern Australian proterozoic domains, of similar age, were emphasised. These include the Eastern Fold Belt of the Mt Isa Province and the Olympic Dam and Moonta areas (Olympic Domain), in South Australia. The association of Cu and Au mineralisation with iron oxides and potassic and/ or sodic alteration, is consistent.

Since this report was completed, timing relationships and correlations of stratigraphic and thermal events across the Curnamona Province have been clarified by results of precise geochronology (Page et al. 2000, in prep). Post and syn-deformation Mundi Mundi granites and some deformed leucogranites in the BHD have been confirmed as being the same age (ca. 1600–1585Ma) as Bimbawrie Suite granites and Benagerie Ridge volcanics in the Olary Domain and Hiltaba Granites and Gawler Range Volcanics in the Olympic Domain. Equivalent ages of the Plumbago Formation and Ettlewood Calc-silicate Member and probably the underlying Cu and Cu/Au mineralised Ethiudna Subgroup (Calc-silicate Suite) of the Olary Domain and uppermost units of the Thackaringa Group in the BHD have also been confirmed.

This theme continued into the second study, where regional (NSWDMR) geological, geophysical and metallogenic data sets were used to select targets for Fe oxide Cu/Au, sediment hosted Cu and skarn associated Cu/Au. Open file exploration data from target areas thus defined, confirmed that interesting Cu/Au targets had not been effectively tested.

## **KNOWLEDGE OF Au AND Cu/Au OCCURRENCE IN THE BHD**

Although earlier compilations provided limited information, more recent studies of the Euriovie Block and in the far south eastern parts of the Broken Hill Block have included useful assessments of Au and have confirmed a widespread association with Cu mineralisation in those areas. "Casual sampling" completed as part of the Willis (2000) study at several Cu prospects (with no previously known Au) confirmed mineralisation with Au at g/t levels, in some cases. A new study (Stage 3) that aims to extend this Au database across the BHD in a systematic way. Existing information is being reviewed and compiled progressively as a basis for this.

Information from several prospects is summarised in the BHEI 2003 excursion guide and additional information will be summarised in a Geological Survey Report in due course.

## **GOLD SAMPLING OF MINERAL OCCURRENCES**

Three campaigns of prospect sampling have been completed to date and although total sampling coverage to date is only ca. 20% of the Euriowie and Broken Hill Blocks, areas of particular interest have been highlighted and tentative observations on Au metallogeny can be made. These are summarised more or less in the order of their stratigraphic setting.

An obvious cluster of anomalies near the far southeast of the block defines a NE trending zone within and parallel to the margin of the magnetic Redan Geophysical Zone. Within this cluster, anomalous trends run either parallel to the zone, or NS-NW, parallel to mapped shear zones. Late (?Delamerian) dilational Au and Au/Cu bearing, vein arrays (eg Panama Hat and Huonville), are hosted by sodic and magnetic metasediments and basic or composite gneisses (Lady Brassey Fm, Thackaringa Gp). These and occurrences in the Battery Tank (Tors) area 15 km to the east were described by Burton (1994).

Other clusters of anomalies are related to Sisters type (magnetite) iron formations within the Lady Brassey or Himalaya Formations of the Thackaringa Group, for example in the Copper Blow, Iron Blow, Sisters and possibly Battery Tank areas. Results from the Razorback area have been disappointing except near Lady Well Tank, where the unit is structurally complex. Proximity to shear zones and structural disruption may be the key. Sampling for Au with Cu in iron sulphide-rich bodies in the Cues Formation has so far produced little encouragement for both commodities. High Au values have been recorded at the Son of Man prospect, but these appear to be related to isolated, late (Delamerian) veins, which may be significant where these veins are common (eg in the SE of the domain). Some Au anomalism has also been found at Yellowstone, where late shearing may also play a part. A cluster of highly Au anomalous samples is associated with granular (folded) quartz-rich Cu/Au lodes on the Diamond Jubilee trend, probably in the Himalaya Formation. Similar more isolated Au occurrences have been confirmed at Golden King (and possibly at Fairy Hill) in the southern Euriowie Block.

The Broken Hill Group has only been a focus for sampling in the Mt Robe area, which has been confirmed as an area of significant Au anomalism. Anomalous Au (~0.5g/t) occurs in samples of polymetallic mineralisation from the Silver King mines and a highly anomalous (57g/t) sample of pyritic quartz was collected from Golden Crest, both near the upper boundary of the Broken Hill Group. Samples from Cu mines NE of Mt Robe in the basal Broken Hill Group are also highly Au anomalous. Gold at the Pinnacles Mine (next section) may also be at this stratigraphic level, justifying increased attention in future campaigns.

Quartz veining in shear zones in the Sundown Group accounts for clusters of strong Cu/Au anomalies in the Corona (Anaconda), Bijerkerno and Mt Gairdner areas of the Euriowie Block. Similar anomalies occur at the King Gunnia Cu Mine and along the schist zone of the same name, in the western BHB and in the Kingfisher Mine area near the Kantappa SZ, in the north west of the BHB. In all but one case, this mineralisation occurs close to intersections of these or related shears with graphitic metasediments of the overlying Paragon Group. Samples from outcropping gossanous quartz veins within the latter in the Bijerkerno area and at Cartwrights Creek (on the Kantappa SZ trend) are highly Au anomalous (7.6g/t, 11.9g/t respectively), but no diggings are associated with either.

Post deformation magnetite-pyrite (Iron Duke type) bodies and breccias spatially associated with 1600Ma (anatectic) Umberumberka Granites locally have textures and compositions comparable with iron oxide associated Cu/Au systems. Unfortunately those sampled to date have not been significantly Cu or Au anomalous.

## **GOLD AND Cu/Au PROSPECT STUDIES – THE PINNACLES & BROKEN HILL**

Encouraging new diamond drilling and Au assay data made available by Pinnacles Mines has led to a focus on compilation and evaluation of this database, and to limited detailed followup sampling and analysis. Gold is commonly associated with the footwall margins (and some hangingwall) margins of the main stratabound upper Pb and Zn (quartz) lodes that have been mined in the past, in some cases reaching potentially economic grades and widths. Thick, newly defined (Zn mineralised) quartz lodes and/or garnet rich intervals intersected from 100m beneath and extending to the west of these include some strongly anomalous Au intervals. Copper anomalous (ca. 0.2–0.5%) intervals are common in the lower (and some upper) parts of these lodes and in some cases form a surrounding halo. The distributions of this Cu, minor Au (ca. 0.1–3g/t), pyrrhotite and pyrite overlap and there is some covariance of Cu and Au. Both are usually peripheral to and separate from higher grade Zn-Pb-Ag intersections within the lodes. Some of the deeper lodes and the fringes of the upper siliceous lode

intervals are characterised by abundant biotite and/or garnet and in some cases Au is hosted by these “altered” rocks. Sodic plagioclase gneiss and basic gneiss occurs in the deepest parts of some holes, but are separated from the mineralisation by a shear zone of unknown displacement.

Detailed re-sampling of selected Au anomalous intervals has highlighted local strong Au enrichment (to oz/t levels) near the weakly (Pb-Zn) mineralised margins of the quartz lodes and in some cases in adjacent garnet and/or biotite rich metasediments. This high-grade Au mineralisation shows no correlation with Cu, but has an apparent covariance with Ag/Pb ratios. The Au in these zones is not obvious and probably occurs as electrum inclusions in sulphides or sulphosalts (as at Broken Hill).

The marginal / footwall mineralisation at the Pinnacles is best described as polymetallic, as it commonly contains variable amounts up to a few percent of Zn and/or Pb, 0.2-0.5% Cu and 0.3 – 3 ppm Au with variable amounts of pyrrhotite and pyrite. This combination is similar to that found in the upper Himalaya Formation to lowermost parts of the Broken Hill Group elsewhere (eg at Polygonum North). The mineralisation, its distribution, the associated Fe-Mg-K “alteration” and possibly under-lying sodic alteration invite comparison with felsic volcanic hosted VMS deposits. The host of the Pinnacles mineralisation has been interpreted to be either the Broken Hill Group or the Cues Formation (Thackaringa Group). Pb-Pb isotope results from the Pinnacles Pb-Zn ore suggest that it is ~10Ma older than the Broken Hill deposit (Parr, pers. comm.) and similar in age to the basal Broken Hill or uppermost Thackaringa Group.

The Broken Hill Pb-Zn-Ag deposit has produced ca.700,000oz of by-product Au. An assessment of the Au distribution in the 1980s-90s confirmed that the ore typically carries 0.1-0.2 g/t Au. It was also found that the Au content increased by about an order of magnitude in some adjacent weakly (a few percent) mineralised quartz lode and garnet-rich rocks, particularly in the hangingwall (?stratigraphic footwall) of 2 and 3 lenses and A lode. The Au occurs as electrum in tetrahedrite and pyrrhotite inclusions in sulphide grains, and correlates with high silver-lead ratios. The enrichments were thought to be metamorphic. The studies apparently did not lead to further assessment, but the possibility that low grade Pb-Zn mineralisation may be Au bearing is worth considering throughout the district.

## DISCUSSION AND CONCLUSIONS

Gold and copper have been mobilised and deposited during a number of thermal events that have affected the BHD and deposition may have occurred due to different processes in each case. Polymetallic (Fe, Zn, Pb, Cu, Ag, Au +-+) mineralisation and some Cu/Au mineralisation is associated with and was probably deposited with uppermost Thackaringa Group to basal Broken Hill Group units, up to the Ettlewood Calc-silicate Member. It represents a target that has not been strongly emphasised due to a previous focus on Iron Oxide associated Cu/Au. Polymetallic, Au bearing mineralisation may also be associated with the final stages of deposition of the Broken Hill Group. Mineralisation at both levels is probably related to extension and syn-depositional basic and felsic magmatism.

Cu/Au and Au mineralisation during deformation, peak - waning metamorphism and syn-post deformation magmatism, is probably responsible for epigenetic mineralisation in geochemical and structural traps. This includes Fe oxide associated Cu/Au mineralisation, mainly in more oxidised units of the Thackaringa Group and various types of vein mineralisation. The potential for orogenic lode Au mineralisation in graphitic units in the upper part of the sequence is well worth considering. The giant, 30 Moz Ashanti deposit (Obuasi, Ghana) is an indication of the potential prize. High arsenic in the Cartwrights Creek area fits this model and it may be significant that anomalies of this type are located in lower zones of the metamorphic gradient in the BHD.

Cu, Ni, PGE and Au mineralisation is associated with mafic to ultramafic intrusions that have been linked to flood basalt extrusion in the Adelaidean. Deposition of Au with pyrite and minor copper occurred in dilational sites, probably during reactivation of shear zones and intrusion of mafic dykes and the Delamerian thermal event. It is probable that these overprint each other in particularly favourable sites. More extensive sampling and detailed followup work is proposed to fingerprint the different style of Au and Cu/Au mineralisation in the BHD. An embryonic proposal to extend current Pb isotope studies into this area is welcomed.

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# **PROTEROZOIC RECONSTRUCTION OF AUSTRALIA: CURNAMONA PROVINCE AND ITS NEIGHBOURS**

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## **INTRODUCTION**

There is a diverse range of geological phenomena that correlate between the component provinces of the north and south Australian cratons and provide evidence for a shared tectonic evolution between c. 1.80 and 1.50 Ga. Correlations exist between the c. 1.71-1.63 Ga basin evolution and stratigraphic architecture of these provinces, metallogenic styles and deposit types, as well as the timing and style of crustal shortening during the c. 1.60-1.50 Ga Olarian and Isan orogenies. Potential correlations in the geological evolution of the South Australian Craton and North Australian Craton have been noted by a number of authors (Laing, 1996; Page et al., 2000b). This contrasts with the interpretation of Myers et al., (1996) in which these cratons did not amalgamate until the c. 1.30-1.10 Ga Musgravian Orogeny. In this abstract we propose a reconstruction of Proterozoic Australia, which allows for the similarities in the geological evolution of the North and South Australian cratons, provides a mechanism for their motions during the Musgravian Orogeny and is consistent with published Palaeomagnetic data.

## **RECONSTRUCTION GEOMETRY**

We propose a pre-1.50 Ga reconstruction in which the South Australian Craton is rotated ~52° counterclockwise about a pole located at ~136°E and ~25°S (present day co-ordinates), relative to its current position. This reconstruction places the Curnamona Province to the southeast of the geophysical continuation of the Mount Isa Inlier. There are several major implications for the reconstruction. It places the basins of the Curnamona Province closer to temporally equivalent basins of the North Australian Craton. It aligns the c. 1.60 Ga to 1.50 Ga orogenic belts preserved in the Mount Isa Inlier, Georgetown Inlier, northern Gawler Craton, and the Curnamona Province, and places them adjacent to each other. It aligns the c. 1.80-1.70 Ga orogenic belts of the Arunta Inlier and the Gawler Craton. In addition, the reconstruction aligns a number of metallogenic belts. In particular, belts containing c. 1.67-1.59 Ga sediment-hosted Pb-Zn-Ag deposits and c. 1.60-1.50 Ga Fe-oxide Cu-Au mineralisation.

## **CURNAMONA AND ITS NEIGHBOURS**

The recent acquisition of geochronological datasets throughout the Proterozoic provinces of eastern Australia has highlighted numerous temporal coincidences (Page et al., 2000a, b; Raetz et al., 2002; Page and Sun, 1998; Giles and Nutman, 2002). The case for correlation during basin development is best supported over the interval c. 1.71-1.63 Ga, inclusive of the deposition of the Willyama Supergroup (Curnamona Province), the Maronan Supergroup (eastern Mount Isa Inlier), the Calvert and Isa superbasins (western Mount Isa Inlier), and the Etheridge Group (Georgetown Inlier).

The Willyama Supergroup, Maronan Supergroup and the Etheridge Group were deposited c. 1.71-1.60 Ga (Stevens et al., 1988; Page and Sun, 1998; Withnall et al., 1997). The Willyama and Maronan supergroups are floored by altered albite-rich metasediments deposited in shallow marine (Corella Formation underlying the Maronan Supergroup) or playa lake (Thakaringa Group/Wiperaminga Group of the Willyama Supergroup) environments. These

units are overlain by turbidites (Llewellyn Creek and Mount Norna formations, Broken Hill and Sundown groups/Ethiunda and Saltbush Groups and Robertson River Subgroup), suggesting a transition to a deep marine environment at c. 1.71 Ga (Page and Sun, 1998; Page et al., 2000b). In the western Mount Isa Inlier this period of deposition is characterised by syn-rift fluvial to shallow marine clastic sedimentary rocks within the Calvert Superbasin (Jackson et al., 2000).

Deposition of the turbiditic sediments overlapped in time with a period of bimodal magmatism c. 1.71-1.67 Ga in the Curnamona Province and the Mount Isa Inlier (Nutman and Ehlers, 1998; Page et al., 2000b). In the Curnamona Province granitic and mafic sills, including the Alma Gneiss, the Rasp Ridge Gneiss and the Round Hill Metagabbro, were intruded to the upper boundary of the Broken Hill Group. Intrusive rocks of this age have not been dated in the Maronan Supergroup, however, bimodal volcanism occurred in the Western Fold Belt of the Mount Isa Inlier at c. 1.71 Ga (Fiery Creek Volcanics, Weberra Granite) and c. 1.675 Ga (Sybella Granite).

Turbidite successions within the Curnamona Province and the Mount Isa Inlier are overlain by an upward fining sequence of carbonaceous mudstone and siltstone. In the Eastern Fold Belt these successions are represented by the c. 1.66-1.61 Ga Toole Creek Volcanics, Marimo Slate, and the Tommy Creek Beds (Page and Sun, 1998). In the Western Fold Belt they are represented by the c. 1.66-1.59 Ga Mount Isa and McNamara groups (Isa Superbasin), and in the Curnamona Province they are represented by the c. 1.66-1.64 Ga Paragon and Mount Howden groups (Page et al., 2000b; Conor, 2000). Temporally equivalent successions are also preserved in the central Gawler Craton (c. 1.65 Ga: Tarcoola Formation; Daly et al., 1998).

In both the Curnamona Province and the eastern Mount Isa Block sedimentation was followed by a major tectono-thermal event (c. 1.60-1.58 Ga; Page and Laing, 1992; Page and Sun, 1998; Giles and Nutman, 2002). This event is manifest as low-pressure metamorphism to granulite facies in the Curnamona Province (Stüwe and Ehlers, 1997) and upper amphibolite facies in the eastern Mount Isa Inlier (Jaques et al., 1982). In the Gawler Craton, this thermal event is defined by c. 1.59 Ga bimodal Gawler Range Volcanics and c. 1.59-1.58 Ga Hiltaba Granite Suite (Creaser and White, 1991; Creaser and Cooper, 1993). The late orogenic Mundi Mundi Granite Suite and Bimbowrie Granite, and undeformed rhyolites in the central Curnamona Province are temporally equivalent. This thermal event marked the onset of orogeny (c. 1.60-1.50 Ga) termed the Isan Orogeny in the Mount Isa Inlier, the Olarian Orogeny in the Curnamona Province, and the Late Kararan Orogeny in the northern Gawler Craton. MacCready et al. (1998) divided the Isan Orogeny into early thin-skinned deformation (c. 1.60-1.55 Ga) and late thick-skinned deformation (c. 1.55-1.50 Ga). In the eastern Mount Isa Inlier the early orogenic phase produced a north to northwest vergent fold and thrust belt (Betts et al., 2000), including highly non-cylindrical nappe-folds at tens of kilometre-scale (Loosveld and Etheridge, 1990). The late orogenic phase produced upright folds, steeply dipping reverse faults and wrench faults (MacCready et al., 1998). The Olarian Orogeny had a comparable evolution. Early high-temperature mineral fabrics associated with the 1.60-1.58 Ga thermal event are folded by north to northeast-vergent inclined to recumbent folds, some with highly non-cylindrical geometry (Forbes et al., in press). These structures are overprinted by upright folds with northeast-trending axial surfaces (Hobbs et al., 1984). An early episode of thin-skinned deformation is also preserved in the Coober Pedy Ridge coincident with c. 1.565 Ga high-temperature metamorphism followed by upright folding

coincident with metamorphism at c. 1.54 Ga (Daly et al., 1998), similar to the western Mount Isa Inlier.

### **PLATE TECTONIC SETTING OF THE CURNAMONA PROVINCE**

The size of Australia's Proterozoic provinces is such that plate boundaries and terrane margins are often not preserved making it difficult to determine the tectonic setting of individual provinces by studying them in isolation. Interpretations for the Palaeoproterozoic evolution of the Australian plate show that basins of the North Australian Craton evolved in a continental back-arc setting contemporaneous with north-dipping subduction, and accretionary and collisional orogenesis along the southern margin of the continent (c. 1.80-1.67 Ga: Giles et al., 2002). This was followed by thermal subsidence of the lithosphere and post-extensional sag-basin development (c. 1.66-1.60 Ga). Betts et al. (2003) relate this transition to the development of an ocean basin to the east of the Australian continent. We suggest that the lower groups of the Willyama Supergroup (Thackaringa, Broken Hill, and Sundown groups) form part of a network of continental back-arc basins and the upper Willyama Supergroup (Paragon Group) records the post-extensional basin evolution associated with the subsidence of the lithosphere.

The Olarian, Isan, and Late Kararan orogenies record a complicated evolution involving subduction along the southern and eastern margin of the continent. The onset of this orogenic event is related to the transition from arc-related magmatism (St. Peters Suite) to continental back-arc magmatism in the overriding plate of a north-dipping subduction zone. Orogenesis was coincident with A-type magmatism with a strong plume signature in the Gawler Craton (Hiltaba Granite Suite). We propose that the early stage of orogenesis was caused by flat subduction as a north-dipping subduction zone migrated over a mantle hotspot or plume. This resulted in a switch from crustal extension in the overriding plate to regional shortening. The thick-skinned orogenic evolution of the Isan and Olarian orogenies is interpreted to record approximately east-west shortening associated with the closure of the ocean basin to the east. This resulted in c. 1.55 Ga arc-magmatism in the Georgetown Inlier (Champion, 1991) and culminated in collision between the Australia and North America (Giles and Betts, 2000).

### **RECONSTRUCTION AND MINERAL BELTS**

The Palaeoproterozoic reconstruction geometry of the Australian continent shows that the Curnamona Province lies at the intersection of two significant mineral belts. The first mineral belt comprises sediment-hosted Pb-Zn-Ag massive sulphide mineralisation, which includes BHT-type deposits and Shale-hosted massive sulphide (SHMS) Pb-Zn-Ag deposits. BHT-type deposits formed during the latest stages of continental back-arc extension whereas the SHMS Pb-Zn-Ag deposits formed during thermal subsidence of the lithosphere (Betts et al., 2003). The second mineral belt is defined by the linear distribution of Fe-oxide Cu-Au deposits, which extends from the southern Gawler Craton through to the Mount Isa Inlier.

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# **DETAILED REGOLITH MAPPING AS A TOOL FOR REFINING THE INTERPRETATION OF GEOCHEMICAL RESULTS AT WHITE DAM, CURNAMONA CRATON, SA**

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Detailed regolith mapping (1:2k) is proving to be an invaluable tool in the interpretation of geochemical data over the White Dam Prospect by allowing the ranking of surface geochemical anomalies. Using this approach exploration assay results can be linked to local dispersion pathways thereby helping to recognise geochemical signatures that are transported (ie. displaced) from mineralisation sources in contrast to ones closely adjacent to potential mineralisation sources. This is an important step in relating surficial regolith assay results with mineralisation sources in areas of transported cover.

## **GEOLOGICAL AND MINERALISATION SETTING**

The White Dam Au-Cu prospect is about 31 km NE of Olary. The mineralisation was discovered by MIM through a combination of soil geochemistry and drilling between 1990 and 1997. The soil geochemistry at White Dam did not clearly delineate the orebody, with the main soil geochemical ‘anomaly’ identified relating to a weakly mineralised sub-cropping margin of the orebody. (McGeough & Anderson, 1998). The mineralisation is a stratabound, hosted in biotite enriched quartzofeldspathic gneiss with abundant leucocratic bands or veins. It is relatively Fe-poor and lacks a strong association with As, Ag, Ni, Cd, Sb and Pb which is typical of other Au-Cu mineralisation (Cordon, 1998).

## **MAPPING**

Regolith-landform maps have been produced at two scales: a regional 1:25k map centred on the White Dam prospect; and, a detailed 1:2k map of the main prospect area. The regional map provides a broad regolith-landform context, while the local map provides a specifically detailed context for the closely spaced surface geochemical sampling program.

The 1:25k mapping was done largely by air-photo interpretation of ortho-imagery provided by PIRSA, and was followed up with field description and ground-truthing. This approach is relatively rapid and provides a good regional perspective for the White Dam deposit and adjoining areas. Its value is limited however when attempting to interpret closely spaced geochemical sample points, particularly in areas of transported cover. The 1:2k mapping was done with a much greater emphasis on field mapping, delineating subtle, yet important changes in the regolith and landforms over mineralisation and the adjacent area. Although more time consuming, the level of detail provided here allows for greater confidence in the reinterpretation of existing data and the ranking of surface geochemistry ‘anomalies’.

## **REGOLITH-LANDFORM SETTING**

The White Dam prospect area is dominated by shallow overland flow (sheetflow) deposits. These occur over erosional rises and within depositional plains directly over mineralisation. The sheetflow deposits have a distinctive ‘contour band’ surface pattern consisting of irregular bands vegetated by bladder saltbush (*Atriplex vesicaria*) in between bands of pebbly surface lag. Erosional rises with slightly weathered bedrock occur to the E of mineralisation



and shed some detritus across the prospect area. To the W and N of mineralisation are alluvial channels and associated plains. Calcretes occur irregularly across the area and are mostly of the fragmented hardpan and nodular morphologies. Recently obtained surface calcrete sample assays indicate Au contents ranging between 86 ppb and approaching detection limit (1 ppb) within the prospect area.

## **SURFACE DISPERSION VECTOR MAPPING**

The identification of centimetre-scale high bands of organic fragments, or ‘stick dams’, as a means of mapping subtle, surface dispersion patterns due to shallow overland flow (sheetflow) has been developed in this study. By recording the flow directions as indicated by the stick dams, surface dispersion vectors can be represented on the regolith-landform maps.

Stick dams are the result of debris accumulation caused by shallow overland flow, and may consist of sticks, leaves, twigs and other plant debris and may macropod droppings. Stick dams can be mostly observed in a perpendicular orientation to surface flow direction, and when forming on the lee-side of bushes and other obstacles (‘shadow deposits’), they may also form parallel to flow. Flow directions are measured by taking a compass bearing through the central axis of the curve or perpendicular to the feature for more linear dams. In the case of linear stick dams, that form parallel to flow, a bearing may be taken along the long axis of the feature. Surface flow vectors can then be shown on regolith-landform maps as individual symbols or data populations from some sites may be shown on rose diagrams.

## **DISCUSSION**

Soil geochemistry previously obtained within the White Dam prospect shows a number of points with elevated Au results. When these points are presented in the context of the regolith-landforms and surface dispersion vectors, a ranking hierarchy can be derived to indicate which ‘anomalies’ are most likely to reflect immediately adjacent mineralisation as opposed to dispersed or transported responses. When these results are compared to the known position of the mineralisation, as delineated by extensive drilling by MIM and partners, it can be seen that some of the previously identified soil geochemistry ‘anomalies’ are displaced from mineralisation due to surface dispersion whilst some directly overlie it.

Continuing work at this site will investigate the effect of the regolith cover on the dispersion of Au and other elements at White Dam with the objective of further developing a regionally applicable exploration model for areas of shallow transported regolith.

## **ACKNOWLEDGMENTS:**

The authors would like to thank the following for their support during this project. CRC LEME, PIRSA, Andy Treloar (Tikalina Station), Nick Shearer (Bullo Ck Station), Steve Law at MIM exploration and David Sproule at Polymetals for all support rendered and for continued access to geochemical data and the White Dam site.

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# **THE MOUNT DAUBENY BASIN: A MINERALISED LATE SILURIAN TO EARLY DEVONIAN PULL-APART STRUCTURE**

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## **INTRODUCTION**

The Late Silurian to Early Devonian redbed-dominated Mount Daubeny Formation was deposited into two fault-controlled basins in far western New South Wales. The Churinga Basin (new name) and Mount Daubeny Basin (MDB) were developed on the western side of the Koonenberry Fault, with the MDB being the better exposed example. Recent mapping and reinterpretation of the MDB has revealed many features consistent with development as a pull-apart basin between the bounding Bedford/Gap Range and Koonenberry Faults. The Basin developed in response to southwest and northeast-directed compression and resultant dextral strike-slip faulting during the Silurian. Understanding basin architecture and the post-Silurian structural history of the Koonenberry Belt has implications for mineral exploration within the Devonian redbed sequence, within pre-Silurian basement as well as the petroleum potential of surrounding Devonian basins.

## **PULL-APART BASIN HYPOTHESIS**

In terms of gross basin morphology, the MDB has two relatively straight fault-controlled sides and at non faulted sides, has irregular basin margins and related folds, developed as a result of convergence between the bounding dextral faults. Other features within the MDB consistent with this hypothesis include: the presence of older basement slide blocks adjacent to the bounding faults; rapid facies changes basinward; complex intraformational unconformities, particularly at basin corners; and the development of igneous centres and related mineralisation within the basin floor (Figure 1).

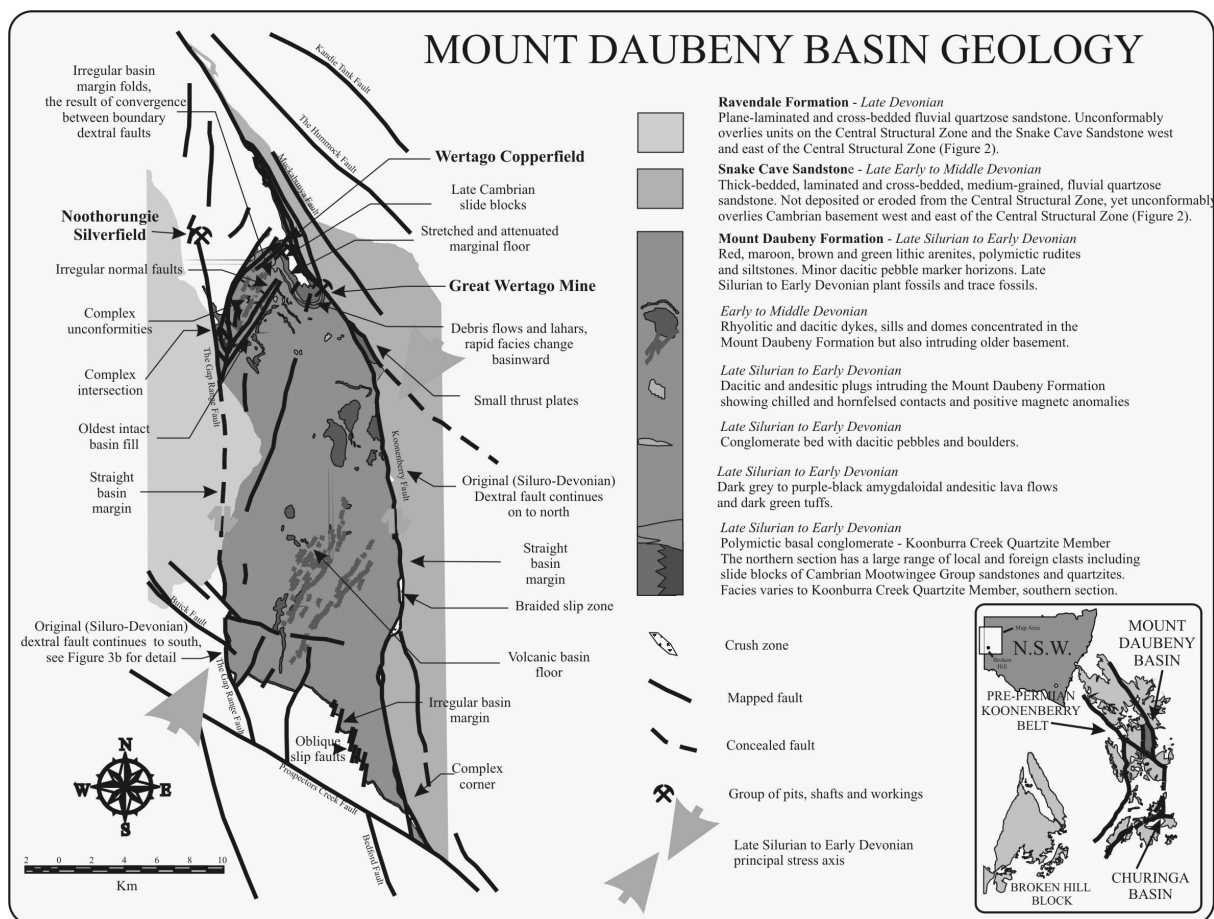
The Koonenberry and The Gap Range Faults each have a north south strike adjacent to the MDB. These sections of the faults represent basin-bounding slip zones at the straight basin margins during Siluro-Devonian dextral fault movement. It is postulated that during basin development, Cambrian basement between the bounding faults and beneath the MDB was stretched and attenuated, progressively subsiding with each movement of the bounding faults. Complex unconformities at basin corners and the abundance of intraformational unconformities are evidence of this rapid subsidence. Continued attenuation of the basement would have led to high heat flows and may have resulted in the development of the igneous centres that intrude the basin as well as magmatism within the adjacent basement. The dominant strike direction of dyke rocks is parallel to the southwest-northeast compression, proposed as the principal stress axis during the Late Silurian and Early Devonian (Figure 1).

Dextral faulting and basin development perhaps initiated during the Benambran Orogeny with southwest-northeast compression developed in response to the collision of the Thompson Fold Belt with the Koonenberry Belt. Deposition of the Mount Daubeny Formation ceased in concert with waning dextral movements on the bounding Koonenberry and Bedford/Gap Range Faults. The central part of the Koonenberry Block most likely remained an elevated block, perhaps a mountainous area with localised depocentres such as the Mount Daubeny and Churinga Basins forming adjacent to strike-slip faults. Unlike the terrestrial MDB environment, time equivalents of the Mount Daubeny Formation, such as the Winduck Interval of the Darling Basin sequence are marine successions (Bembrick 1997). This observation and the fact that no Mid Devonian Snake Cave Sandstone exists on the Central Koonenberry belt, suggests that the Central Koonenberry Belt remained an elevated area from the Late Silurian until the Late Devonian deposition of the Ravensdale Formation. The unrepresented Mid Devonian Snake Cave interval was most likely not deposited or, was deposited but, soon after deposition, was completely eroded off the Central Koonenberry Belt prior to the deposition of Ravensdale Sandstone.

## **METALLOGENY AND IMPLICATIONS FOR FURTHER EXPLORATION**

Recognition of the mode of basin development and elucidation of the structural history of the area surrounding the MDB has implications for the mineral potential of the Koonenberry Belt. The setting and formation of known mineralisation can be placed in context. Copper, silver and gold mineralisation is known in the MDB, within bounding fault planes and within Cambrian basement rocks immediately north of the Basin margins. At the Noonthorungie Silverfield (Figure 1), argentiferous galena was mined in widespread steeply dipping quartz – siderite - calcite veins, along with rich secondary mineralisation (chlorargyrite, embolite and cerussite). Hand

picked ore (circa 1890 - 1892) proved to be very rich in silver (up to 6528 g/t). A broad, magnetic anomaly coincident with old workings within the Noonthorungie Silverfield may indicate an associated subsurface intrusion. The Great Wertago Mine (Figure 1) was discovered in 1875 and is part of a fault or shear-controlled lode system intermittently developed along 8 km of the Koonenberry Fault and marked by malachite and azurite staining in outcrop. Nearby the Wertago Copperfield (Figure 1) occurs around the thickened northern termination of an andesite body - perhaps prospects are near a source vent for the andesitic magma.



**Figure 1.** Geology of the Mount Daubeny (pull-apart) Basin based on the work of Neef and Bottrill (1991), Buckley (2000) and Mills and Hicks (2000)

The MDB is a time-equivalent of parts of the Cobar Basin, subjected to a similar deformational history with structures involved in basin formation overprinted by later deformations. Cobar-style mineralisation may occur within the basin and mafic shear zone-hosted mesothermal lode gold may also be expected in Cambrian basement rocks adjacent to the Koonenberry Fault. Elucidation of the mode of deposition of the Mount Daubeny Formation within the MDB has provided a window on the timing of deformations affecting the southern Koonenberry Belt. These deformations have provided fluid pathways for mineralisation and have also affected sedimentation in adjacent troughs where oil and gas potential exists Bembrick (1997).

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# GEOLOGICAL MAPPING AT THE POTOSI OPEN PIT

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## INTRODUCTION

The Potosi deposit is located 2 km north-east of the city of Broken Hill. It was originally discovered in 1883 and was mined on a small scale in the late 1800's till the early 1900's. Evaluation by Pasminco Limited in 1991 led to the definition of an open pit reserve. The first ore was milled in April 1996 (Morland and Leever, 1998) and mining ceased in January 2000 after producing approximately 750,000 tons of ore. On completion of mining, bench mapping was conducted within the Potosi pit. This work was combined with limited data collected during the mining operation with the aim of producing a geological map, as well as bench plans and ore outlines. These data suggest the Potosi mineralisation, although significantly affected (and perhaps upgraded) by deformation, retains much evidence for a syngenetic origin. Although dwarfed by the Broken Hill main lode, the Potosi mineralisation is also of the Broken Hill type. The stratigraphic location of the Potosi mineralisation, below that of the main lode (Figure 1), also makes the mineralisation noteworthy and imparts exploration implications for both identified mineralisation and greenfields areas in the Broken Hill block.

## POTOSI OPEN PIT GEOLOGY

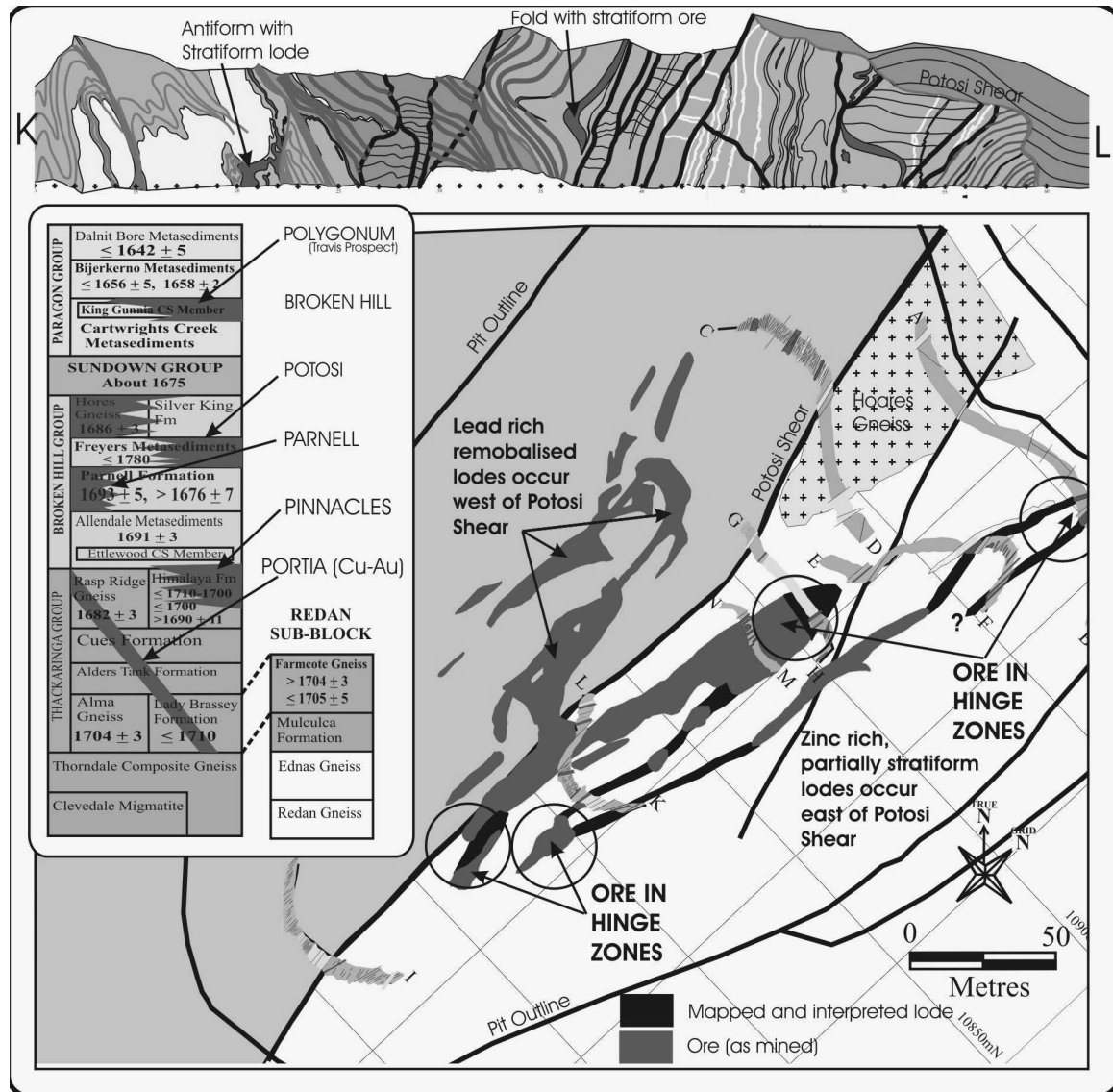
Central to the understanding of Potosi geology is the question of its syngenetic (stratiform) nature or its epigenetic (structural) emplacement. Two distinct domains of mineralisation, a "shear hosted" domain within the Potosi Shear and the "psammite hosted" domain on the eastern limb of the Potosi Synform dominate the geology of the open pit. An apparent addendum to the complexity of the open pit geology is the presence of ore mobilisation and structural upgrading of the lodes, with even the psammite hosted lodes of the "unsheared" eastern limb containing abundant, rounded blue quartz gangue and a deformed (*durchbewegung*) texture and locally sheared margins. Mineralisation comprises sub-massive to massive, medium-coarse grained, black, iron-rich sphalerite (marmatite), with lesser interstitial, fine-medium grained galena and minor chalcopyrite and pyrrhotite. Within the "unsheared" eastern portion of the deposit, mineralisation is typically enveloped by a blue-quartz alteration halo, with variable disseminated galena, pyrrhotite, pyrite, chalcopyrite, sphalerite, gahnite and garnet. In cross section view the "Unsheared" sulphide bodies are oriented sub-parallel to the fold axial surface and plunge of a mesoscopic synform (dips 60° NW and plunges 15° towards 063° M). McGunnigle et.al. (1998), highlighted a strong structural control to the mineralisation, characterised by remobilisation within the Potosi Shear plus the presence of a blue quartz alteration halo, suggesting the possibility of structural emplacement of primary mineralisation and subsequent remobilisation improving the economics of the deposit.

As can be expected with massive sulphide ore, the lodes at Potosi are amenable to visual grade control and mining methodologies. Mapping within a production based, cost sensitive environment is often given a low priority and little mapping was conducted during mining at Potosi. From a mining point of view, lodes (or ore outlines) were defined by economic grade cut offs and minimum mineable widths, using sectional interpretation. When geological mapping is applied and lodes are defined by lithology and grade reconciliation plans, it becomes apparent that transgressive, vein like, brecciated '*durchbewegt*' sulphides occur within hinge zones. In sectional view, economic ore outlines appear as shoot like bodies with an orientation and plunge similar to that of the axial trace of the Potosi synform. However, mineralogical and lithological criteria from detailed bench mapping and examination of blast-hole data, reveals that deformed stratiform lodes continue around the Potosi Synform, wholly within Freyers Metasediments (Unit 4.5). Local uneconomic segments gave the impression, during grade control mapping, that the lodes were not continuous (McGunnigle et.al., 1998)

## METALLOGENY AND IMPLICATIONS FOR FURTHER EXPLORATION

The stratigraphic sequence, including the Freyers Metasediments, the Hores Gneiss plus the sulphide bearing lode rock units and pegmatite, is repeated about the Potosi Synform. Locally, the sulphides and lode rocks are transgressive to the primary layering or are partially transposed into S2 and S3 via D2 and D3 shearing. Ore has also been transposed within the retrograde shear schistosity. Lodes within the retrograde Potosi Shear and some S3 fabrics are more vein like and often galena rich. Sulphides can be seen within all the fabric controlled structural situations within the Potosi Open Cut and transgressive vein-like brecciated '*durchbewegt*' sulphides are common in the hinge and on the flanks of the Potosi Synform. In summary, stratiform massive sulphide is folded about the Potosi Synform and has been remobilised into all subsequent structures.

The Hores Gneiss is host to the Broken Hill mineralisation yet the Potosi occurrence proves that economic Broken Hill-type orebody occurs in other parts of the Broken Hill Group. New models, developed from direct observation of active sea floor deposits suggest that minerals are deposited beneath the sea floor mound in stacked systems; observations at Potosi are consistent with this model. Morland and Leever (1998) observed that the better developed sections drilled so far in the Freyers Metasediments (unit 4.5) at Potosi, correspond to the higher grade intersections in the overlying Hores Gneiss, like the Silver Peak shoot. The recognition of this stacked nature is a reminder that exploration beneath a resource is often rewarded.



**Figure 1.** Stratigraphic location of the Potosi mineralisation and simplified representation of the open pit geology. Example face mapping section (upper portion of figure) relates to line L to K in the plan view.

The mapping work of Wolfgang Leyh of Eaglehawk Geol. Consulting at Potosi is thankfully acknowledged. Published with permission of the Director-General of the NSW Department of Mineral Resources.

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# METALLOGENESIS IN THE OLARY DOMAIN: EVIDENCE FROM TRACE ELEMENT AND SULPHUR ISOTOPIC STUDIES OF PYRITE

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## INTRODUCTION

The trace element geochemical and textural characteristics of the different generations of Olary Domain pyrites allows us to make a number of observations about the conditions they formed in and the deformational history they preserve. In the Olary Domain, pyrite is by far the most abundant sulphide. Unlike most other sulphides which recrystallised after peak metamorphism and associated deformation, textures exhibited by pyrite reflect the entire metamorphic and deformational history undergone by the sulphide occurrences. Textures vary considerably between localities and commonly reflect changes in metamorphic grade between localities and the rheological behaviour of the refractory pyrite relative to the matrix minerals during deformation. Pyrite deformation in both the brittle and ductile fields is recorded in the textures of pyrites from the Olary Domain.

## TRACE ELEMENT AND ISOTOPIC COMPOSITION OF PYRITE

Six main stages of pyrite growth in Willyama and Adelaidean sulphide occurrences have been identified on the basis of textural and geochemical differences in this study. Pyrite I forms the cores of many composite pyrite grains it is interpreted to be pre-metamorphic. Pyrite II occurs as euhedral to subhedral disseminated grains associated with chalcopyrite and pyrrhotite most likely generated through remobilisation of pyrite I. Pyrite III is closely associated with pyrrhotite, the lack of zoning and frequent alignment of the crystals within the host pyrrhotite suggests pyrite III is an exsolution phase. Pyrite IV occurs in fine veinlets penetrating cleavages of muscovite, it is also associated with clusters of epidote suggesting a possible formation during a retrograde stage of metamorphism. Pyrite V is found in association with chalcopyrite in epigenetic quartz veins cross-cutting Olarian fabrics. Pyrite formation in the Adelaidean sequences is dominated by pyrite VI. Pyrite VI is associated with the emplacement of Delamerian granitoids, such as the Anabama Granite.

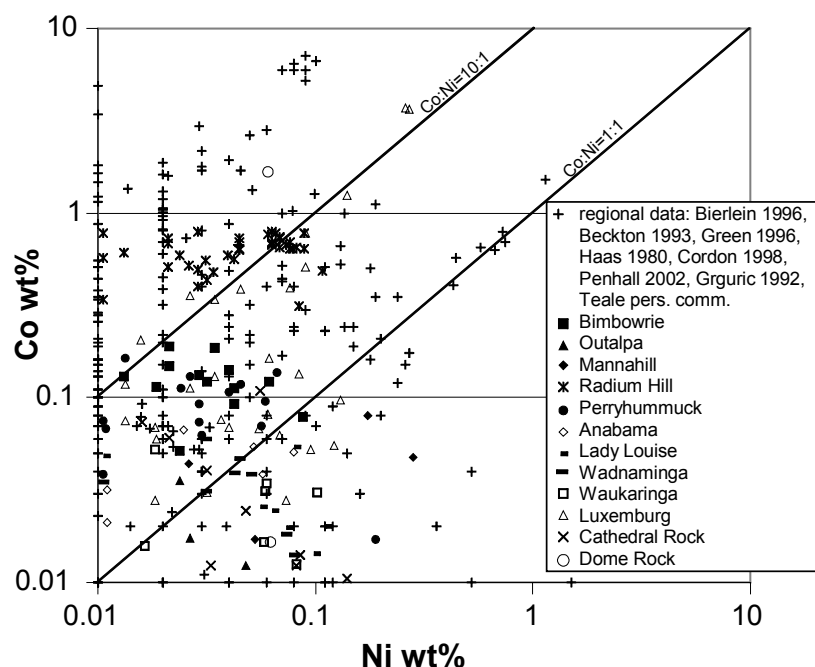


Figure 1: Cobalt- Nickel concentrations in pyrite from the Curnamona Province

Pyrites from different settings have been analysed for their trace element composition to identify possible genetic relationships or source indications. This is most prominently expressed in their cobalt and nickel content (see Figure 1). High cobalt content and high Co/Ni ratios are interpreted as to indicate a magmatic affiliation of the mineral forming solution. In Figure 1 this is most evident for the Luxemburg and Radium Hill locations, both of which are within or in close spatial association with magmatic rocks. Cobalt content of these pyrites is generally high and the Co:Ni>10. Pyrites of Adelaidean age usually have low Co content and also low Co:Ni

ratio (e.g. Anabama, Figure 1). 135 sulphide samples from 15 locations were analysed for  $\delta^{34}\text{S}$ . Samples were broadly classified into “epigenetic”, “stratabound”, related to “Iron Formation” and of Adelaidean origin. The overall spread in  $\delta^{34}\text{S}$  values are from -16 to +11‰. Most analyses yield values between -2 to +4‰ (see Fig. 2). The rather unimodal distribution of  $\delta^{34}\text{S}$  values

suggests a rather uniform source of the sulfur. The low ratios can be explained by local influx of biogenic sulphur, “heavy” sulphur ratios most likely are related to a contribution of sulphur from oxidising, possibly evaporitic environments.

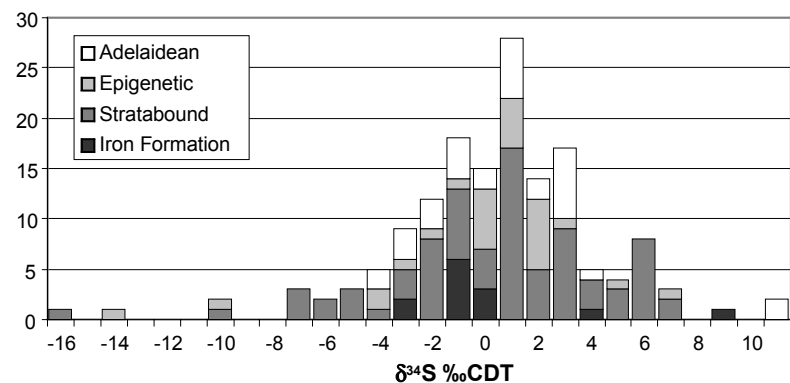


Figure 2: Sulphur isotope ratios of pyrite from the Curnamona Province. Included are data from Bierlein (1996)

## METALLOGENIC EVOLUTION

The different generations of pyrite and their petrographic relationships allow us to put the evolution of the Olarian/Adelaidean mineralising system into a temporal and tectonic context. The evolution of the basin into which the Willyama Supergroup sediments were deposited in is still the subject of much debate. Similarities exist between the Macarthur basin, Mt Isa inliers and the Curnamona Province and it has been suggested that these basins were once linked. During the period of extension and basin formation exhalative mineralisation styles such as the stratiform Cu-Pb-Zn deposits at Polygonum and North Portia occurred. The felsic volcanoclastic material deposited during the early stages of basin formation and associated pyrite has a relatively low Co and Ni content but still retains the high Co:Ni ratios as a consequence of this, Pyrite I can be linked to early mineralisation during the opening of the Willyama basin.

Subsequently sediments belonging to the Strathearn Group were deposited on top of the oxidised Curnamona group volcanoclastic and quartzose sediments in the subsiding basin, defining a distinct redox boundary with local concentration of sulphides (Bimba formation, Ethiudna, Mt Howden, Lady Louise). High Co sulphides formed from basinal brines reacting with mafic rocks, such as the Woman in White amphibolite. The source of sulphur for this style of mineralisation is thought to be minor scale remobilisation of sulphides deposited during sedimentation.

# FLUID MIGRATION AND HYDROTHERMAL BRECCIATION IN THE OLARY DOMAIN, SA

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## INTRODUCTION

The Olary Domain contains many different examples of brecciated rock. The breccias are the site where the most intense effects of hydrothermal alteration are visible indicating a possible genetic link between the processes of brittle deformation and alteration. Breccias are mostly located in the central and northern part of the Olary Domain where they have been found in the Wiperaminga, Strathearn and Mount Howden Subgroups, but occur predominantly in the Ethiudna Subgroup. Previous studies (Cook and Ashley, 1992; Yang and Ashley, 1994) identified four main types of breccia: calc-silicate breccias, albitite breccias, iron formation breccias and breccias containing albititic clasts in a biotite matrix. This study focuses on three localities, Cathedral Rock, Doughboy and the Telechie Valley each of which exhibit different aspects of the brecciation process as observed in the Olary Domain. The structural and microstructural setting, contact relationships with the host lithologies and mineralogy have been examined in detail in an attempt to place the process of brecciation into the regional deformational history of the area. The deformational history used in the paper is that which is outlined by Flint and Parker (1993).

## DOUGHBOY BRECCIA

The Doughboy breccia, located in the northern Outalpa Inlier, is an elongated body of breccia that stretches 1.5 km from southwest to northeast and is approximately 0.5 km. It is surrounded by pelitic metasediments and lies in the core of a macroscopic  $OF_3$  synform that plunges to the southwest. The breccia exhibits a strongly developed near vertical  $OS_3$  fabric which is axial planar to the  $OF_3$  fold. The contact between the breccia and the metapelitic schists is exposed best at the southern margin of the body. Here the schists generally display a more highly strained fabric than those more distal from the contact.

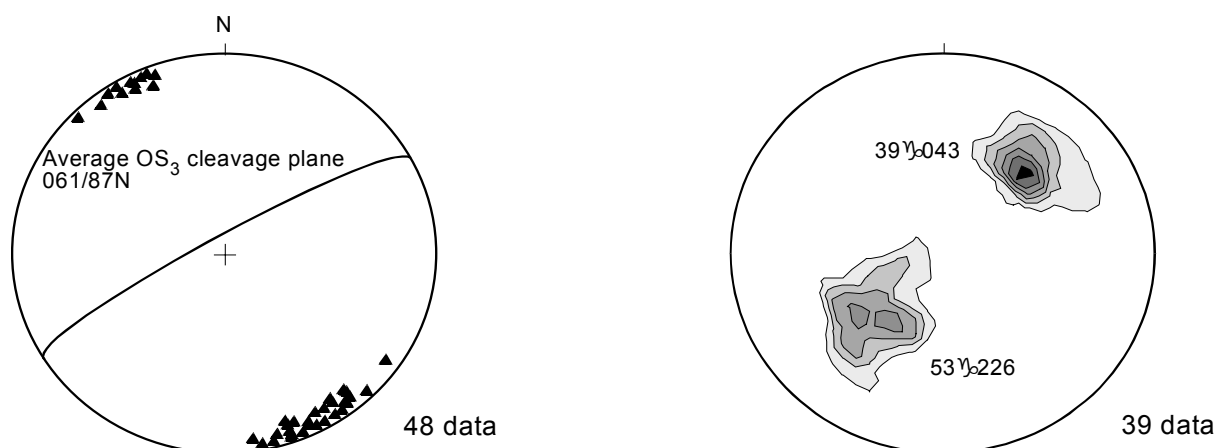


Figure 1: Stereonets showing the structural position of the Doughboy breccia (Clark & James, 2003)

The breccia body contains rounded to sub-rounded albitic clasts, dominantly under 1 cm in diameter, supported by a foliated, fine-grained matrix of biotite + quartz + plagioclase + k-feldspar + actinolite + magnetite. Clasts are oriented in a direction roughly parallel with the



OS<sub>3</sub> fabric and exhibit no compositional variation and little internal deformation. Hydrothermal alteration in the Doughboy breccia is evident as zones of intense albitisation, magnetite veining and development of coarse-grained aggregates of interstitial actinolite.

### **CATHEDRAL ROCK BRECCIA**

At Cathedral Rock the breccia is situated in the fold closure of a parasitic tight to isoclinal south plunging ENE-trending OF<sub>2</sub> antiform. The breccia is bound on both sides by a northeast trending OD<sub>3</sub> shear zone. The breccias are hosted by the Ethiudna subgroup and the breccia can be observed to grade from massive to laminated calc-albitite rocks with calc-silicate-rich veins to clast supported and matrix-supported breccias.

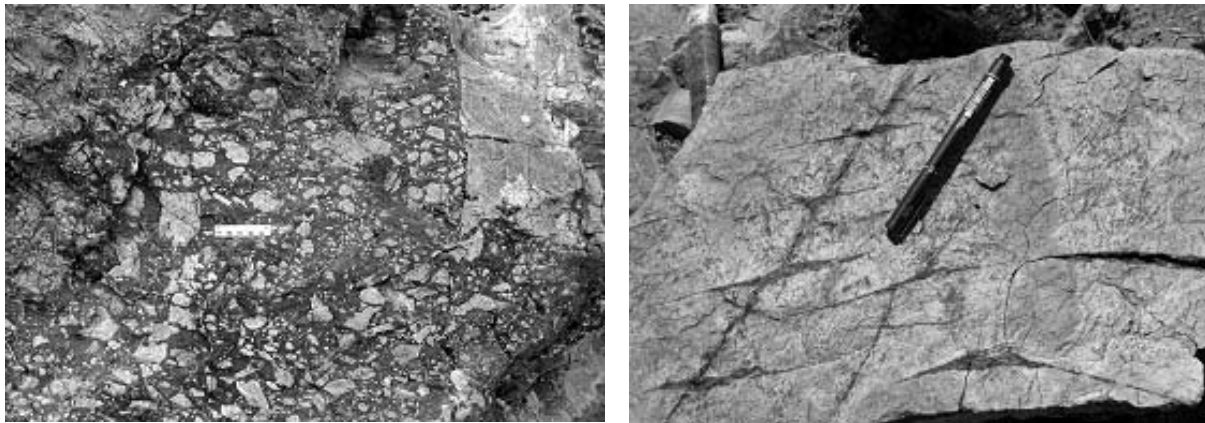


Figure 2: Cathedral Rock breccia (left) and amphibole veins associated with the OS<sub>3</sub> fabric (right)

The Cathedral Rock breccia consists of angular to sub-rounded inequidimensional randomly oriented albite-quartz rich clasts up to several meters across supported by an unfoliated, coarse grained matrix of clinopyroxene + actinolite + albite + quartz + magnetite. Granitic pegmatite dykes cut the breccia causing replacement of the calc-silicates by biotite. Alteration of the Cathedral Rock breccia manifests itself as a progressive overprinting of white to pink albite + quartz + hematite and local development of interstitial actinolite.

### **TELECHIE VALLEY BRECCIA**

There are two styles of breccias outcropping in the Telechie Valley. They are an actinolite matrix breccia, which outcrops in a series of discrete bodies along the middle of the valley. This style of breccia grades from local veins of actinolite in a calc-silicate lithology to a fully developed actinolite breccia in a northeasterly direction. There is a strong relationship between the breccias and the process of albitisation in the valley. Albitisation is preferentially developed along OS<sub>3</sub> cleavage planes implying a syn or post OD<sub>3</sub> albitisation event. The

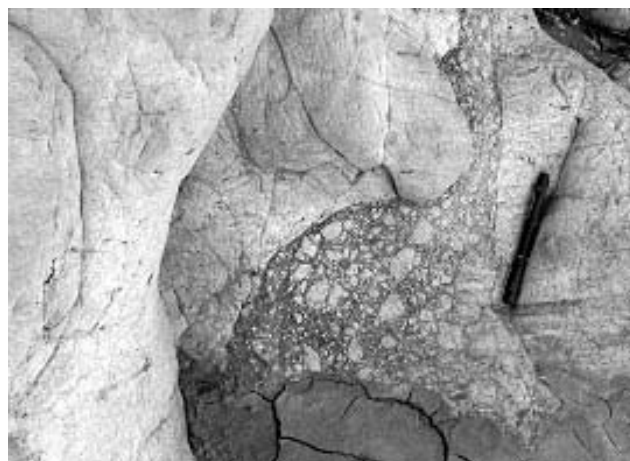


Figure 3: Intrusive breccia pipe

intraformational breccias in the valley demonstrate a high degree of structural control and are preferentially located in the hinges of OF<sub>3</sub> antiforms in the area is an intrusive / transformational breccia. This breccia also has an actinolite matrix but in a number of

localities this has been altered to biotite. Transformational breccias intrude the Poodla granite on the western side indicating that brecciation postdates granite emplacement. Previous studies of the isotopic composition of the breccia matrix have indicated a metamorphic origin of the fluid involved in brecciation.

## STRUCTURAL ANALYSIS

Structural mapping has been carried out at the three localities in an effort to put the breccias into the regional tectonic framework. In all localities breccias are structurally controlled and dominantly associated with OD<sub>3</sub> structures suggesting a syn to post OD<sub>3</sub> timing. Microstructural analysis of breccia related quartz veins has provided a link between the generation of fluid inclusion planes and the breccia geometry. Future analysis of this generation of fluid will further constrain the source of the fluids involved in the brecciation process. Monazites associated with the fluids will also provide a temporal constraint on the brecciation process.

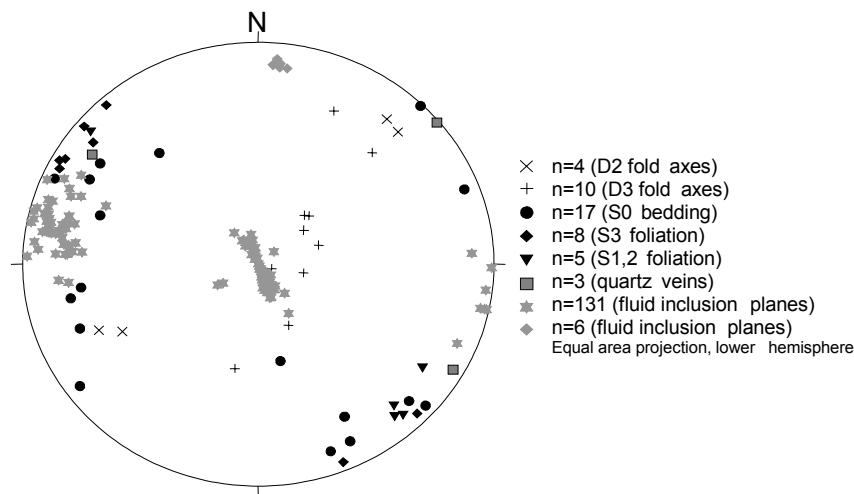


Fig 4. Relationship between fluid inclusion planes and various structural fabrics identified in the Telechie Valley

## BRECCIATION PROCESSES IN THE OLARY DOMAIN

The principal mechanism for the two styles of brecciation identified in this study is the variation of fluid pressure inducing brittle failure (Clark & James, 2003). The structural positions of the investigated breccias indicate a link between the OD<sub>3</sub> fabrics and structures and breccia formation. One of the major problems of this relationship is the nature of the OD<sub>3</sub> event which has historically been defined as a retrograde event (Flint & Parker, 1993). A retrograde event would not produce enough fluid to initiate brecciation in the observed localities. Therefore a new fluid generating mechanism needs to be identified. A number of processes can be proposed to explain the origin of the brecciating fluids. For example the breccias formed later in the tectonic history of the region and that prior to brecciation the rocks of the Willyama Supergroup underwent a rehydration process during an extensional event. Examples of in-situ as well as intrusive breccias are found in the overlying Adelaidean and in the Mt Painter region, indicating that brecciation in the Willyama Supergroup may not be restricted to the Olarian Orogeny

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# THE ECONOMIC SIGNIFICANCE OF THE VOLCANO-EXHALITE ASSOCIATION IN THE OLARY DOMAIN

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Iron-rich rocks, in places manganiferous, are not uncommon in the Olary Domain and bear comparison with such lithologies as 'garnet sandstones' and iron formations that are a feature of the Broken Hill Domain. The Olary exhalites have been previously and notably studied by M. Laffan (1994), Lottermoser and Ashley (1996), Ashley et al. (1998). They have received the attention of the exploration industry, eg. Newmont, Australian International Nickel, Carpentaria Exploration, MIM and Esso Exploration, and are commonly base and precious metal anomalous. As with the Broken Hill Domain the distribution of exhalites is stratigraphically restricted, occurring in and below the lower Saltbush Subgroup (Broken Hill or lowest Sundown Group equivalent). A new factor of importance, not clearly recognised previously, is the common association of these rocks with both felsic and mafic volcanic units. This is partly because the existence of felsic volcanism has been proven only in recent years, eg. Buckley (1993), Ashley et al. (1996). Moreover these volcanics of the ca. 1710 Ma Basso Suite are commonly iron-rich (magnetite and pyrite), and are in places accompanied by iron formations.

This presentation is based upon on-going studies of the following four volcanic-associated, exhalite-bearing sequences:

- 'Creag Dhubh', Northern Walparuta Inlier – mafic volcanic association
- Doughboy Mine – felsic volcanic association
- Mount Mulga Barite Mine – felsic volcanoclastic sediment association
- Cathedral Rock-Meningie Well area – potential Broken Hill Group

## CREAG DHUBH, NORTHERN WALPARUTA INLIER

Creag Dhubh is not a formal geographic name, but has been coined because of an impressive and rugged black hill that forms the highest relief in the area. A large lens of banded quartz-grunerite-spessartine rock causes the prominence, with the black colour being due to the release of manganese by the weathering of manganoan garnet and possibly amphibole. The Creag Dhubh exhalite is the largest of a number of such manganiferous pods, which is developed in psammites that immediately overlie a unit that locally contains a prominent amygdaloidal metabasalt.

The sequence is structurally complicated, not least by overturning and later deformation by F3 (Pointon, 1980). Recent detailed mapping shows lithostratigraphic units in the Creag Dhubh area to be repeated across the axis of a long-limbed isoclinal synform. Sedimentary facies is uncertain but from the current best estimate the sequence is as follows:

### ETHIUDNA SUBGROUP (youngest)

1. Blue grey albitic metasiltstone (Peryhumuck Calcalbitite, containing an extensive breccia body)
2. Medium-grained metasandstone
3. Psammopelitic schist coarsening downwards
4. Schistose bedded biotite-psammite, upwards fining, (sporadically near base contains siliceous and manganiferous banded quartz-grunerite lenses, ?meta-chert)
5. Variable unit containing a large amygdaloidal metabasalt pod and laterally a fragmental and locally conglomeratic chemical sedimentary horizon including: manganoan cotecules; manganoan garnet-grunerite rock; siliceous units (?meta-chert); local conglomerate with plagioclase-rich clasts (volcanic) in siderite matrix with layered carbonate at the 'base'.
6. Banded quartz-ribbon calcsilicate

### *Possible structural discontinuity*

### WIPERAMINGA SUBGROUP (oldest)

7. Thick upwards fining psammite-andalusite pelite.

A somewhat speculative northwards younging direction is given in the north limb of the isocline where unit 6 (above) is apparently replaced by the 'volcanic' conglomerate (unit 5).

One stratigraphic interpretation is indicated above. However in the absence of better facing information others are possible; the previous consensus of opinion is that unit 5 is equivalent to the Bimba Formation, which would mean that the ordering above would need to be reversed. Whatever the detail, this set of rocks is stratigraphically slightly below the Broken Hill lode horizon, but is possibly in the Pinnacles Mine position.

The basalt-chemical sediment association contained within unit 5, together with the siliceous lenses at the base of unit 4, show enrichment with respect of iron and manganese, a combination shared by Broken Hill Group, indeed Laing (1996) considered the metabasalt to be the equivalent of the Parnell Formation. The potential economic significance of these units was recognised by Esso Exploration Australia, and as such they were the subject of exploration activity ca. 1982 (pers com. G. Clarke).

#### **DOUGHBOY MINE, NORTHERN OUTALPA INLIER**

The small historic Doughboy Mine workings are situated on a ridge crest 5.5km southwest of Bimbowrie Homestead. The sequence is stratigraphically below the position of the Broken Hill Group, and in the Curnamona Group. The mineralised horizon is associated with an extensive W-E trending vertical felsic metavolcanic unit, which is equated with the newly recognised Basso Suite (Buckley, 1993; Conon, 2000). The volcanic unit is 300m thick and at least 5km long. The predominant lithology is quartz-feldspar-biotite gneiss, however near the mineralised horizon it is spessartine-bearing and weathers black. To the south is a sequence of albitised metasediments and volcanics that is in part intensely migmatized. To the north are schistose metasediments that contain a Basso Suite metagranite sill and are intruded by a later 'Bimbowrie Suite' granite.

The mineralised horizon is more than 800m long, its eastern extent being blanketed by metavolcanic scree. Malachite-azurite staining is sporadically obvious along most of the exposed length of the mineralised horizon, but only the more highly mineralised outcrops have been prospected. The mineralised horizon comprises felsic schist (?volcaniclastic precursor) to the south and psammopelitic and biotite-rich schists (metasediments) to the north. Near the contact of the felsic and other schists are small lenses of quartz-garnet-biotite rock, banded quartz-spessartine rock and honey-coloured quartzite. These iron-manganese-rich units are interpreted as primary exhalites that were formed either on the sea floor or early during burial.

There are apparently two lode horizons indicated by parallel lines of workings, one developed along the southern part of the mineralised horizon, and the other near the contact of the metasediments and the northern metavolcanics. This northern mineralised zone does not appear to be as ferruginous as the south, but in places is fluorite-rich. Zdziarski (1997) recognised the zinc spinel, gahnite, within the economic mineral assemblage, this perhaps being the only occurrence known to date within the Olary Domain.

In 1975 the Doughboy Mine area was sampled and geologically mapped by Australian International Nickel during a regional investigation that concentrated upon 'iron formations'.

#### **MOUNT MULGA BARITE MINE.**

The Mount Mulga Barite Mine is near Old Boolcomata, within an area that was mapped in some detail by Esso Minerals (Archibald, 1980). The primary target horizon of Esso's investigation was the Bimba Formation, a unit of regional extent (equivalent to the Ettlewood Calcilicate Member) characterised by calcsilicate, pyrite and base metal anomalism.

Stratigraphically below the Bimba Formation is the Ethiudna Subgroup, which in the Mulga Bore Creek section is 200m thick, comprising schist, quartz-feldspar-mica gneiss, blue-grey metasiltstone, and quartz-albite rocks (felsic metavolcanics). These volcanic units are locally Cu-Au mineralised, and have been dated at ca. 1.710 Ma (Page et al. 1998). A thick (up to 70m) metasandstone sequence marks the base of the Ethiudna Subgroup, the lower red part of which is iron-rich (magnetite, pyrite) and volcaniclastic. The basal portion of the red volcaniclastic metasandstone is finely layered and overlies a pelitic unit ('middle schist' of Esso), which is interpreted as the upper part of the underlying Wipieraminga Subgroup. The meta-sandstone is a laterally continuous marker, with the Mount Mulga Barite lode being developed at its base.

The barite lode comprises barite-quartz-magnetite-sulphide rock, and is layered at its contact with the overlying layered metasandstone. Elsewhere it is more massive and in places forms veins cutting across the stratigraphy. The deposit was originally developed as a copper mine and significant background Cu-Au values (up to 0.3% Cu and 1.27 ppm Au) are reported in the literature (Ashley et al. 1995). The Mount Mulga Barite deposit is interpreted as an exhalite developed in association with felsic volcanism at a possible unconformity separating

the Wiperaminga and Ethiudna Subgroups. Barium and iron enrichment (also Cu-Au mineralisation) is observed elsewhere in this stratigraphic position, eg. Meningie Well, Ameroo Hill, Walparuta Cu-Au Mine.

### CATHEDRAL ROCK-MENINGIE WELL AREA

Geological mapping of Esso Exploration (Archibald. 1980) indicates that lenticular coticles, iron-formations and mafic rocks are present in pelite above the Bimba Formation in the Cathedral Rock-Meningie Well area. Laffan (1994), Lottermoser and Ashley (1996) showed these chemical sediments to be manganiferous and geochemically similar to iron formations developed within the Broken Hill Group, and indeed Laing (1996) considered this horizon to be equivalent to the Broken hill Group. A volcanic association is less obvious with this example, although minor mafic rocks have been mapped 600m NE of Blue Dam.

The lithostratigraphy preserved in the sheared isoclinal synform south of the Raven Hill Pegmatite Mine is as follows:

#### STRATHEARN GROUP

1. ?Saltbush Subgroup - andalusite schist with small coticle (ie. 'garnet sandstone') boudins
2. Graphitic schist (3m)
3. Psammopelites and thin psammities (locally albitic) (40m). Along strike in Mulga Bore creek calcsilicate ellipsoids (deformed) are common.
4. Plumbago Formation - fine grained graphitic psammite and pelite (2m)
5. Bimba Formation - ferruginous weathered unit (?pyritic calcsilicate) and calcsilicate (5m)

#### CURNAMONA GROUP (ETHIUDNA SUBGROUP)

6. Calc-albite metasiltstone

Stratigraphically units 1 to 3 above are unusual for the Olary Domain. Unit 3 has not been recognised elsewhere eg. Walparuta, Mount Howden, although ellipsoids and disseminated garnet are present at Ameroo Hill. Coticles in unit 1 are suggestive of either Broken Hill Group or basal Sundown Group. While graphitic units 4 (Plumbago Formation) and 2 possibly represent breaks in deposition, it can be speculated that parts of the upper Broken Hill Group (ie. units 1 to 3) extend as far west into the Olary Domain as Mulga Bore Creek.

### CONCLUSIONS

Firstly, the coexistence of iron-rich volcanics and manganiferous exhalites is a factor that enhances the prospectivity of the Curnamona and Thackaringa Groups, and is an avenue worthy of exploration for both base metals and copper-gold. Secondly, manganiferous coticles (garnet sandstones) and iron formations above the Bimba Formation strongly suggest that the upper Broken Hill Group extends some 50 km northwest of what has previously been considered the Olary Domain-Broken Hill Domain boundary, it follows that the geographic range of potential BHT mineralisation can be similarly extended.

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# DEPOSITIONAL ARCHITECTURE OF THE UPPER WILLYAMA SUPERGROUP, CURNAMONA PROVINCE.

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A formal, useable lithostratigraphic scheme has been developed for the Olary Domain (OLD), Curnamona Province, utilising where possible previous work which is mostly unpublished or informal (Conor, 2000). In addition, the scheme has benefited from new geochronology (Page et al. in prep.), which has pin-pointed chronostratigraphic ties with the stratigraphy of the Broken Hill Domain (BHD) (Fig. 1). The Curnamona Province is a largely buried circular Palaeo-Mesoproterozoic entity, which includes a basin fragment that contains sediments and volcanics of the Willyama Supergroup. The upper Willyama Supergroup is Pb-Zn prospective, not only because it hosts the Broken Hill deposit but also because it is tied chronostratigraphically to Mount Isa and northern Australia (Page et al. in prep.). The region was overprinted by Cu-Au mineralisation late during the ~1600 Ma Olarian Orogeny, a period which encompasses the formation of the Olympic Dam Cu-Au-U-REE deposit.

Deposition of the Willyama Supergroup is constrained by recent U-Pb chronology from ~1720 Ma to ~1640 Ma. However, neither the base nor top of sediment basin-fill have as yet been recognised. Of great significance is a thin tuffaceous chronostratigraphic marker unit, the Plumbago Formation, which was discovered during the early stage of the BHEI chronostratigraphic program (Page et al. 1998). The Plumbago Formation (1693±3 Ma) forms a couplet of regional extent with the Bimba Formation of the OLD and its equivalent, the Ettlewood Calc-Silicate Member (BHD).

The Plumbago Formation is overlain by the following different lithostratigraphic units: to the east in the Ettlewood area – the upper Broken Hill Group (above Ettlewood Calc-Silicate Member), to the west in the Ameroo Hill and Walparuta areas – the Saltbush Subgroup (Sundown Group equivalent), and in the Mount Howden area – the Mount Howden Subgroup (Paragon Group equivalent). The evidence for the Plumbago Formation marking a flooded depositional, rather than erosional, surface is firstly that it has escaped erosion in spite of being thin and friable; secondly, slow deposition in deep water is suggested by the basal parts of both the Saltbush and Mount Howden Subgroups being graphitic and highly aluminous (sillimanite/ chialstolite). Thus the evidence to date points to the Plumbago Formation marking a critical depositional surface with younger sediment packages onlapping or downlapping successively in a NW direction. Conor (2002) considered the Plumbago Formation to punctuate a major flooding event that approximates the interval between the Curnamona Group (ie. lower Willyama Supergroup) and the Strathearn Group (upper Willyama Supergroup).

Three models are presented diagrammatically. Figure 2, which is the preferred option, shows the Plumbago Formation becoming bent under the influence of a postulated listric extensional structure that surfaced to the east of Broken Hill. The required sedimentation geometry is satisfied by the structure being a growth fault that controlled sedimentation in a 'second order' basin. Figure 3, discussed in Conor (2002), shows the Plumbago Formation as a flat surface with successively younger sediment packages infilling the basin from the east. The third model (Fig. 4) shows a post-depositional structural scenario whereby the observed geometry is produced by extension along a surface immediately above the Plumbago Formation. An extensional regime of this sort would be expected to ramp downwards in places, so that upper Willyama Supergroup rocks are juxtaposed upon units much lower in the succession, but this is not observed.

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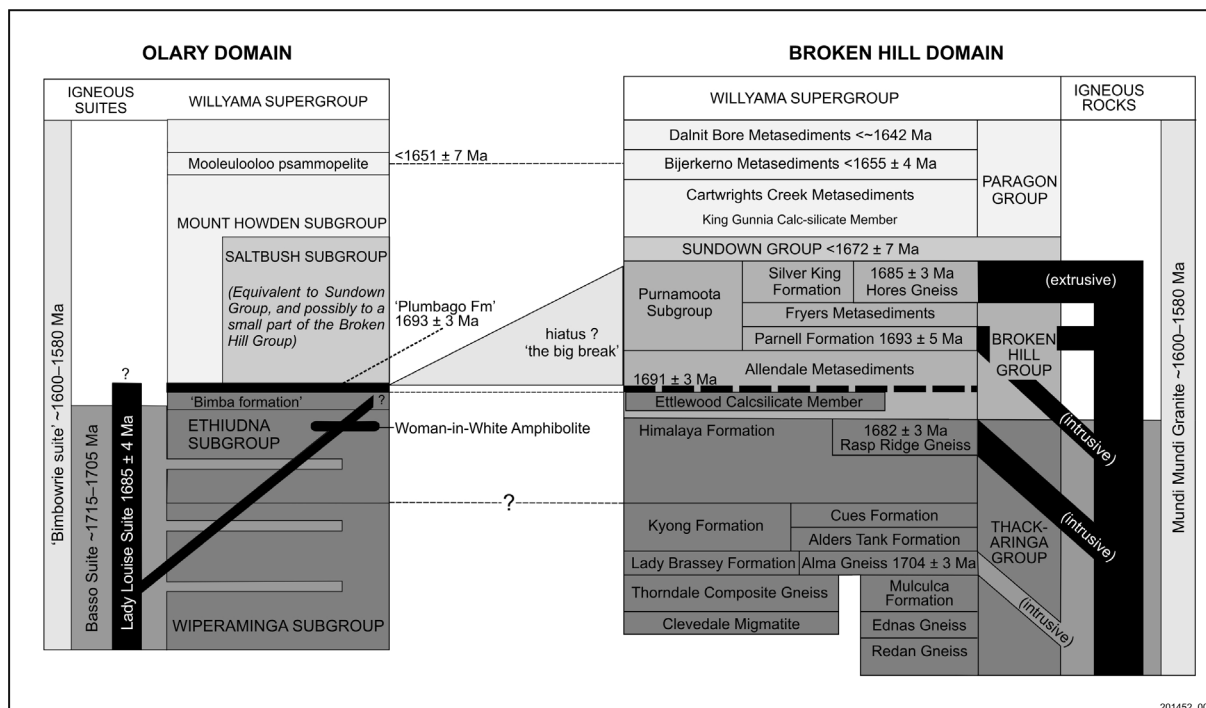


Figure. 1. Stratigraphic correlation diagram, Olary vs Broken Hill Domains

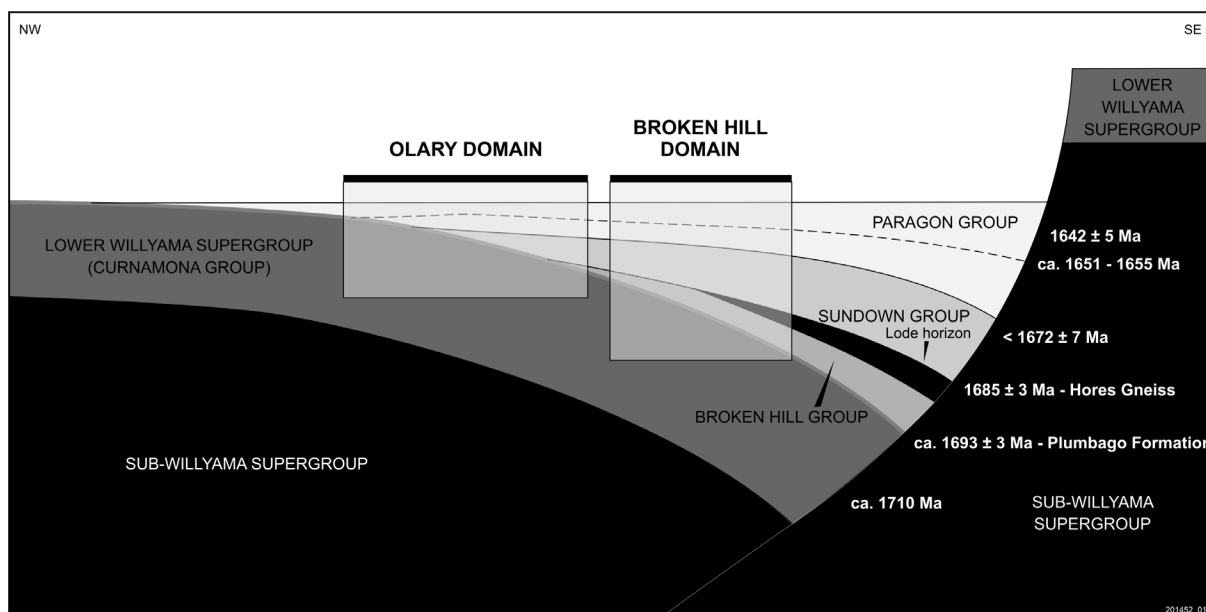


Figure 2. Model: onlapping depositional morphology of the upper Williyama Supergroup; Bimba-Plumbago Formations couplet shown bent by half-rift growth fault.

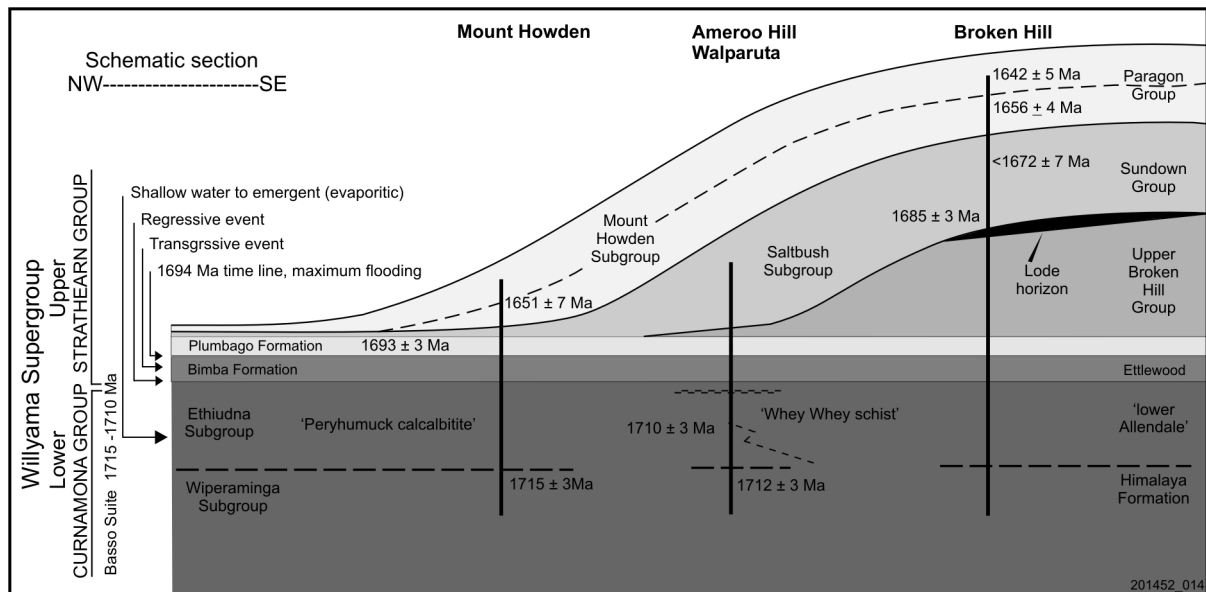


Figure 3. Model: downlapping depositional morphology of the upper Willyama Supergroup; Bimba-Plumbago Formations couplet held horizontal.

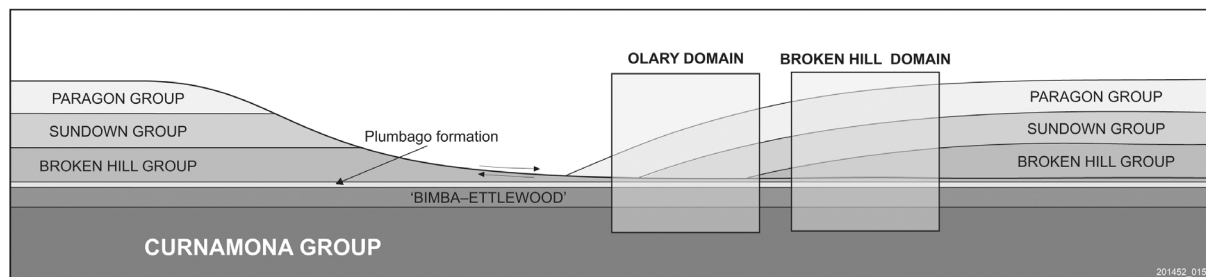


Figure 4. Model: Curnamona Group and upper Willyama Supergroup juxtaposed across extensional fault parallel to upper surface of the Plumbago Formation.

N.B. Reference for isotopic dates shown in Figures 1 to 3, see Page et al. (in prep).

# RE-EVALUATION OF THE REGOLITH AT KALKAROO Cu-Au-(Mo) DEPOSIT, OLARY DOMAIN, SOUTH AUSTRALIA WITH THE USE OF PORTABLE INSTRUMENT MINERAL ANALYSER (PIMA).

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## INTRODUCTION

The Kalkaroo copper-gold-(molybdenum) deposit is located approximately 90 km west north west of Broken Hill on the Benagerie Ridge Magnetic Complex, northern Olary Domain. Briefly, the geology encompasses typical Willyama Supergroup basement hosting the iron oxide related Cu-Au-(Mo) mineralisation of the Kalkaroo deposit. Upon this basement, a thick kaolinitic weathering profile was developed during the Late Cretaceous associated with the Arckaringa Palaeosol of Firman (1988). Overlying the Arckaringa Palaeosol is up to 100 m of Tertiary to recent cover that forms part of the Lake Frome embayment (Callen 1990).

At the Kalkaroo deposit the Lake Frome embayment consists of the Palaeocene to Middle Eocene Eyre Formation (up to 40 m thick), which is overlain by the Late Eocene to Miocene Namba Formation (~50 m) and approximately 15 m of Quaternary cover. The Eyre Formation consists of quartzose sands and gravels with a kaolinite matrix, whereas the Namba Formation comprises grey, brown and black ‘puggy’ smectite clays with minor kaolinite and silts, the Quaternary cover consists of red quartzose sand.

Previous logging of reverse circulation drilling at the Kalkaroo deposit has failed to distinguish the Eyre Formation from the weathered Willyama basement (Arckaringa Palaeosol). However, it is in the Eyre Formation that significant gold intersections (2 m @ >2 ppm Au) in placer (“deep lead”) deposits have been identified. To overcome this, hyperspectral (PIMA) and visual re-evaluation of drilling at the Kalkaroo deposit was undertaken to delineate the extent of the Eyre Formation.

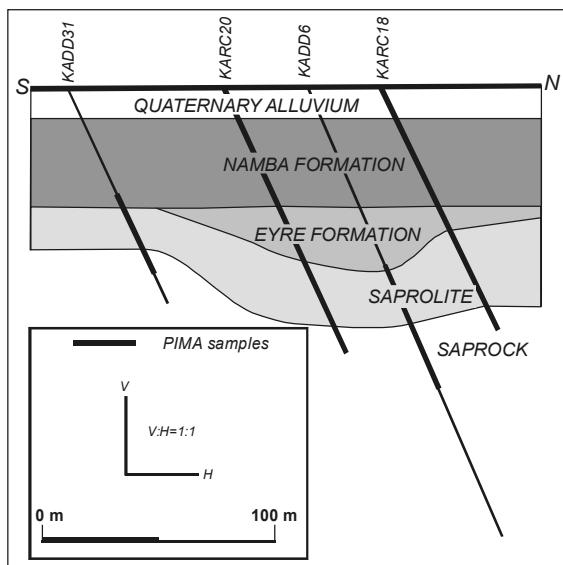


Figure 3. Cross-section of the Kalkaroo deposit showing PIMA sample locations.

## METHODS

Representative samples were selected for very near infra-red (VNIR) spectral analysis at two or four metre spacings from two reverse circulation (KARC18 and KARC20) and two diamond (KADD6 and KND31) exploration drill holes in a north-south line across the Kalkaroo deposit (Figure 1). The absorption spectra of these samples were then analysed by a PIMA device over the 1300 – 2500 nm wavelength ranges (VNIR). These spectra were then stacked into spectral libraries in order, according to the hole and depth (Figure 2).

## RESULTS

The VNIR absorption spectra for the analysed Lake Frome embayment and the Arckaringa Palaeosol samples were compared against

spectral libraries of common aluminosilicate clays to identify the dominant clay mineralogy. The aluminosilicate clay mineralogy for the Quaternary cover is dominated by illite. However, the overall absorbance peaks for these samples are low, which suggests that the quartz and Fe-oxides that dominate the analysed samples have diluted the absorbance of the illite clays. The Namba Formation is composed mostly of smectite clays (nontronite, montmorillonite), although minor kaolinite (less than 30 percent) is also present. Kaolinite is the dominant aluminosilicate clay in the Eyre Formation and Arckaringa Palaeosol.

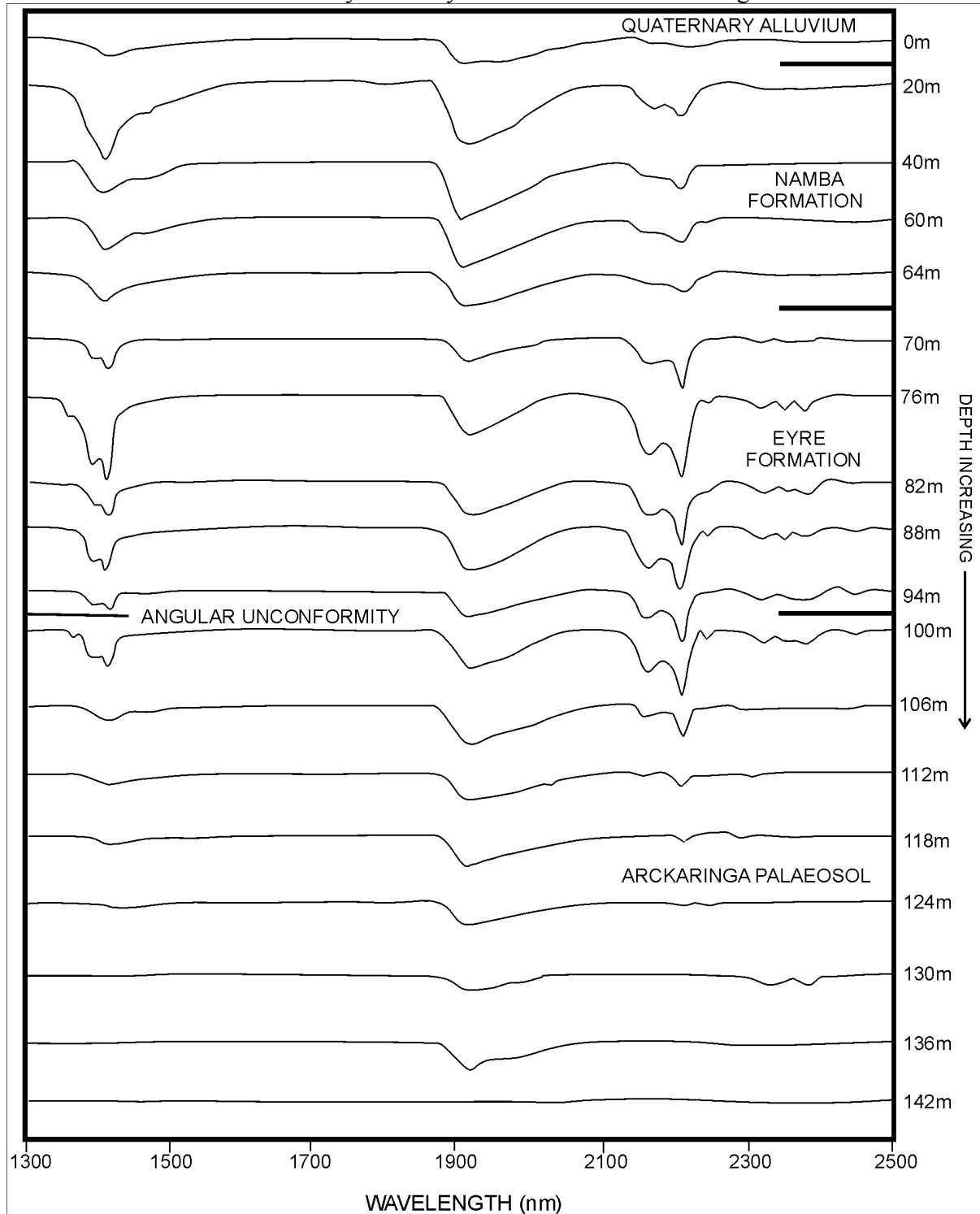


Figure 4. Stacked, hulled, infra-red spectra with respect to depth for hole KARC20.

Owing to the similarities in chemical composition between the Eyre Formation and the upper part of the Arckaringa Palaeosol, the relative clay abundances for both units are almost the same. However, the relative crystallinity of transported kaolinite in the Eyre Formation should be lower relative to the *in situ* kaolinite in the Arckaringa Palaeosol (Tan *et al*, 1998). Lawie (1996) proposed a method to determine transported from *in situ* kaolinitic regolith by taking the ratio of the 2171 nm and 2160 nm absorbance wavelengths to measure the relative kaolinitic crystallinity. This method was applied to the Eyre Formation and Arckaringa Palaeosol at the Kalkaroo deposit. Figure 3 shows a progressive rise in the relative kaolinite crystallinity within the Arckaringa Palaeosol from the base of KARC20 to the boundary of the Eyre Formation a depth of 97 to 98 m. Above this interval the Eyre Formation shows a progressive drop in the relative kaolinite crystallinity until the Namba Formation at 66 to 67 m. This data shows that VNIR spectroscopy can be used for differentiating the Eyre Formation from the Arckaringa Palaeosol at the Kalkaroo deposit. Consequently, palaeodrainage and associated “deep lead” gold exploration models can be assessed for the Eyre Formation and used as a predictive tool for further gold discovery at the Kalkaroo deposit.

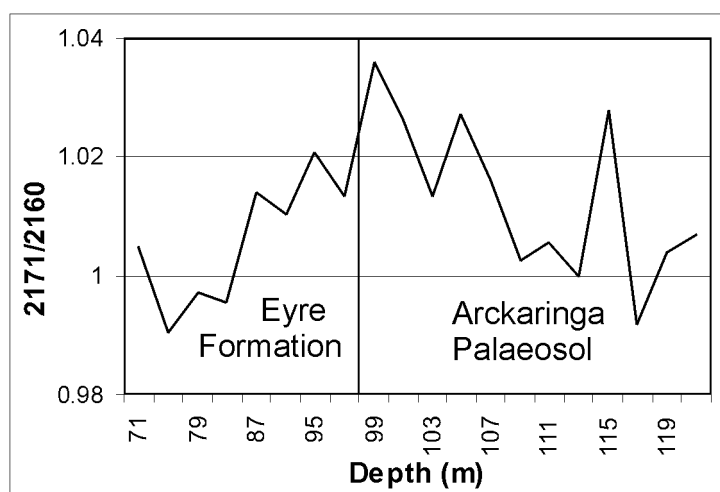


Figure 5. The 2171/2160 nm absorbance ratio with respect to depth for samples taken from KARC20 at the Kalkaroo deposit.

## ACKNOWLEDGEMENTS

MIM Exploration, A/Prof Paul Ashley, Mark McGeough.

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# **DELAMERIAN METAMORPHISM IN THE CURNAMONA PROVINCE: CONSTRAINTS FROM THE PROGRADE “RETROGRADE” SHEAR ZONES**

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## **INTRODUCTION**

The use of shear zones as an avenue to determine the physical conditions associated with terrain reactivation is now well established. This is because unlike their wall rocks, which often preserve complex multi-event histories, shear zone volumes commonly only preserve the record of reactivation, and the conditions associated with it.

The Curnamona Province contains a system of terrain scale shear zones that locally dominate the structural and metamorphic character of the terrain. Typically these shear zones are expressed as steeply dipping schist belts that truncate earlier formed higher-grade structures. Although the Curnamona shear zones represent a volumetrically important feature of the terrain, and link into a crustal-scale shear zone system (Leven et al., 1998), there are comparatively few direct age constraints on their timing. Field evidence shows that some shear zones are truncated at the base of the Adelaidean unconformity. Furthermore there is a general spatial correspondence between the peak metamorphic Olarian grades and the grade of the shear zones (Laing, 1996). Both these lines of evidence have been used to infer that the bulk of the zones formed during the retrograde (D3) evolution of the Olarian Orogeny, and were reactivated during the Cambrian Delamerian Orogeny. In this scenario, amphibolite-grade shear zones would be Proterozoic in age, and greenschist facies overprints Cambrian.

## **AGE CONSTRAINTS**

We have undertaken a reconnaissance study to determine the age of selected garnet-staurolite-bearing shear zones using Sm-Nd isotopic dating. The selected shear zones formed at temperatures between 475 and 540°C and pressures of around 3.5 – 4.5 kbar. Although the shear zones are lower grade than their enclosing wall rocks, garnet zoning patterns suggest that the shear zone assemblages formed on prograde metamorphic paths, indicating that strictly speaking, they are not retrograde shear zones.

Two contrasting shear zones from the Murtaroo area in the eastern Olary region have been dated. The first is a sharply defined east-west trending structure in the TMI data. It truncates D<sub>3</sub> folds, and has an apparent dextral transcurrent component. The sampled shear zone fabric at GR 0491952 6426563 is defined by coarse-grained muscovite-biotite-quartz, which envelops syn-tectonic euhedral garnets up to 1.5 cm in diameter. The garnet is overgrown by coarse syn-tectonic staurolite. Three individual garnets and their leachates, together with the whole rock give an age of  $505 \pm 13$  Ma. The second shear zone is a diffuse roughly east-west trending structure. At the sampled location (GR 0491272 6411714) the shear zone assemblage is quartz-poor, and dominated by chlorite which envelops abundant euhedral garnets up to 3 cm in diameter, and minor staurolite. Analysis of garnet and the whole rock gives  $517 \pm 14$  Ma. A third example comes from a chlorite-garnet schist in the Thackaringa region. A single euhedral garnet 12 cm in diameter containing inclusions of orthoamphibole and staurolite was slabbed and the core and rim analysed, giving an age of  $500 \pm 10$  Ma. The

coarse-grain size of the analysed garnets in all three samples, and the comparatively low metamorphic grade indicates that these ages are likely to be growth ages (as opposed to resetting).

## **DISCUSSION**

The preliminary Delamerian ages obtained from garnet-bearing shear zones in the Curnamona Province suggests that the widespread amphibolite-grade metamorphism in the shear zones may be in part a consequence of the Delamerian Orogeny. While there is little doubt that some shear zones are truncated at the Adelaidean unconformity, the isotopic evidence present here points to significant reactivation of individual segments during the Delamerian. In places this reactivation is associated with significant metasomatism, and locally Cu-Au mineralisation.

The identification of pristine Delamerian mineral assemblages allows the thermal conditions in the Curnamona basement during the Delamerian to be evaluated. Conceivably the spatial coherence in metamorphic isograd patterns between the regional peak conditions and the shear zone assemblages, suggests that the regional pattern of Olarian metamorphism may be strongly influenced by Delamerian-driven exhumation.

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# IS THERE A WILLYAMA SUPERGROUP SEQUENCE IN THE MOUNT PAINTER INLIER?

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## INTRODUCTION

The pre-Adelaidean basement sequence in the Mount Painter Inlier has many lithological and geochemical similarities to the Willyama Supergroup, that is Broken Hill Type (BHT) sequences. For example, there are banded iron formations, quartz-garnet rocks, garnet-gahnite rocks, Corrua-style scheelite occurrences, psammites, pelites, quartzites and unique Potosi-type rocks (including Hores Gneiss equivalents). Thus it is for good reason that stratigraphic correlations have been made and prospectivity linked to that lithological and geochemical correlation. However, the true age of this basement, predominantly supracrustal sequence is constrained only by intrusive rocks dated at ~1560-1590 Ma, with volcanic sequences at ~1575 Ma.

The purpose of this study is to examine the age of this pre-Adelaidean basement sequence or sequences and so investigate the BHT correlative links. The method chosen is the U-Pb zircon dating of detrital zircons, a powerful tool in provenance determinations, providing a fingerprint or bar-code for the source. This method also allows one to make conclusions as to the maximum age of sedimentation.

## GEOLOGICAL FRAMEWORK

The basement of the Mount Painter and Mount Babbage Inliers (MPI and MBI respectively) has been interpreted in three generally different stratigraphic frameworks. Coats and Blisset (1971) and more recently Elburg et al (2001) consider the entire basement as a single sequence. Teale (1993) has divided the basement rocks of the MPI and MBI into three sequences: a multiply deformed, polymetamorphic Palaeoproterozoic sequence comprising 6 suites, a minor Palaeo- to Mesoproterozoic succession and a younger metamorphosed Mesoproterozoic group of volcanics and sediments. Paul (1998) also noted on structural grounds that the basement could be subdivided into an older Palaeoproterozoic and a younger Mesoproterozoic sequence.

## SAMPLES

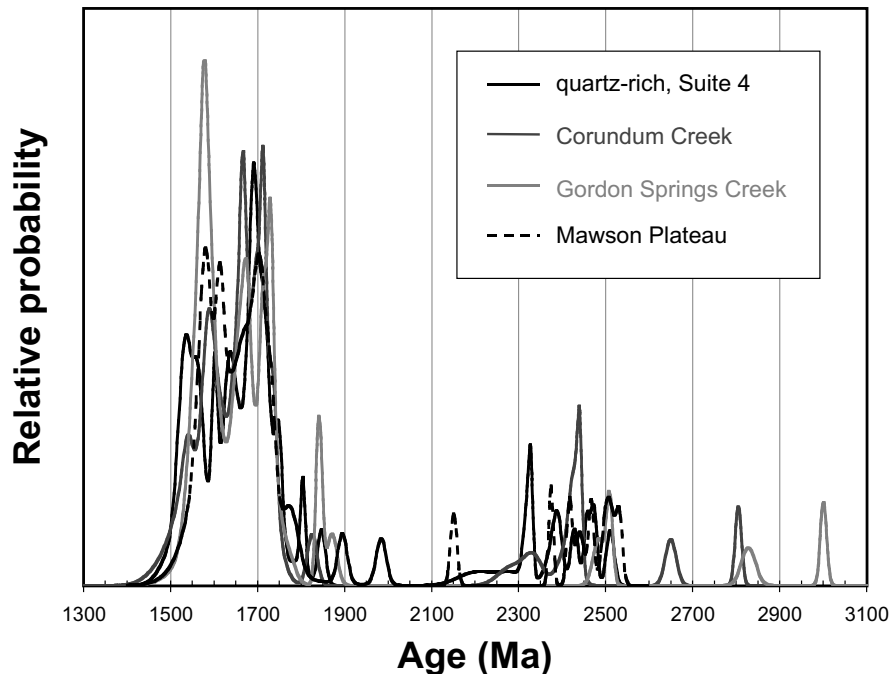
Quartzites and quartz rich sediments have been sampled from the three sequences of Teale (1993; using the Suite names as per Fig. 4.30 for the older sequence). The inferred Palaeoproterozoic sequence has been sampled within Hot Springs Creek (quartz-rich, Suite 4, central MPI), the Mawson Plateau area (Suite 5, northern MPI), Gordon Springs Creek and Corundum Creek Suite 4, southern MPI), and a quartz rich sample from Suite 4 (an inferred Hores Gneiss equivalent). The Mount Adams Quartzite of the Mesoproterozoic sequence was sampled, as was the Freeling Heights Quartzite near the Cockscomb Mine. The latter locality is noted for horizons that contain abundant quartzite cobbles. These have been interpreted to be cobbles of an older ?Palaeoproterozoic quartzite eroded and incorporated in the Mesoproterozoic Freeling Heights Quartzite. Samples were also collected from the third sequence of Teale (1993), the minor Palaeo- to Mesoproterozoic succession near Parabarana Hill; these did not yield zircons, but further work is in progress on alternate samples.

Zircons were separated from each of the above samples, mounted in epoxy and then sectioned approximately in half. Cathodoluminescence (CL) images were prepared for all grains and were critical in the selection of the areas within the grains to be analysed by SHRIMP. The MPI and MBI pre Adelaidean sequences have been affected by deformation and metamorphism prior to deposition of the Adelaidean sequences, and then again during the Delamerian Orogeny. Thus the SHRIMP analytical spots were carefully chosen so that the youngest component of zircon growth was analysed in each grain. In many cases the grains are not structured, being simple igneous zircon from centre to rim.

The data for the four inferred Palaeoproterozoic samples are shown in Fig.1. As is commonly seen in detrital zircon age spectra, there are a number of more dominant peaks, or age groupings and then older "noise". In this case the older zircon components, say between 1850 Ma and up to 3100 Ma, are present as subordinate peaks, in most cases reflecting just one or two analyses at any particular age. The striking and major result from this data is that there are significant age peaks younger than 1630 Ma, variably in the range from 1560 Ma to 1600 Ma.



There are the anticipated Willyama Supergroup ages of between say 1680 Ma and 1720 Ma, but in each of the four samples there are zoned igneous zircon grains that are younger than 1630 Ma. Clearly these four sediments were deposited after that time and are not time correlatives of the Willyama Supergroup.

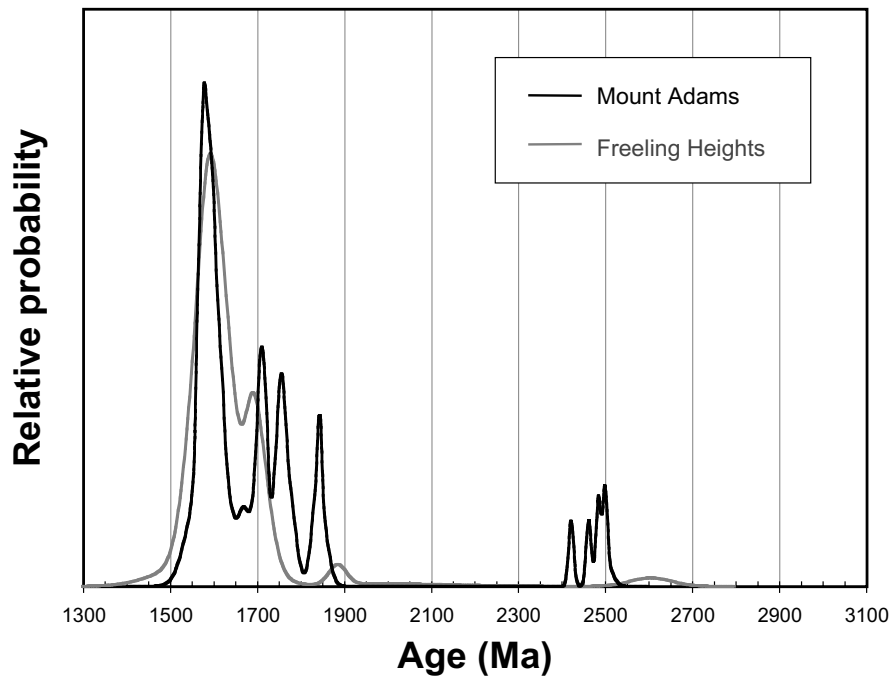


**Figure 1.** Relative probability plot for near to concordant  $^{207}\text{Pb}/^{206}\text{Pb}$  ages for the four inferred Palaeoproterozoic quartzite and quartz rich sediments from the MPI.

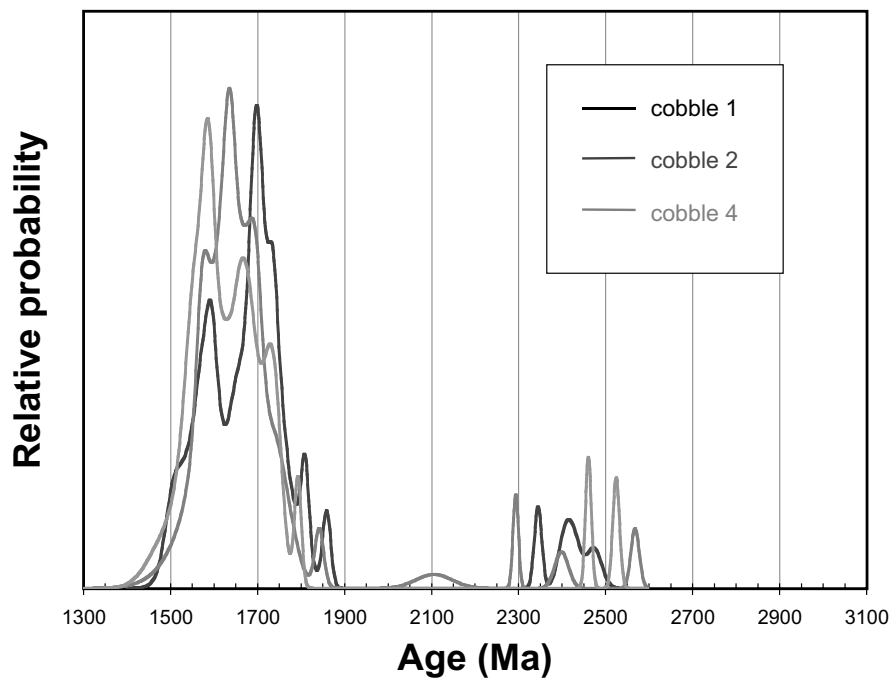
In detail, there is considerable structure in the age spectra between 1560-1630 Ma. For example the sample from the Mawson Plateau has a significant age peak at about 1580 Ma. The samples from Corundum and Gordon Springs also record this age peak. The sample from Hot Springs creek (quartz-rich, Suite 4) has a more prominent 1690-1710 Ma age grouping, but also appears to record a slightly younger peak at around 1550 Ma or a little younger. Whilst the analyses used to construct these age spectra are all near to concordant, subtle radiogenic Pb loss can occur essentially along concordia if the overprinting event is closely spaced in time. Thus it may be possible that in some cases the age peaks may be shifted slightly along the age curve. However, there can be little doubt that simple igneous zircon significantly younger than 1630 Ma was incorporated in each of these four sediments, and so they are all interpreted to be younger than the Willyama Supergroup.

The data for the two Mesoproterozoic samples are shown in Fig.2. In both cases the spectra are significantly different from those above for the previously interpreted Palaeoproterozoic sequence. There is very little older “noise”, with the dominant age peaks at ~1580-1590 Ma. The Mount Adams sample has some subordinate peaks in the 1700-1850 Ma age range, with the dominant peak at ~1580 Ma. The Freeling Heights Quartzite is dominated by ~1590 Ma zircon grains with a subordinate grouping slightly younger than 1700 Ma. There can be little doubt that the provenance of these two quartzites is significantly different to the more complex and mixed sources likely for the inferred older sequence samples. These two Mesoproterozoic samples have relatively clean age spectra and most likely were derived proximally from 1580-1590 Ma igneous sources such as the Mudguard Volcanics or the contemporaneous and intercalated volcanic rocks such as those in Harts Creek or near the Cockscorn Mine.

The results for three of the cobbles from the Freeling Heights Quartzite are shown in Fig.3. All three record “noise” in the region 2300 Ma to 2600 Ma, with dominant age peaks between 1580 Ma and 1740 Ma. In each case the more dominant peak is different, though all three record an ~1580 Ma peak. For Cobble 4 this ~1580 Ma peak is the more prominent, whereas for cobble 2 an ~1640 Ma peak is more dominant, whilst for cobble 1 ~1700 Ma is the most prominent. From these age spectra, it is probable that these three cobbles are truly derived from the “older” quartzite sequences and thus have a different provenance to their host.



**Figure 2.** Relative probability plot for near to concordant  $^{207}\text{Pb}/^{206}\text{Pb}$  ages for the Freeling Heights Quartzite and Mt Adams Quartzite, MPI.



**Figure 3.** Relative probability plot for near to concordant  $^{207}\text{Pb}/^{206}\text{Pb}$  ages for the cobbles from the Freeling Heights Quartzite, MPI.

## SUMMARY

Detrital zircon age spectra for quartzites and quartz rich sediments sampled from the three sequences of Teale (1993) clearly show that the time of deposition of the pre-Adelaidean basement sequence in the MPI is younger than 1630 Ma, most probably in the age range 1580-1590 Ma. Thus these are not time correlatives of the Willyama sequence as determined from the current data-set and whilst the lithological comparisons are compelling the sequences in the MPI are significantly younger. Importantly, the age spectra for the Mesoproterozoic quartzites are far simpler, indicating a perhaps more evolved provenance. These quartzites are dominated by igneous zircon from proximal Mesoproterozoic volcanic rock sources. Thus whilst there is no evidence in this data-set to suggest that there is a Willyama aged sequence at Mt Painter, it is also clear that there are a number of sequences with different provenances. At this stage we are not able to make any comment on the age of the sequence near Parabarana Hill.

The observed additional deformations in the former Palaeoproterozoic sequence, not recorded in the Mesoproterozoic Freeling Heights Quartzite suggest that there may be older and younger Mesoproterozoic sequences in the MPI.

The presence of BHT horizons, that is garnet-quartz rocks and quartz-gahnite horizons for example, in metasedimentary rocks younger than the Willyama Supergroup suggests that similar processes may also have been operating during the Mesoproterozoic. This clearly has important implications for mineral explorers.

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# **NON-COAXIAL FOLDING IN THE ALLENDALE MINE AREA, BROKEN HILL, NSW**

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## **INTRODUCTION**

Useful information relating structural geometry, orientation of interfering fold generations and large-scale movements of rocks can be determined from the identification of fold interference patterns. The kinematic and mechanical processes involved in fold superposition and the development of fold interference patterns are well understood (e.g. Ramsay, 1962; Thiessen and Means, 1980; Ramsay and Huber, 1987), resulting in the classification of four end-member types of fold interference patterns described as Type 0 to Type 3 (Ramsay, 1962; Ramsay and Huber, 1987).

The Early Proterozoic Broken Hill Block, central western New South Wales, is a polydeformed terrane where the identification of fold interference patterns has been used to constrain the structural evolution (e.g. Marjoribanks et al., 1980; Hobbs et al., 1984). Marjoribanks et al. (1980) showed that coaxial folding played an important role in the early evolution of the Broken Hill Block from the identification of Type 3 fold interference patterns. Hobbs et al. (1984) since constructed a 3D model based on the identification of Type 1 and Type 2 fold interference patterns. In this study, structural mapping conducted in the Allendale Mine Area in the northern Broken Hill Block has revealed previously unidentified, well-preserved Type 2 mushroom fold interference patterns. The discovery of these structures has provided an insight into the complex deformation history of this area, which can be extrapolated to a more regional scale.

## **THE ALLENDALE MINE AREA**

The Allendale Mine Area has undergone multiple phases of deformation associated with upper greenschist to lower amphibolite facies metamorphism. The eastern Allendale Mine Area comprises garnet and sillimanite rich metasediments of the Parnell Formation, and the western Allendale Mine Area comprises andalusite bearing metasediments of the Freyers Metasediments (Brown et al., 1991). These units are within the lower to middle Broken Hill Group of the Willyama Supergroup. In this study, the Allendale Mine Area has been subdivided into the western, central and eastern domains.

### *Western Domain*

The western domain of the study area is dominated by andalusite bearing pelites with minor garnet. Andalusite porphyroblasts are up to 1-2cm length and are often wrapped by the dominant layer parallel fabric in the area, or overprint the fabric and occur within the plane of the S<sub>2</sub> fabric. Sillimanite is observed as long, wispy needles up to 3 cm length, and is oriented within the dominant, lithology parallel foliation preserved in the rocks. In thin section, the sillimanite is observed to be retrogressed to sericite. Garnet occurs as small, ~1mm size grains scattered throughout the rock. These grains appear to overprint the dominant lithology parallel fabric in the area. Muscovite is often observed as unoriented grains up to 5 mm width, and overprints all other minerals and fabrics. The structural geometry of this domain is dominated by meso- to macro-scale Type 2 mushroom fold interference patterns. These structures are the result of fold interference between F<sub>2</sub> recumbent folds and F<sub>3</sub> upright, ~N-S trending folds.

### *Eastern Domain*

The eastern domain of the Allendale Mine Area is dominated by psammitic units interlayered with minor pelite and contain minor sillimanite and garnet. Garnets within the psammitic units occur as porphyroblasts up to 5 mm width and are occasionally mantled by quartz and feldspar. Small, ~1 mm size grains are scattered throughout the rock. Within the southeastern Allendale Mine Area the psammitic sediments locally become more pelitic and occasionally contain andalusite nodules. The structural geometry of this domain is dominated by upright, ~N-S trending F3 folds. Recumbent F2 structures were not identified, however a weak S2 fabric is preserved throughout this domain.

### *Central Domain*

The central Allendale Mine Area comprises pelite dominated sediments that are rich in garnet and sillimanite. Garnet porphyroblasts within the sediments comprise up to 20% of the whole rock and are 5 to 30 mm in size. Smaller round garnets ~1 mm in size are scattered throughout the sediments and overprint the main fabric in the rocks. Sillimanite occurs as wisps up to 5 mm length and are now retrogressed to sericite and quartz in thin section. The central domain is defined by an early shear zone that trends ~N-S through the study area (termed the 'central shear zone' in this study). The shear zone is defined by well developed S-C fabrics and sheared porphyroblasts. Porphyroblasts are defined by garnet and often have pressure shadows which are both symmetric and asymmetric. Garnets without pressure shadows often have a sigmoidal shape. Andalusite porphyroblasts are occasionally seen on the western boundary of the shear zone, and often show evidence of shearing, indicating they grew before the shearing event. The andalusites are now often retrogressed to quartz and sericite. Mineral lineations within the shear zone are moderately to well preserved and are defined by sillimanite and biotite, with occasional andalusite on the western edge of the shear zone. Mineral lineations plunge moderately to steeply south to east. In thin section, the sediment hosting the porphyroblasts appears mylonitic, indicating high strain focused within the central shear zone. The boundaries of the shear zone are well defined with the effects of shearing diminishing quickly within 10 meters away from the shear zone. This is observed as a decrease in the development of S-C fabrics.

## **DISCUSSION**

Mapping in the Allendale Mine Area raises the question of the role of the 'central shear zone' in the evolution of the area. This shear zone is of importance as it defines the boundary of two zones of differing structural geometries. Within the western Allendale Mine Area recumbent F2 folds that are overprinted by upright F3 folds to produce Type 2 mushroom fold interference patterns dominate the structural geometry of the area. However, within the eastern zone, the F2 folds appear absent and the structural geometry of the area is dominated by upright F3 folds. Difference in the structural style between the western and eastern domains suggests that the 'central shear zone' may define a structural boundary in which rocks on either side have undergone different movement histories.

Recumbent folds are commonly associated with thrusting associated with large scale shear zones or faults (detachment structures) over which lateral translation of the bulk rock results in the development of nappe structures. Nappe structures develop above the basal detachment structure. Within the Allendale Mine Area, the western domain is considered to represent the hangingwall of a detachment structure where recumbent folds have developed above the shear zone. The eastern domain may lie beneath the detachment structure where recumbent folds

do not develop. This accounts for the focus of recumbent F2 folds in the western domain, and implies the central shear zone was active during D2. Overprinting by upright folds during the D3 event resulted in the development of Type 2 fold interference patterns in the western Allendale Mine Area and upright folds in the eastern Allendale Mine Area.

On a larger scale, the Allendale Mine Area is located within the hinge zone of a large-scale fold with a sheath-like geometry (Forbes et al., in press). This structure is interpreted to be a sheath fold or a highly non-cylindrical nappe that developed during intense horizontal shortening during the Olarian Orogeny (1.6-1.58 Ga; Page et al., 2000). The regional structure is interpreted to be associated with a large-scale detachment, however this has not been located within the regional Allendale Area or the Broken Hill Block. The Allendale Mine Area is located within the hinge zone of the regional sheath-like structure (Forbes et al., in press), and the central domain detachment shear zone may represent a smaller-scale detachment structure within the larger sheath-like structure.

Detachment structures have not been previously described within the Broken Hill Block, which has lead to difficulty in understanding the development of recumbent folds identified throughout the area. The identification of a potential synthetic detachment off a larger scale detachment in the Broken Hill Block could provide insight into the structural history and crustal architecture of this terrane during the Olarian Orogeny.

## CONCLUSIONS

Locally, the geological evolution of the Allendale Mine Area is dominated by thrust tectonics and the development of recumbent folds in the hangingwall of a relatively small detachment. The structural geometry of the western domain is dominated by Type 2 fold interference patterns that are the result of F2 recumbent folds overprinted by F3 upright folds. The eastern domain represents the footwall of the detachment. The structural geometry of this zone is dominated by upright F3 folds. The S2 fabric that is observed axial planar to recumbent folds in the western domain is weakly to moderately preserved throughout the eastern domain. The central domain of the Allendale Mine Area is defined by a shear zone and represents a small-scale detachment that is associated with the development of the F2 recumbent structures observed in the western domain. This shear zone was active during D2. The results of this study highlight that the distribution of strain can be partitioned during crustal shortening resulting in structural domains with different geometries and deformation styles.

## ACKNOWLEDGMENTS

Work reported here was conducted as part of the predictive mineral discovery Cooperative Research Centre and this abstract is published with the permission of the CEO, pmd\*CRC. Matt Noble, Catherine Spaggiari, David Giles, Quinton Hills and Chris Doyle are thanked for field assistance and useful discussions.

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# DETAILED REGOLITH-LANDFORM MAPPING FOR MINERAL EXPLORATION: PROGRESS ON THE BROKEN HILL 1:25,000 REGOLITH-LANDFORM MAPPING SERIES

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## INTRODUCTION

Mineral explorers are faced with unique challenges when looking for world class orebodies in the regolith-dominated terrains surrounding Broken Hill. “It’s all dirt!” – is the common catch-cry. Those who can get past that ask; what do we sample? Where do we find it? How should we interpret the results? Will we find orebodies? The answers are regolith-landform maps, regolith-landform maps, regolith-landform-maps and... maybe!

The Balaclava 1:25,000 regolith-landform map was released at the Broken Hill Exploration Initiative (BHEI) conference in 2000. The abstract accompanying the map (Foster, *et al.*, 2000) concludes by saying “It is hoped that the publication of this map will be the first release of a series of other maps from the region, particularly the southern part of the Broken Hill Block and the northern Murray basin margins.” Indeed, it was. This abstract and presentation details the advances and changes in the Broken Hill 1:25,000 mapping project since the release of the Balaclava 1:25,000 sheet, including the lessons learned and developments made during the production of the Redan (Brachmanis, *et al.*, 2001), Triple Chance (Debenham, *et al.*, 2001), Kinalung West-Quondong West (Brachmanis, *et al.*, 2001), Mount Gipps (Lewis, *et al.*, 2002) and Pinnacles (Senior, *et al.*, 2002) sheets, and the on-going production of Wahratta (Foster, *et al.*, *in prep.*), Rockwell and Thakaringa sheets.

## BACKGROUND

Regolith-dominated terrains in the Broken Hill region have traditionally been mapped uniformly as ‘Cainozoic rock units’, limiting an understanding of the landscape as a whole. Traditional geology maps published for the region capably show where bedrock is exposed at the surface. These areas tend to correspond with known mineralisation. However, based on the geology mapping, highly prospective rocks do exist in regolith-dominated terrains adjacent to these exposed bedrock areas, buried at variable depth by transported sediments and weathered materials. Surface expressions of mineralisation are identified when metals are dispersed through the landscape mechanically (sediment and seed transport), hydromorphically (regolith and groundwaters) and biochemically (cycling through plants).

Regolith-landform mapping at 1:25,000 scale in the Broken Hill region was initiated during the work of Hill (2000). While mapping regolith-landforms at the regional 1:100,000 scale (Hill, 2001), the need for more detailed mapping was identified. The purpose of the Broken Hill 1:25,000 regolith-landform mapping project is to characterise regolith materials and their associated landforms, and to identify surface dispersion pathways. This work compliments the existing 1:25,000 scale geology map series, published in the late 1970s-early 1980s.

Detailed regolith-landform maps are a useful tool for realising the potential of a regolith dominated area by providing a systematic framework in which to carry out mineral exploration. For mineral explorers, tenement scale regolith-landform maps locate, identify and characterise regolith sampling media. Further to this, they provide a context in which to place the sampling media by identifying geochemical dispersion pathways within the contemporary landscape.

Land managers and pastoralists also find these maps useful for developing land management practices. At an individual property scale, areas of erosion and deposition are identified, together with the distribution of soil and vegetation types. Scientist and students working in western New South Wales can also use these maps to contribute to understanding of wider regolith and landscape evolution research.

## METHODOLOGY

After recognising that an area needs to be regolith-landform mapped, previous mapping and geophysics for the area is examined and the best possible aerial photographs for the area are acquired. The 1:25,000 regolith-landform map production methodologies are detailed in Foster (*in prep.*).

The system used to map the Broken Hill 1:25,000 regolith-landform map series is based largely on the RTMAP unit scheme described in Pain *et al.* 2000. This approach takes into account the purpose of the mapping program



and the end-users of the map product, while maintaining the integrity of a systematic division of materials and landforms. This scheme is used because it is independent of an interpreted chronology or stratigraphy (Hill, 2002). It is important to recognise this because regolith units are often of variable thickness, discontinuous laterally, and can be independent of substrate and “weathering periods” (Pain *et al.*, 2000).

The RTMAP system divides regolith materials into transported and *in situ* categories, and then further subdivides each of these. For example, transported materials are divided into aeolian, alluvial, colluvial and lacustrine sediments, and *in situ* materials are divided according to weathering grade. The RTMAP scheme also provides a comprehensive list of landforms, hierarchically divided according to type. A combination of regolith material and landform is represented on each map unit polygon as a 3 to 4 letter code, together with a numerical modifier to further subdivide broadly similar units.

A map unit table (database) was developed specifically for the 1:25,000 scale mapping project. Under the headings of *regolith lithology*, *landform*, *surface form*, *minor attributes* and *vegetation*, a series of descriptive unit characterisations were assembled with little genetic interpretation. This database of units can be used and modified for future 1:25,000 scale mapping projects.

## MAPPING UNITS AND EXPLORATION STRATEGIES

The major regolith landform units of the southern Broken Hill Block and northern Murray Basin margins are made up of low hills and rises comprising variably weathered bedrock and indurated regolith materials, and broad alluvial and colluvial systems in the lower parts of the landscape. A significant aeolian component contributes to the regolith materials across the entire landscape. A brief, general description of the major regolith and landform types is provided here. As previously mentioned, exploration sampling strategies in regolith dominated terrains must consider the context of the media sampled and its landscape position. At the end of each regolith type description, considerations for mineral exploration are mentioned.

### Alluvial

Alluvial regolith-landform associations comprise alluvial sediments within channels, swampy channels, alluvial and depositional plains, drainage depressions and swamps. These alluvial sediments are dominated by quartzose and lithic sands and gravels, with minor silts and clays. The large alluvial channels tend to be dominated by an open woodland of river red gums (*Eucalyptus camaldulensis*), whilst other alluvial units, such as plains, swamps and fans, are likely to host a chenopod shrubland. Stream sediment sampling can be a reliable vector to mineralisation, provided the sediment type and source and the likelihood that these materials have travelled considerable distances is considered. Vegetation may also be a reliable sampling media in these areas.

### Colluvial

Broad colluvial units dominate the margins of the southern Broken Hill block and northern Murray Basin area. These regolith-landform units usually comprise sub-rounded to sub-angular lithic and quartzose sands and gravels. These materials are associated with landforms including low hills and rises, depositional and erosional plains, sheet flow fans and drainage depressions. They are vegetated by chenopod shrublands, containing mostly species of bladder saltbush (*Atriplex vesicaria*) and bluebush (*Maireana* sp.), with minor grasslands or open woodlands of casuarina (*Casuarina pauper*) and mulga (*Acacia aneura*). In some cases colluvial landforms display a distinctive contour banding pattern. When sampling materials in these areas, one must consider sediment type and source, the distance travelled by the material and vectors to its source.

### Aeolian

Well-sorted, red-brown fine sands and silts contribute to most regolith materials over western New South Wales. It is considered as a minor component of most regolith landform units, but does occur in a significant quantity to warrant being named an aeolian unit. These sediments accumulate as undulating sand plains and longitudinal dunes, often associated with alluvial tract boundaries. Aeolian dunes host grasslands dominated by spear grass (*Stipa* sp.) and *Astrebla* sp., and aeolian sand plains have a closed shrubland dominated by weeds (*Cassia* sp. and *Dodonaea* sp.). Sampling these sediments as part of an exploration program will display a diluted response and it must be considered that these sediments have travelled a significant distance.

Other transported materials depicted on the 1:25,000 map series include lacustrine sediments and anthropogenic fill. The lacustrine sediments are those clays and silts associated with the Stephens Creek Reservoir, while the fill sediments are confined to residential, industrial and mining areas.

### Saprolith

Slightly and moderately weathered bedrock exposures are associated with low hills, rises and erosional plains. The original lithology and texture of the rock is identifiable and primary minerals are replaced, to varying degrees, by clays and iron oxides, on the surface and in open fractures. The vegetation that mainly colonises

these regolith-landform units is a chenopod shrubland dominated by bluebush (*Maireana* sp.) and bladder saltbush (*Atriplex vesicaria*), with open woodlands featuring casuarinas (*Casuarina pauper*) and mulgas (*Acacia aneura*). Traditional bedrock sampling programs are used in these areas, taking into account the weathering, and degree of weathering, and secondary mineral development, together with sampling of materials such as regolith carbonate accumulations (see Indurated regolith materials).

#### **Indurated regolith materials**

Traditional geology maps for this region have represented the location of silcretes, ferricretes and calcretes with limited description, and only general outlines. The new 1:25,000 scale series refines their location and landscape boundaries and maps the material more specifically. For example, silcretes are classified according to the material that has been silicified (e.g. alluvial sediments or highly weathered bedrock) and the associated landform, with an overprint pattern (on the polygon) to show siliceous induration. Iron-oxide indurated regolith is represented in the same way. Regolith carbonate accumulations (RCAs or 'calcretes') occurrences are often too small to map at 1:25,000 scale so their occurrence is described in the minor attributes section of the regolith-landform unit description. The morphology of the RCA is also recorded.

### **CONCLUSION**

The competitive advantage for mineral explorers in the regolith-dominated terrains surrounding the outcropping riches of Broken Hill will go to the exploration company brave enough to explore within 'the dirt'. These companies will be armed with tenement-scale regolith landform maps, which characterise all the elements of the landscape and its materials. By recognising and understanding these materials and their place in the landscape, explorers can realise the potential of the Broken Hill regions regolith dominated margins and beyond.

### **ACKNOWLEDGEMENTS**

The author gratefully acknowledges the support of the Cooperative Research Centre for Landscapes, Environment, Mineral Exploration and the New South Wales Department of Mineral Resources and Geoscience Australia, and co-workers and contractors within these organisations. In particular the author wishes to acknowledge Steve Hill, for sharing his knowledge and passion for the Broken Hill region and for his invaluable collaboration, inspiration and support. Thanks also to Ancret Lewis and Dirk Kirste for their comments on this manuscript. The cooperation of Broken Hill landholders is also appreciated.

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# **STRUCTURAL HISTORY OF THE BIMBOWRIE INLIER: ROLE OF LOW-ANGLE SHEAR ZONES AND WIDER IMPLICATIONS FOR TECTONOTHERMAL EVOLUTION OF THE WILLYAMA SUPERGROUP.**

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## **INTRODUCTION**

Although low-angle extensional shear zones are preserved in many of the world's Phanerozoic orogens (e.g. North America Cordillera, Hercynian of western Europe), they have yet to be described in any great number from the Precambrian. Given their greater antiquity and increased likelihood of having been deformed by younger deformational events this is not surprising. Despite the effects of later deformation, some elements of the original extensional geometry and history should persist, particularly where extension involved the juxtaposition of rocks with different magmatic and metamorphic histories as is the case in the metamorphic core complexes of the North American Cordillera and western Europe (Davis and Lister, 1988; Costa and Rey, 1995). Such juxtapositions are a universal feature of metamorphic core complexes and provide a useful parameter whereby extension might be recognised in older and much more intensely deformed Precambrian orogens. The Paleoproterozoic Willyama Supergroup has several features in common with these metamorphic core complexes, not least of which is the presence of a regionally extensive detachment surface that separates two ca 1700 Ma metasedimentary sequences subjected to different degrees of partial melting and bimodal magmatism. Recognition of this structure not only underscores an important distinction already drawn between upper and lower parts of the Willyama Supergroup on lithostratigraphic grounds (Willis et al., 1983; Conor, 2000) but provides a new tectonothermal framework by which this classical low pressure (P) – high temperature (T) granulite terrane may be better understood. This detachment surface and its associated structures have been investigated in the Bimbowrie Inlier where metamorphic grades and deformational strains are lower than in the neighbouring Broken Hill domain.

## **GEOLOGY AND STRUCTURAL ELEMENTS OF BIMBOWRIE INLIER**

Metasedimentary rocks in the Bimbowrie Inlier are represented by the Curnamona and Strathearn Groups (Conor, 2000). Both groups share a common history of multiple deformation (D1-D4) and initial (M1) low pressure (P)-high temperature (T) metamorphism but only rocks of the Curnamona Group have been intruded by 1705-1680 Ma bimodal magmatic rocks. Included in these magmatic rocks are deformed A-type granites as well as former dolerite sills and dykes now represented by amphibolite (Ashley et al., 1996; Page et al., 2000; Conor and Fanning, 2001). Their metasedimentary host rocks (Wiperaminga and Ethiudna Subgroups; Conor, 2002) have been extensively migmatized and comprise mainly sillimanite grade psammopelitic schists and quartzofeldspathic gneisses with minor amounts of intercalated quartzite, marble and calc-silicate rock. Migmatization occurred during the earliest recognisable deformational event (D1) and gave rise to a crude compositional banding (S1) that was deformed by all later deformational events (D2-D4). A mineral fabric defined by biotite and fibrolite, and oriented parallel to the compositional/migmatitic layering in metapelitic rocks is also taken to be S1. Based on detrital zircon ages, deposition of the Curnamona Group occurred no later than 1710 Ma (Page et al., 2000). A metalliferous unit occurring at the top of the Ethiudna Subgroup and known locally as the Bimba Formation is also included here in the Curnamona Group.

In contrast, the stratigraphically overlying Strathearn Group (Saltbush Subgroup) is inferred to be younger than 1700 Ma and was initially metamorphosed under andalusite rather than sillimanite grade conditions. It consists mainly of psammopelitic rocks with lesser amounts of graphitic schist towards the base of the sequence (Plumbago Formation). It is totally devoid of A-type granites and mafic intrusions, and unlike the variably oxidised and magnetite-bearing Curnamona Group, is chemically reduced. The boundary between the Curnamona and Strathearn Groups therefore corresponds to a marked change in oxidation state and magnetic susceptibility that manifests itself on aeromagnetic images of the region as a prominent linear anomaly. This redox boundary locally coincides with the Bimba Formation but for the most part this unit is missing, as is often the case with other parts of the sequence (Plumbago Formation, Ethiudna Group) so that the Saltbush Group commonly rests directly on the Wiperinganga Subgroup. The presence of recrystallised mylonites along this contact further demonstrates that this boundary is tectonic rather than stratigraphic. The same tectonic boundary has been recognised in the Broken Hill domain where it forms the boundary between the Sundown and Broken Hill Groups (White et al., 1995). However, while White et al. (1995) interpreted this boundary as a former thrust fault, it consistently emplaces the younger Sundown Group on older rocks and for this reason is more likely to have originated as an extensional structure.

#### **EARLY TECTONOTHERMAL EVOLUTION OF WILLYAMA SUPERGROUP**

It is equally evident that this extensional shear zone must predate the D2 deformation because it has been recumbently folded by the D2 structures. D2 folding took place after 1640 Ma and was accompanied by crustal thickening and higher pressure metamorphism as evidenced by the replacement of andalusite by fibrolite in rocks with S2 as the dominant fabric and the growth of syn-D2 garnets with rims that are more grossular-rich than their cores. Concomitant with this event, the original D1 thermal structure was inverted such that sillimanite grade migmatites now lie structurally above lower grade andalusite-bearing rocks in the overturned limbs of D2 isoclines. These relations are inconsistent with earlier interpretations of the tectonothermal evolution in which low P-high T metamorphism was not only equated with crustal thickening but thought to be a consequence of D1 nappe emplacement (e.g. Marjoribanks et al., 1980; Hobbs et al., 1984). In our interpretation there is no need for a linkage between crustal thickening and initial low P-high T metamorphism. Instead, we propose that low P –high T metamorphism is related to crustal thinning and bimodal magmatism accompanying D1 extension.

In this interpretation, the Strathearn and Curnamona Groups, along with their Broken Hill equivalents, represent upper and lower plates of a Paleoproterozoic metamorphic core complex in which the more intensely metamorphosed lower plate was transported upward beneath the upper plate along a low angle shear zone. The juxtaposition of metamorphic rocks formed under different conditions is in keeping with this interpretation as is the restriction of migmatites and 1705-1680 Ma bimodal magmatic rocks to the lower metasedimentary sequence. During the earlier stages of extension, the Curnamona Group would have been at much deeper crustal levels where conditions were much more conducive to magmatic intrusion, high temperature metamorphism and partial melting. It is also important to note that many amphibolites were derived from highly fractionated Fe-rich tholeiites whose composition is consistent with intrusion into a continental rift or extensional tectonic environment (James et al., 1987). This, and the fact that A-type granites are typically associated with the initial stages of continental rifting, are strongly suggestive of a tectonic model involving extensional rather than contractional processes. Such a model may have important implications for the formation and distribution of mineralisation because any

regional scale shear zone of the type postulated here would not only have acted as a major fluid conduit but provided a favourable chemical environment (redox boundary) for the entrapment of metals.

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# THE BROKEN HILL EXPLORATION INITIATIVE

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## INTRODUCTION

The Broken Hill silver-lead-zinc ore body is possibly the world's largest accumulation of base metals. The pre-mining size of this fabulous deposit is estimated to have been 280 million tonnes of high-grade lead-zinc. Since 1883 the Broken Hill Line of Lode has produced well over \$70 billion of metal. This deposit stands out as a giant ore body by world standards and yet it is only one of thousands of known mineral occurrences in the Curnamona Province and adjacent areas.

In this era of global mobility of investment funds, high quality geoscience information is fundamental to attracting and maintaining exploration and mining investment in Australia. Furthermore, the complexity of the Curnamona Province geology demands a cooperative effort to fully appreciate the nature of controls on mineralisation and provide a knowledge framework for exploration in the region.

## BHEI — 1994-2000

In 1994, the South Australian, Commonwealth and New South Wales governments launched the Broken Hill Exploration Initiative (BHEI). The initiative was jointly funded by the three governments and involved a total expenditure of \$16 million through to the year 2000. The purpose of the initiative was to stimulate mineral exploration in the Broken Hill region and adjacent areas in South Australia. The project area extended from Mount Painter in South Australia to the Koonenberry region in NSW and included the Proterozoic Curnamona Province. At that time, the Broken Hill ore body was recognised as not having the mine life to sustain the Broken Hill community in the longer term. Similarly, there were concerns about the consequent impact on Port Pirie of mine closure.

An important objective of the BHEI was to establish a modern geoscience framework for more effective and efficient exploration by industry. This framework was to consist of very high quality regional geological, geophysical and geochemical mapping and data coverages. State funding for BHEI was through the NSW Discovery 2000 initiative and the South Australia Exploration Initiative (SAEI). It is notable that the SAEI was the first of the state exploration initiatives in Australia and set a new benchmark for international jurisdictions in the provision of geoscience information in support of exploration investment.

The BHEI has been a multi-disciplinary project, bringing together high-resolution potential field (magnetic and gravity) data with regional geology, petrophysics, petrology, geochronology, geochemistry, seismic and radiometric data, structural analysis, and metallogenesis studies to provide new insights into the geological evolution of the Broken Hill—Olary region, thereby establishing a firmer and more effective basis for mineral exploration.

A key component of the BHEI has been the acquisition of new geophysical data. In excess of half a million line kilometres of airborne magnetic and radiometric survey data have been

obtained, with line spacings of 100 m in areas of outcrop to 400 m in areas of substantial cover.

Over 11 000 gravity observations have been made in the region. PIRSA has obtained 8400 gravity readings in the Olary and Curnamona 1:250,000 map areas, with close to 3000 readings being obtained at Broken Hill and Koonenberry by the NSWDMR and Geoscience Australia.

The geophysical data obtained have been extensively used to interpret the geology of the region. Studies have also been carried out to understand the magnetic properties of rocks.

Major data set releases on CDROM have been a feature of the BHEI. Comprehensive GIS data sets have been released including geological, geophysical and exploration data over key regions in NSW and South Australia.

An outstanding contribution of the BHEI was 300 km of deep seismic reflection surveys in the Broken Hill region. This work included a major contribution from the Australian Geodynamics CRC.

## **THE NEW BHEI**

The BHEI initiative has proved to be an outstanding success, producing vast new datasets and knowledge and generating industry enthusiasm for exploration in the Curnamona region. This important collaborative initiative between the three governments has recently been renewed under the auspices of the National Geoscience Agreement. More recently the Cooperative Research Centres for Landscape, Environments and Mineral Exploration (CRCLEME) and Predictive Mineral Discovery (pmd\*CRC) have joined the BHEI.

The Commonwealth, NSW and South Australian governments support CRCLEME which is enhancing our understanding of the regolith and developing tools for improving mineral exploration in covered areas. With Australia's extensive regolith this is a national priority for exploration research where potential rock packages are commonly covered by thick cover. Scientists from Geoscience Australia, CSIRO and universities are delivering important breakthroughs for exploration geoscience within this CRC for the Curnamona. Similarly, all three governments are supporting coordinated research in the Broken Hill region by pmd\*CRC, which is focussing on reducing the discovery risk through improved targeting methods.

The recent exploration and research in the Curnamona Province have dramatically increased opportunities for explorers. The new geophysical coverages, new hyperspectral mapping, regolith science, research on structure and controls on mineralisation, geochronology and isotopic studies have taken understanding of the Curnamona mineral systems to a new level. More particularly, the information coverage available over the Broken Hill region sets a new global standard. Information includes detailed lithostratigraphic and regolith mapping coverages, metallogenic mapping, high resolution airborne magnetics and radiometrics, exploration datasets (drilling and geochemistry), detailed gravity, high resolution hyperspectral mapping, and now, airborne gravity data.

More recently, the NSW contribution to the BHEI has been through the Exploration NSW initiative. In 2002, Exploration NSW funded a state-of-the-art airborne hyperspectral survey



(HYMAP™) which provides very high spatial resolution imagery and information on the mineral composition of rocks and soil. This will lead to new mineral exploration opportunities in the Broken Hill area. Processing of this vast data set would allow detailed mapping of alteration systems which are key vectors to mineralisation.

An even more recent highlight was the completion in March this year of an airborne gravity gradiometry survey over the Broken Hill area. This survey used the revolutionary FALCON™ system which has been developed by BHP Billiton. The release of this Broken Hill data late in 2003 will constitute the first public release of any FALCON™ survey data. This survey was conducted in collaboration with pmd\*CRC and will contribute to the refinement of a three dimensional model of the Broken Hill Block originally developed as a project between Pasminco and Fractal Graphics. Understanding of the third (and fourth) dimension is critical to predict the likely depositional sites for major mineral systems in three dimensional space. This is the frontier for modern mineral exploration.

Exploration NSW is also improving geoscience and mineral exploration databases to ensure that the results of the extensive exploration work at Broken Hill are available to new explorers.

PIRSA Geological Survey Branch is continuing detailed (1:25 000 scale) basement and regolith mapping and other studies in key areas of the Willyama Inliers. The current mapping focus areas are the Mingary 1:100 000 sheet area (including the Broken Hill Domain in South Australia), Willyama Supergroup stratigraphy in the Weekeroo Inliers, granites and metasediments in the Billeroo area north of Crocker's Well and regolith on the Kalbarri 1:100 000 sheet areas. The mapping is complemented by solid geology interpretation utilising geophysical data in the extensive covered areas around the Inliers. A major revision of the 1:500 000 solid geology interpretation for the South Australian portion of the Curnamona Province has been completed. CSIRO is processing ASTER multispectral satellite data with the aim of producing mineral maps to assist mapping of regolith and basement geology, including alteration signatures. A new GIS data package on DVD incorporating all available geological layers, geophysical imagery & grids, digital geochemistry and drillhole data has just been completed and is available at this conference.

PIRSA is supporting collaborative research on aspects of the tectonic history and architecture and associated mineralising systems of the Curnamona Province. Collaborating research organisations include Adelaide and Monash Universities, Geoscience Australia, pmd\*CRC and CSIRO. The ultimate goal of this research is to provide a better understanding of controls on mineralisation and, together with geological and geophysical data, assist in improved targeting for mineral exploration.

Recent studies under the BHEI have underlined the important iron oxide copper-gold potential in the Curnamona Province. The occurrence of such deposits is now well established and the region offers tantalising opportunities for deposits similar to Ernest Henry. The NSWDMR has released an invaluable CD-ROM package on Cu-Au opportunities in the Broken Hill region.

Recent BHEI geochronology studies have provided an insight to the fourth dimension of Curnamona geology. The stratigraphic sequence developed by the NSWDMR at Broken Hill has now largely been validated and calibrated. We also now know that the Paragon Group, at

the top of the Broken Hill sequence, is a time equivalent of the Isa Superbasin, spanning the ages of the host rocks to the Mt Isa and McArthur River orebodies. The fine-grained, originally organic-rich facies of the Paragon Group has similarities with Isa Superbasin facies. Stratabound Pb-Zn anomalism has been detected in the Paragon Group at a time equivalent position to the Mt Isa Pb-Zn orebody. Furthermore, correlations between various levels of the Broken Hill and Olary stratigraphies are now firmly established, including correlation between the base metal and tungsten-bearing Bimba Formation of the Olary Block and the zinc-tungsten bearing Ettlewood Calc-Silicate Member some 500m stratigraphically below the Broken Hill orebody.

pmd\*CRC-CSIRO lead-isotope studies supported by BHEI are setting the various mineral deposit types in the Curnamona Province into the above chronostratigraphy. This work will further refine the mineral systems correlations with the Proterozoic of Northern Australia, particularly the Mt Isa - Macarthur River – Century group of world-class deposits.

International promotion of exploration investment is now an essential element of the states' strategy for a sustainable exploration and mining industry. The states join with the Commonwealth each year in participation at the Prospectors and Developers Association of Canada Conference (PDAC) in Toronto, Canada. The Curnamona Province and its exploration opportunities were featured at the 2003 PDAC.

A critically important feature of the BHEI has been the BHEI conference. BHEI2003 is the sixth of these conferences which have proved to be the key events for the release of new breakthroughs in mineral exploration-related research in the Curnamona Province and adjacent terrains. The challenge for the BHEI is to turn the excellent datasets over the Curnamona into understanding that will inform and excite explorers in the 21<sup>st</sup> century. To assist with planning for future BHEI projects pmd\*CRC and CSIRO are conducting an audit and gaps analysis to identify additional key information and knowledge required to attract increased exploration investment to the Curnamona Province.

Broken Hill has embarked on a new phase of its mining history with new entrants on the Line of Lode, new information, new opportunities and a major commitment by governments, industry and research organisations to create a revitalised mining industry in this region which was the birthplace of Australia's industrial development.

Information on BHEI products and outputs can be obtained from the following web sites:

<http://www.minerals.nsw.gov.au>

<http://www.pir.sa.gov.au>

<http://www.ga.gov.au>

## **ACKNOWLEDGEMENTS**

Published with the permission of the Director-General - NSW Department of Mineral Resources, the Executive Director – Primary Industry and Resources South Australia and the Chief Executive Officer, Geoscience Australia.

# A REVIEW OF BROKEN HILL ORE SYSTEM MODELS

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This pmd\*CRC project (running from January to November 2003), aims to critically review published Broken Hill Ore System (BHOS) genetic models, and with the aid of computational modelling, to define multiple working hypotheses which best fit the weight of evidence available. These hypotheses are projected to become the basis for improved exploration models for finding new Broken Hill Type deposits.

## DEVELOPMENT OF BROKEN HILL GENETIC CONCEPTS

Wilkinson (1884) and Marsh (1890) first noted a 'fissure-vein' appearance of the orebody, and proposed a late-magmatic replacement hypothesis. This was challenged by Jack (1891), Pittman (1892), and Jaquet (1894), who proposed a syn-tectonic 'saddle-reef' model based on the observed tapering of the folded orebody limbs. Sutherland (1891) and Stelzner (1894) first suggested that the orebody was of sedimentary origin, noting the conformable nature of the lode to the wall rocks. However it was the late-magmatic replacement model that was the dominant genetic theory until c.1965, propelled with seminal papers by Andrews (1922) and Gustafson et al. (1950), amongst others.

In the early 1950's Haddon King conceived an exhalative origin for the orebody after inspecting stratiform mineralization in the Zambian Copperbelt. After ten years of intense debate, his subsequent paper with Bren Thompson (King & Thompson, 1953), and important papers by Stanton & Russell (1959) and Stanton & Richards (1961), proved to be a watershed for the general acceptance of a synsedimentary origin for the BHOS.

Syngenetic models were progressively developed between 1965-1993. Variations were conceived regarding the mineralizing environment (volcano-sedimentary- Stanton, 1976; prograding deltaic- Haydon & McConachy, 1987); the source of the ore fluids (mantle-derived- Plimer, 1985; basin leached- Phillips et al., 1985), and the fluid flow mechanism (compactive expulsion- Sawkins, 1984; magma-driven convection- Parr & Plimer, 1993).

Research undertaken by the Australian Geodynamic CRC (1993-2002) challenged a number of entrenched ideas on Broken Hill, and their new geochemical and structural data supported a syn-metamorphic/remobilized epigenetic model for the BHOS (e.g. Nutman & Ehlers, 1998; Gibson et al., 1998). This idea gained further support from structural studies of the line-of-lode by White et al. (1995) and Rothery (2001), who suggested the orebody was syntectonically emplaced into dilational structures, possibly aided by carbonate replacement.

Since 1990 there have been a number of concise reviews that have compared and classified Broken Hill Type deposits (e.g. Beeson, 1990; Parr & Plimer, 1993; Walters 1998; Large et al., 2000). However, a comprehensive evaluation of the genetic models for the BHOS has not been published since Stevens (1975).

## CURRENT APPROACH

At this stage of the project, the most viable genetic concepts from the literature have been identified. The main dichotomy is between pre-tectonic versus syntectonic origin. 'Tectonic' in this case refers to the period covering the Olarian Orogeny, including peak and retrograde metamorphism. Most models or concepts can be partitioned as end-member parameters within this dichotomy, and are summarized in Table 1. Isotopic data and deformed nature of the orebody render most post-tectonic models 'highly unlikely' and have not been included in this table (although some remobilization of the ore is considered post-tectonic). Some aspects of the geodynamic setting of the Curnamona Province are disputed, however the most likely scenario involves the creation and inversion of an intracontinental rift basin. A summary of the event sequence can be found in Page et al. (2000).

The most viable pre-tectonic models involve the timing of mineralization of the BHOS to be broadly contemporaneous with the deposition of the rift sequence, either debouching onto the sea floor (syngenetic-exhalative, Parr & Plimer, 1993) or precipitating beneath the seafloor (dia-epigenetic, Haydon & McConachy, 1987). There is general agreement on the main species that have contributed to the BHOS ('fluid composition' in Table 1), however the source of the metals/alteration elements, and their transport and deposition processes remain unclear. The chemistry of the ore fluids has been mainly extrapolated from experimental work (e.g. Cooke et al., 2000), although in some cases they have a weight of indirect evidence supporting them. For

example, the concept of a reduced ore fluid is supported by the composition of the orebody and alteration halo. Evidence includes high Mn/Fe ratios (Spry & Wonder, 1989), the presence of pyrrhotite and lack of pyrite, the low Fe<sub>2</sub>O<sub>3</sub>/FeO ratios (Huston et al., 1998), positive Eu<sup>2+</sup> anomalies (Lottermoser, 1989) and the presence of Au (Cooke et al., 2000). These facts are tempered by experimental and comparative evidence from SEDEX deposits that suggest reduced ore fluids are relatively deficient in Pb-Zn but rich in Ba (Large et al., 2002), and thus suggest an oxidized, neutral to alkaline ore fluid to produce giant Pb-Zn, Ba-poor deposits.

The most viable syntectonic models are focused on the line-of-lode, and involve the emplacement of the ore into dilatant structural sites, followed by chemical and/or mechanical remobilization. They can explain the markedly linear shape of the orebody and its apparent co-incidental relationship to fold structure and high-temperature shear, as well as the skarn-like gangue mineralogy (Gustafson, 1950; Rothery, 2001). Thus, most of the evidence is structural, and careful assessment of the various structural models for the BHOS is required (e.g. Laing et al. 1978; White et al., 1995; Webster, 1996). The main conceptual variations relate to the amount of metal that was transported to the present ore site via solution rather than by solid-state processes (Plimer, 1987; Marshall & Spry, 2000), and whether or not there was a preexisting orebody. Most parameters defining the nature of the fluid system are either experimental (e.g. Mavrogenes et al., 2001) or extrapolated from fluid-inclusion data (Wilkins, 1977; Prendergast, 1996). It is interesting to note that a syntectonic ore fluid would have most likely remained under-saturated in Pb-Zn-Ag for a protracted period, given the high solubilities of these metals and the estimated 10-15°C/Ma cooling rate from peak metamorphism (Harrison & McDougall, 1981).

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**Table 1.** Summary of viable model parameters from literature. Numbered parameters (**in bold**) represent possible end-member systems or concepts.

	Nature of ore system fluids			Fluid flow mechanism	Metal deposition process
	Reservoir	Composition	Salinity/redox state/temperature		
Pretectonic	1. A devolatilized mantle fluid <sup>1</sup> 2. Crustal magmatic fluid <sup>2</sup> 3. Connate basin brines <sup>3</sup> 4. Seawater <sup>4</sup>	<b>Seawater/connate fluid:</b> H <sub>2</sub> O-Na-Cl-Ca <b>Metal-rich fluid (either mantle, crustal or basin derived):</b> P-Si-Ca-Mn-Fe-Pb-Zn-Ag ± CO <sub>2</sub> <b>Metal Complexes:</b> CO <sub>3</sub> , Cl, F <b>Sulphur content:</b> Σmetals ≈ Σsulphur (5-12 wt%) <sup>5</sup>	<b>pH:</b> 1. Relatively low (~4-5) <sup>6</sup> 2. Neutral to slightly alkaline <sup>7</sup> <b>Salinity:</b> High (>18 wt% NaCl) <sup>8</sup> <b>Redox state:</b> 1. Low f(O <sub>2</sub> ), H <sub>2</sub> S>>SO <sub>4</sub> <sup>6</sup> 2. High f(O <sub>2</sub> ), SO <sub>4</sub> >>H <sub>2</sub> S <sup>9</sup> <b>Temperature:</b> 150-350°C <sup>9, 5, 6</sup>	1. Free convection driven by high geothermal gradient and/or high level mafic/felsic intrusions <sup>11</sup> 2. Deep fracturing in mantle releasing devolatilized fluids up major discharge fault/s <sup>1</sup> 3. Compactive expulsion of metal-bearing connate brines up major discharge fault/s <sup>3</sup>	1. Cooling of ore fluid upon mixing with basin seawater <sup>2</sup> 2. Physically trapped in permissive layers below seawater interface <sup>4</sup> 3. Mixing of a H <sub>2</sub> S-rich fluid with a Pb-Zn-rich, sulphate absent brine <sup>12</sup> 4. pH contrast (e.g. carbonate layers) <sup>4</sup> 5. f(O <sub>2</sub> ) contrast <sup>6</sup>
	1. Prograde metamorphic fluid <sup>13</sup> 2. Metal-rich fluid <sup>14</sup> 3. Sulphide melt <sup>15</sup> 4. Retrograde metamorphic fluid <sup>16</sup>	<b>Prograde metamorphic fluid:</b> H <sub>2</sub> O-CO <sub>2</sub> -(NaCl-CO-N <sub>2</sub> -CH <sub>4</sub> ) a(H <sub>2</sub> O) ~0.5 <sup>13</sup> <b>Metal-rich fluid:</b> Na-Si-CO <sub>2</sub> -Pb-Zn-Mn-K-Fe <sup>14</sup> <b>Sulphide melt:</b> Pb-Ag-Sb-Mn-F-CO <sub>3</sub> -Zn-Ca <sup>15</sup> <b>Retrograde metamorphic fluid:</b> 1. H <sub>2</sub> O-CO <sub>2</sub> -CH <sub>4</sub> <sup>16</sup> 2. NaCl-(K-Ca-CH <sub>4</sub> -CO <sub>2</sub> ) <sup>16</sup>	<b>pH:</b> retrograde fluid neutral to weakly acid <sup>16</sup> <b>Salinity:</b> 1. Moderate (~10 wt% NaCl) <sup>14</sup> 2. High (23 wt% NaCl) <sup>16</sup> <b>Redox state:</b> 1. Low f(O <sub>2</sub> ), H <sub>2</sub> S>>SO <sub>4</sub> <sup>13,17</sup> 2. High f(O <sub>2</sub> ), SO <sub>4</sub> >>H <sub>2</sub> S <sup>16</sup> <b>Temperature:</b> 300-830°C <sup>18</sup>	1. Hydrothermal convection of metamorphic fluids driven by high geothermal gradient 2. Transposition, metamorphic differentiation and partial melt mobility causing element partitioning between the lenses <sup>18,15</sup> 3. High strain gradients causing solid-state sulphide mobility into low strain sites <sup>18</sup>	1. Dilational zones in the line of lode (fold hinges) <sup>18</sup> 2. Chemical contrast (e.g. replacement of carbonate layers) <sup>18</sup> 3. Metasomatic upgrading under low fluid/rock conditions <sup>19</sup> 4. Temperature decrease
Synectonic					

<sup>1</sup> Plimer (1985), <sup>2</sup> Parr & Plimer (1993), <sup>3</sup> Sawkins (1984), <sup>4</sup> Haydon & McConachy (1987), <sup>5</sup> Spry (1987), <sup>6</sup> Large et al. (1996), <sup>7</sup> Large et al. (2002) <sup>8</sup> Lydon (1983), <sup>9</sup> Walters (1998), <sup>10</sup> Lottermoser (1989), <sup>11</sup> Garven & Bull (1999), <sup>12</sup> Hobbs (2000), <sup>13</sup> Phillips (1981), <sup>14</sup> Prendergrast (1996), <sup>15</sup> Mavrogenes et al. (2001), <sup>16</sup> Wilkins (1977), <sup>17</sup> Williams (1998), <sup>18</sup> Rothery (2001), <sup>19</sup> Bodon (1996).

# **A PRACTICAL APPROACH TO REVIVING THE FORTUNES OF A MATURE WORLD CLASS DEPOSIT: THE PERILYA BROKEN HILL LEAD ZINC MINE**

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## **INTRODUCTION**

The purchase of the Broken Hill Mine in mid 2002 has resulted in Perilya acquiring a large exploration holding centred on one of the world's most renowned base metal districts. In the 10 months to April 2003, Perilya mined 1.4Mt @ 8.8% Zn, 3.6%Pb and 34.5g/t Ag from its Southern Operations and is now achieving production rates equivalent to 2.4Mt per annum. The Perilya Broken Hill Mine is now in the lowest cost quartile of world zinc producers and has been cash positive since January 2002. The future of Broken Hill is dependent on maximizing extraction of the current resource and locating, defining and systematically mining new discoveries. The ability to achieve these objectives rests on a detailed understanding of the geology of the Broken Hill ore body, including the complex structure and resultant ore-body geometry, and defining practical vectoring guides for exploration.

## **BACKGROUND**

When Perilya acquired the project in mid 2002, extensive work was required on mine geology and exploration digital data sets before a framework could be produced on which to base mining and exploration targeting decisions. Lack of geological control impeded potential to make new discoveries, and compromised mining of ore through inaccurate interpretations. Problems had evolved from the sheer size of the Broken Hill deposit, the fragmentation of the ore body between different companies over the last 118 years, and the long mining and exploration history. As Perilya has gained confidence in the proper application of geology at the mine, numerous opportunities to add value have emerged.

Some of the major changes implemented by Perilya to facilitate rapid understanding of the deposit and exploration potential include:

- South facing geological sections through the Southern Operations were changed to north facing, in line with the rest of Broken Hill, breaking 100 years of tradition but allowing sensible integration of geology through the Line of Lode;
- One geological legend and database structure was established for all drilling programs, eradicating at least four independent coding and colour schemes for the same ore body. Recently, CBH has adopted the same coding scheme for exploration on the central CML (J. Collier, pers comm. 2003); and
- Validating the databases.

## **APPROACH**

The approach that Perilya has applied to mining geology and exploration has been to:

1. Streamline mining processes in the Southern Operations (ZC, NBHC and Southern Cross) for maximum extraction of ore, with a focus on minimizing dilution and achieving a high overall grade;
2. Define targets in the Southern Operations that are close to mine infrastructure and can be accessed from current mine development (low risk – high yield);

3. Define step-out targets in the Southern Operations based on a solid geological framework;
4. Re-open the North Mine by establishing a decline to access the previously defined reserve beneath the pit floor.
5. Apply knowledge gained from the Broken Hill ore-body to exploration in the district, with the primary objective of locating economic mineralisation in advanced target areas for mining in the near future;
6. Utilize new technology for old exploration areas in the district, including incorporation of regolith mapping, geomorphologic-geochemical studies, HyMap and gravity;
7. Consider other commodities in the area, such as high grade Au-Ag, Cu-Au and Pt-Pd.

## **SOUTHERN OPERATIONS**

Reinterpretation of the Southern Operations was aimed at locating quality targets and building a robust geological model from which to begin step-out exploration. This project included:

- Building a database structure that allows a variety of information to be queried and plotted on section or viewed on-screen, including multiple lithologies, gangue and sulphide minerals, rock and ore textures, structure and retrograde assemblages;
- Entering detailed geology from old logs for all current stoping areas in the mine and selected key sections;
- A complete geological sectional interpretation of the Southern Operations (1:500 scale, 450 sections, spaced every 20m covering 3,000 m of strike and 1,500 m vertical) utilizing a combination of old hand drafted sections and drilling completed since the old sections were abandoned in 1995;
- Interpreting sections in detail (1:1,500 scale) every 200m, defining:
  - Geological and structural relationships;
  - Distribution of gangue minerals (such as blue quartz, green and grey feldspar, cummingtonite, tremolite, bustamite, rhodonite, hedenbergite, calcite, staurolite, sericite, chlorite, and zeolite);
  - Sulphide minerals (including pyrrhotite, pyrite, arsenopyrite (loellingite), galena and sphalerite); and
  - Geochemistry (Zn, Pb, Ag, Cu and Fe).
- Interpreting level plans of backs mapping geology and drill hole geochemistry (1:2,000 scale)

Over 40 targets have been defined in and along strike of the Southern Operations as a result of this approach, giving potential for several million tonnes of ore outside known resources. All targets have at least several drill intercepts defined by historic drilling, and are considered low-risk opportunities. Underground drilling has recently commenced to test these targets and infill resource and reserves. Two large follow-up targets are discussed below.

## **SEAL (SOUTH EASTERN A-LODE)**

The SEAL is an isolated A-Lode ore body of approximately 1.5Mt at greater than 20% Pb plus Zn. When Perilya acquired the mine the definition of SEAL was incomplete. Systematic drilling commenced several months ago, yielding better than expected results including high-grade intercepts on the southern-most section (9m true width @ 19.7% combined Pb plus Zn), leaving the ore body open to the south. The target will be tested on 20m sections for 100m further south once exploration development is complete. The northern extension of SEAL has



been defined (EAL) over 700m of strike, and significant drilling is scheduled in the near future.

## **SOUTHERN EXTENSION**

The Southern Extension encompasses the down plunge extension of the mine in the area south of section 130. It was drilled on 200m centres during the 1990's and significant high-grade mineralisation was identified. Best results included 8.7m @ 20% Pb plus Zn on section 140 located 200m south of the current mine development, and 9.8m @ 27% Pb plus Zn on section 150, 100m further south. The ore is hosted by a crosscutting structure ('dropper' style in mine terminology), which is a continuation of the main controlling structure for C-Lode and B-Lode droppers. Development is now scheduled south of the current operations to allow cost-effective drilling of the Southern Extension.

## **MINING**

One of Perilya's goals is metal production at lower costs, by maximising grade and minimising dilution. This is being achieved with a change of focus in the mine geology and planning area. The emphasis is on building robust geological models, which form the basis for resources and reserves, mine planning, scheduling and future cash flow predictions. This is achieved by implementing the following:

- Reinterpreting planned stopes using all available geological data in integrated 3D models;
- Providing additional geological information in critical areas utilising two underground diamond drill rigs;
- Re-mapping of underground openings under strict survey control, enabling efficient stope design;
- Using grade control to verify the accuracy of geological models, to monitor the mining process, to provide daily grade predictions to the mill and to provide a basis for mine – mill reconciliation;
- Sampling and logging of production blast holes by competent production drillers. Apart from providing additional grade information, blast hole data has been used to modify stope designs, change blasting layouts and extend stopes where geological information has been sparse due to lack of available diamond drill sites; and
- Routine "broken ore" sampling of development headings and stope draw points by samplers on every shift to help control bogging of stopes, ensuring mining ceases when grades fall below an accepted cut-off.

A combination of these factors allows resource optimisation and results in many improvements. Further quality assurance changes are still required to improve mining systems and procedures to industry accepted 'best practice'.

## **FUTURE**

Systems are now in place for efficient mining and exploration in the Southern Operations. Drilling of over 40 targets has been prioritised and ranked based on potential net revenue, cost of exploration, size and grade, geometry and access. The aim of exploration drilling will be to deliver quality, well-defined ore bodies to mining based on systematic and complete drilling. Mining in the future will also look at high-grade narrow vein stopes.

Reopening of the North Mine with decline access from the No 1 open pit allows mining of 3 Lens. Initial surface and underground exploration in the area will be dedicated to extending the current reserve in both 3 Lens and 2 Lens (outside of the reserve), and to testing the zinc lode potential to the north and west of the planned development.

Regional work has included a complete and thorough compilation of extensive exploration and mining databases for the tenement package. This has identified several drill targets at Little Broken Hill and the Pinnacles and illustrated that drilling is required in numerous areas along the Potosi trend, in conjunction with more green fields type exploration throughout the exploration licences.

A fresh approach to Broken Hill is appropriate for its future, and will embrace the proper application of time honoured geological techniques, combined with new technologies such as regolith mapping and related geochemistry, HyMap imagery to aid in alteration and structural definition, and enhanced gravity and magnetics. A focus on structure and alteration will be the key to exploration targeting.

Perilya is confident that it can add to the current mine life at Broken Hill, through effective and well targeted exploration in the areas adjacent to one of the world's biggest base metal mines.

# **GARNET Sm-Nd AGE CONSTRAINTS ON THE TIMING OF TECTONISM IN THE SOUTHWESTERN CURNAMONA PROVINCE: IMPLICATIONS FOR EXISTING MODELS AND CORRELATIONS**

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## **INTRODUCTION**

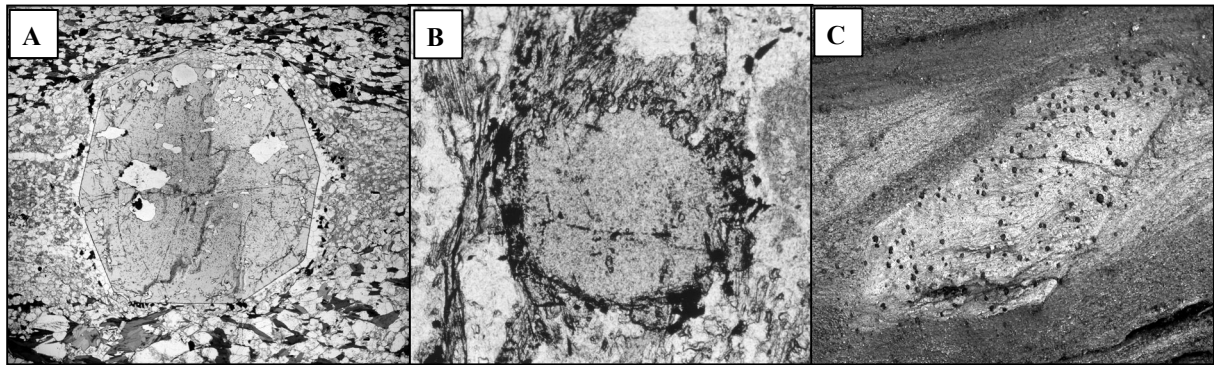
Despite the enormous effort expended in documenting the stratigraphic, structural and metallogenic evolution of the Curnamona Province (for a review see Raetz et al., 2002), there are still considerable ambiguities regarding the timing of regional deformation and metamorphism. A number of studies have highlighted the uncertainties surrounding the timing and duration of the Olarian Orogeny, and the structural evolution that accompanied it (e.g. Page et al., 2000). The bulk of the geochronological studies have focused on the Broken Hill Domain, and have largely used zircon U-Pb ages of magmatic rocks that were interpreted to bracket deformation. Several workers (e.g. Nutman & Ehlers, 1998; Gibson, 2000) have suggested that high-T tectonism occurred as early as 1690-1650 Ma, and was manifest by the development of anatectic mineral assemblages. This conclusion is supported to some extent by monazite U/Pb ages which also indicate pre-~1615 Ma metamorphism (Venn, 1997), and provide evidence for pre-1630 Ma deformation (Teale & Fanning, 2000). On the basis of fabric development in 1550 Ma granites (Nutman & Gibson, 1998), the total duration over which high-T metamorphism and deformation may have occurred is > 100 Ma. The inferred c. 1690-1670 Ma high-T tectonism has been interpreted to be extensional in nature, with low-angle detachments cutting out sections of stratigraphy (Gibson, 2000). In contrast, in a recent U/Pb geochronological study, Page et al (2000) found no evidence of pre-1600 Ma metamorphism, and concluded that metamorphism and deformation occurred in the interval 1600-1590 Ma. This suggestion is supported by Stevens (2000), who unequivocally states that there was no pre-1600 Ma metamorphism.

## **AGE CONSTRAINTS**

In this contribution we present the results of our initial attempts to date structural fabrics in the Weekaroo region in southwestern Curnamona Province, using Sm-Nd isotopic compositions of garnet. In principal this approach has several major advantages over the use of U-Pb isotopic analyses of accessory minerals to date tectonism in the Curnamona Province. (1) Garnet is a common metamorphic mineral that grows from mid-greenschist to granulite grade conditions, meaning that age constraints can be obtained from essentially right across the terrain. (2) The phase equilibria of garnet-bearing assemblages are well understood. As a consequence, garnet ages can be directly related to the P-T evolution of the terrain. (3) Porphyroblast matrix relationships mean that garnet growth can almost always be related to foliation development. (4) Closure temperatures in garnet Sm-Nd systems are ~ 700-750°C. This means that recorded ages will be growth ages across most of the Curnamona Province.

In the southwestern Curnamona Province, garnet-bearing metapelitic assemblages are generally restricted to units within the Wiperaminga Subgroup of the Curnamona Group, in the lower parts of the stratigraphic sequence, and the Saltbush Subgroup of the Strathearn Group towards the top of the section. There are three distinct microstructural settings for garnet growth within the metapelites. (1) In the majority rocks, garnet is an early grown

mineral, either contained within andalusite porphyroblasts or enveloped by matrix foliations that are bedding parallel, irrespective of the grade of the matrix assemblage. Commonly this early grown garnet does not contain strongly oriented inclusions (Fig. 1a), suggesting that growth occurred in comparatively weakly foliated rocks. (2) The second style of garnet is the near ubiquitous formation of overgrowths on garnet (1). The overgrowths are present throughout the stratigraphy. In places these overgrowths form trails that grow along upright east-west-trending foliations (Fig. 1b). Compositional mapping of composite Type 1 and Type 2 garnets indicates that Type 2 growth occurred after partial resorption of Type 1 garnet. This implies that garnet growth did not occur continuously, and suggests that the composite garnets record the polymetamorphic evolution of the terrain. Conceivably this polymetamorphic character could reflect overprinting of the inferred 1690-1670 Ma tectonothermal event by the undoubted metamorphism at around 1600 Ma. (3) The third type of garnet occurs as a replacement of andalusite (Fig. 1c), and is commonly associated with staurolite. Locally the post-andalusite assemblages also include kyanite and staurolite, and on the basis that there appears to be a single generation of retrograde staurolite in the terrain, we correlate the post-andalusite garnet growth with the formation of kyanite.



**Figure 1:** Garnet-bearing mineral textures from Wiperaminga sub-group metapelites. (a) Type 1 garnet enclosed by bedding parallel foliation; field of view = 2.2 cm. (b) Type 2 garnet overgrowths in the hinge of an upright E-W trending fold. The overgrowths trail along the axial fabric which, trends approximately north-south in the image. (c) Type 3 garnet in reactive replacement of andalusite; field of view = 5 cm.

Two garnet-bearing assemblages separated by ~300 m from the Wiperaminga Subgroup were chosen in an attempt to place age constraints on the timing of the bedding parallel foliation in the western Walparuta Inlier in the Olary Domain. One sample was chosen from a hinge of the ENE-trending upright to northerly-reclined fold system traditionally interpreted to be regional F3. The sample contains bedding and a bedding parallel foliation, both folded by F3. Traditionally the bedding parallel fabric would be regarded as regional S1. The sampled garnets are euhedral and range between 5 and 12mm in diameter. They contain unoriented inclusions, implying growth prior to local deformation, and are overprinted by the bedding parallel fabric. Although compositional mapping indicates that they have little or no development of the Type 2 garnet overgrowths, the rims were shaved off to remove any overgrowth material. The samples were leached in order to minimise contamination by REE-bearing phosphates. Sm-Nd isotopic data gives the following ages SAMPLE 1:  $1583 \pm 6$  Ma (garnet - whole rock),  $1609 \pm 8$  (garnet leachate - whole rock). SAMPLE 2:  $1583 \pm 5$  Ma (garnet - garnet leachate - whole rock). In the sampled area, maximum metamorphic temperatures were  $< 620^{\circ}\text{C}$ , and the identical ages obtained in both samples suggests that they reflect growth ages. The significance of the slightly older age obtained from the whole rock – garnet leachate is unclear at this stage.

Analysis of the Type 2 garnet overgrowths is hampered by their fine grain size, which makes it difficult to shave off the garnet rim without incorporating core material, and the ubiquitous presence of ilmenite inclusions formed via the breakdown of biotite to form the garnet rims. However one garnet from the Cathedral Rock region with a rim large enough to shave off, and a distinct colour difference between core and rim allowed us to obtain a pure rim, which gave an age of  $513 \pm 12$  Ma (whole rock - garnet - garnet leachate). Preliminary analysis of Type 3 garnets obtained from a weakly foliated reaction texture replacing andalusite gives  $495 \pm 30$  Ma (whole rock - garnet - garnet leachate).

## DISCUSSION

At this stage we have found no evidence of garnet growth in the Wiperaminga Subgroup prior to  $\sim 1585$  Ma, and our data is consistent with the interpretations of Page et al., (2000). Conceivably there are older generations of metamorphic garnet, however the consistency of the microstructural relationships across the terrain suggests that the Type 1 garnet samples that we have dated are representative of the regional picture. In general, the growth of garnet in metapelitic rocks reflects increases in both pressure and temperature. In this context, models for an early high-T extensional evolution of the Curnamona Province (Gibson, 2000) may not favour garnet growth. However the presence of garnet contained in unretrogressed andalusite porphyroblasts in the Wiperaminga Subgroup indicates that it formed early, prior to or associated with the onset of the high geothermal gradient regime required to stabilise andalusite-bearing assemblages (at least in the western Walparuta Inlier). Therefore we interpret the major tectonothermal event in the western Olary Domain to have occurred at around 1585 Ma, and to have been associated with compressional deformation leading to the formation of the regional  $S_1 \rightarrow S_3$  fabrics. This is consistent with the inferred timing of the regional granites in the Olary Domain (Ludwig & Cooper, 1984), which largely to exclusively derive from melting of the Willyama Supergroup (Barovich & Foden, 2002). It is obvious that these granites represent the major thermal expression in the terrain, and we interpret them to reflect compressional melting of the sedimentary packages. The timing of metamorphism and associated multiple foliation development in the western Olary Domain is slightly younger than the 1600-1590 Ma ages inferred from the Broken Hill region (Page et al., 2000), suggesting that there may be a degree of diachrony in the terrain.

The *ca.* 1585 Ma ages obtained for tectonism in the southwestern Curnamona Province link it to a much broader tectonic regime that is one of the most significant periods in the evolution of the Australian Proterozoic. Essentially the entire eastern half of the Australian Proterozoic underwent approximately north-south compressional deformation and was exposed to high geothermal gradients at this time. In the Gawler Craton, the Arunta and Mt Isa Blocks tectonism occurred in a continental interior setting, with expressions ranging from dominantly felsic magmatism (Gawler) to regional medium to high-grade metamorphism (Arunta and Mt Isa). The heat sources are in part linked to the extraordinary geochemical compositions of the sedimentary packages and associated granites. However in the Musgrave Block, tectonism at *ca.* 1585 Ma was associated with the generation of arc-like felsic rocks (Scrimgeour et al., 1999). We suggest that the continental-scale compressional deformation at *ca.* 1585 Ma was driven by northward collision between the Gawler Craton, and terrains that had built onto the southern margin of northern Australia over the interval 1700-1640 Ma. In this scenario, detrital zircon and geochemical data, which points to the Willyama, sequences being derived from central Australia (Page et al., 2000; Barovich et al., 2002), suggests that the Willyama Supergroup is part of the north Australian Craton (as opposed to belonging to the Gawler Craton). The comparatively juvenile felsic rocks in the Musgrave Block probably reflect the

development of offshore arcs that received little or no input from either the north Australian or Gawler Cratons.

The Cambrian ages obtained from the Type 2 garnet overgrowths and the Type 3 garnet-bearing reaction textures indicates that the polymetamorphic character of the western Curnamona Province does not reflect the superposition of multiple Proterozoic events. Instead it points to a pervasive metamorphic overprint associated with the Delamerian Orogeny. The formation of Type 3 garnet  $\pm$  staurolite-bearing assemblages at the expense of andalusite implies an increase in pressure. This interpretation is supported by the growth of staurolite-kyanite bearing-assemblages at the expense of andalusite that appear to be texturally equivalent to our dated assemblages. Significantly the presence of late kyanite has been used to support an anticlockwise P-T evolution for the Olarian Orogeny. However the Cambrian ages for both Type 2 and Type 3 garnet growth implies that the up-pressure, anticlockwise P-T path reflects the causal superposition of two unrelated metamorphic assemblages separated in time by  $\sim 1100$  Ma. Therefore the “*apparent*” anticlockwise PT evolution holds no implications for the thermobarometric evolution of the Olarian Orogeny. The suggestion that the younger high-P assemblages are associated with the Delamerian Orogeny is consistent with the compositional patterns in garnets, which show that Type 1 garnet was partly resorbed prior to Type 2 growth. It is also consistent with bulk rock metamorphic assemblages that indicate the terrain underwent retrogression prior to prograde Type 2 and Type 3 garnet growth.

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# GEOLOGICAL MAPPING USING ASTER SATELLITE IMAGERY WITHIN THE CURNAMONA PROVINCE

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## INTRODUCTION

The recent availability of 14 band data from the satellite-borne ASTER (Advanced Spaceborne Thermal Emission Reflectance Radiometer) sensor, by Japan's ERSDAC and NASA has created significant interest into new opportunities of geological and regolith mapping. Previous laboratory studies of mineral spectral properties and airborne multi-spectral surveys have indicated the potential to identify and discriminate mineralogy from their diagnostic visible, near infrared, shortwave infrared and thermal infrared spectral signatures (Clark *et al*, 1990). The ASTER sensor images within a 60 x 60 kilometre scene area from three 15 metre pixel resolution visible-near-infrared (VNIR) channels, six 30 metre pixel resolution shortwave infrared (SWIR) channels and five 90 metre pixel resolution thermal infrared (TIR) channels (Fujisada *et al.*, 1998). This provides significantly more spectral resolution and potential capability than Landsat which has only one band within both the 2.1 to 2.4  $\mu\text{m}$  SWIR and the 8 to 12  $\mu\text{m}$  TIR wavelength region. An extensive range of data products for ASTER scenes are now available via ERSDAC and NASA-USGS web sites, including calibrated radiance at the sensor, surface reflectance and emissivity data sets and digital elevation model data (<http://asterweb.jpl.nasa.gov/gettingdata/>; <http://www.ersdac.or.jp/eng/index.E.html>).

Several geological case studies have previously described the application of ASTER imagery for geological mapping in weathered Precambrian areas of Mt Fitton (Hewson *et al.*, 2001). In particular mineral groups including AlOH, MgOH, carbonates and silicates were able to be discriminated and mapped within the 1-2 ASTER scenes covering these areas. The availability of multiple ASTER scene acquisitions has opened the possibility of mosaicing geological interpreted image products into "seamless maps". The opportunities of generating such image derived products have been investigated by the Curnamona ASTER Project, funded by PIRSA and supported by CRC-PMD and CSIRO's Glass Earth. The results of this study are in part described within this paper.

## METHODOLOGY

Over thirty ASTER scenes were acquired within the Curnamona Study area (Figure 1) and mosaiced within ERMMapper software. Several issues were addressed during pre-processing, including band leakage ("Cross Talk") between SWIR bands, different acquisition conditions (variable atmospheric water vapour and solar angle) and cloud cover. Various band ratios were devised to highlight AlOH, MgOH/carbonate, quartz from ASTER's SWIR bands 4-9 (Level 1B, radiance at the sensor data) and TIR bands 10-14 (Level 2, surface emissivity) mosaiced imagery acquired across the entire Curnamona province. Generating interpreted geological products from band ratios however can be limited by the number of useful bands

that effectively “classify” the spectral signature of the mineral group or rock/regolith unit. ASTER’s six SWIR bands and five TIR bands were more fully utilised using spectral unmixing techniques with ENVI software and applied to the individual ASTER scenes encompassing the Broken Hill area and SA’s Winnininnie 100K mapsheet. The resulting image products of both the individual and mosaiced ASTER scenes were incorporated into Arcview 3.2 and compared with GIS data bases provided by PIRSA (Curnamona Province SA\_Geology GIS, 2002) and DMR (Broken Hill Geoscience Database, 2002).

## RESULTS

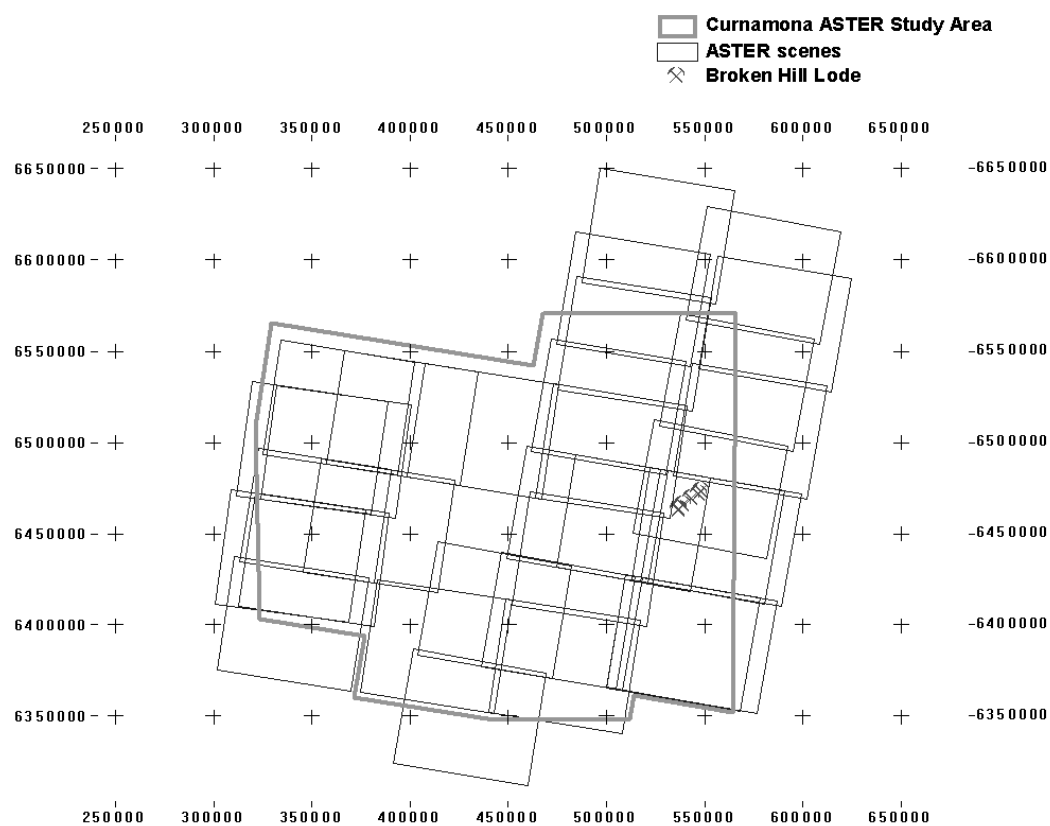
The band ratio,  $(b5+b7)/b6$ , was used to highlight the sericite/white mica content, based upon its main spectral absorption feature at  $2.2\ \mu\text{m}$  and shown for the entire study area (Figure 2) and close up for the Broken Hill area (Figure 3a). This image product highlights units including metasedimentary composite gneiss as well as some regolith material including colluvium (*i.e.* flanks of Mundi Mundi fault). In addition, the compositional nature of the AIOH mineralogy and its chemistry was interpreted using the RGB composite of ASTER ratios  $b5/b6$ ,  $b7/6$  and  $b7/5$ , based upon shifts in the wavelength position of the  $2.2\ \mu\text{m}$  absorption feature. This RGB ASTER image showed variations within psammite and pelitic metasedimentary units of the Broken Hill area and also the Winnininnie 100K mapsheet areas. The significance of the wavelength shift of the AIOH absorption feature, initially described by Duke (1994), has been demonstrated by Yang *et al.* (2001) and Cudahy *et al.* (2000) for studies of hydrothermal and VMS systems using hyperspectral sensing. The units showing a variation in the symmetry of the  $2.2\ \mu\text{m}$  spectral feature, identified by ASTER bands 5, 6 and 7 compare favourably with field spectrometer measuring within these SWIR wavelengths and also with previous hyperspectral surveys at Broken Hill. Early results of the recent 2002 HyMap survey also indicate similar occurrences of sericite/white mica (Figure 3b) and AIOH compositional variations. Work by Robson *et al.* (2003) also indicated the variation of white mica spectral signatures within Broken Hill psammites. Further study of ASTER imagery in comparison to detailed lithological mapping is suggested to investigate the significance (*i.e.* original lithological variation vs. hydrothermal alteration) of this compositional related variation in AIOH spectral signatures observed at Broken Hill.

ASTER image products were also generated using band ratio,  $(b6+b9)/b8$ , to highlight the  $2.3$  to  $2.4\ \mu\text{m}$  spectral absorption feature associated with MgOH (*i.e.* amphibolites) and carbonate rich units within the Curnamona Province. However the limited spectral resolution of ASTER within the SWIR wavelength region precluded the discrimination of between MgOH and carbonate mineralogies. Areas of quartz-rich regolith were also simply generated using the band ratio  $b13/b10$  of the mosaiced ASTER TIR surface emissivity imagery and clearly highlighted the flanks of the Broken Hill block defined by colluvium and alluvium.

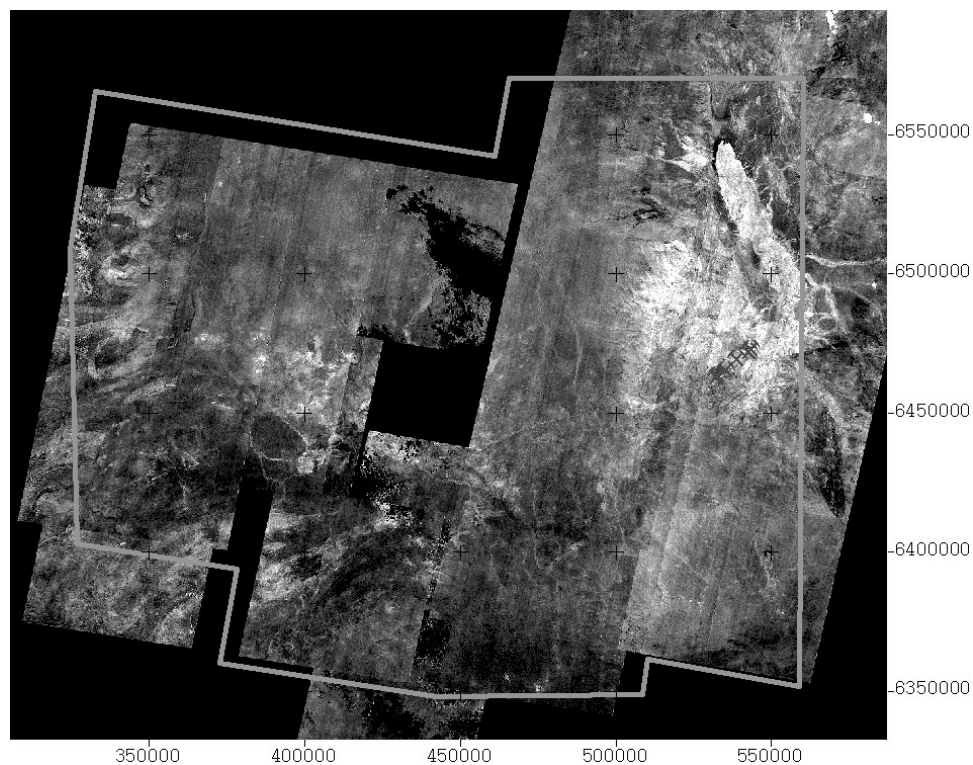
Spectral unmixing of the Broken Hill and Winnininnie ASTER SWIR and TIR imagery produced more distinctive and separate signatures (“endmembers”) related to either particular mineral group (*i.e.* AIOH, MgOH or quartz), or related to a particular outcrop/regolith unit with an overall distinctive spectral signature. Unmixing of the Winnininnie ASTER produced five different endmembers from the SWIR and six from the TIR imagery. While some of these endmembers appeared to be related to a variety of quartz and clay-rich regolith units, others appeared to be associated with either outcropping areas of Adelaidean dolomite and siltstones or to Willyama Inlier granites and metapelites. A variation of AIOH composition was also observed within the Billeroo Inlier granites and migmatites and also within units of the Willyama SuperGroup. A final interpretation of the significance of these endmembers for



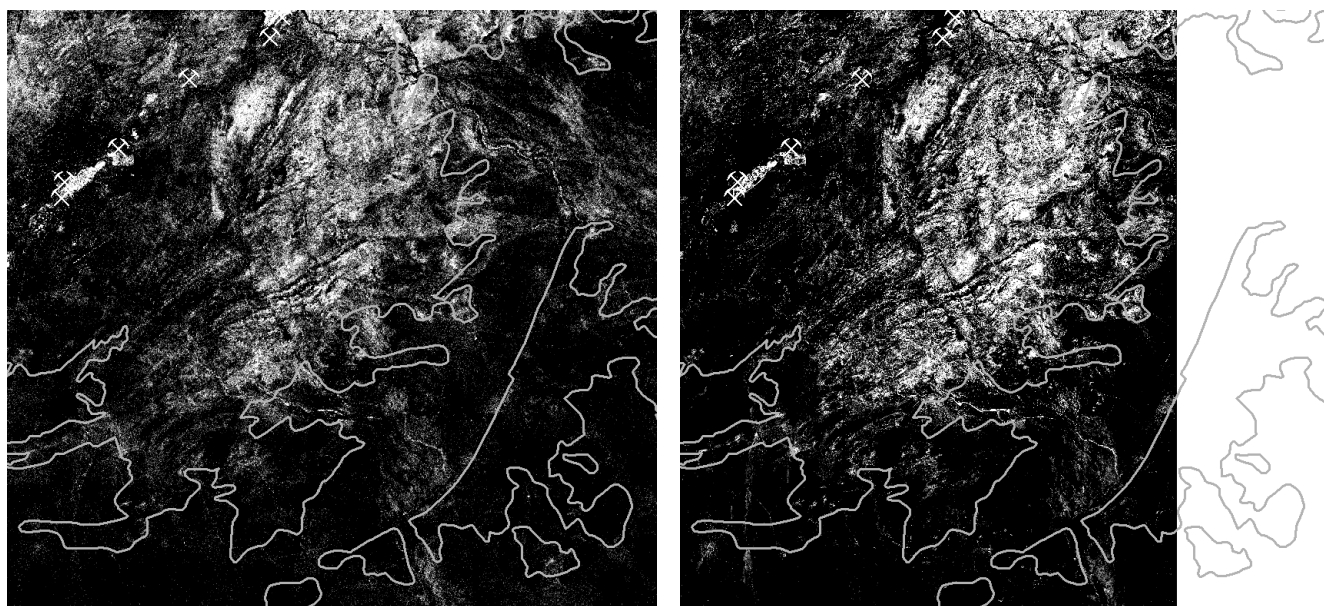
mapping regolith, outcrop geology or possible areas of alteration awaits further ground truthing and field investigations.



**Figure 1** Curnamona ASTER Study Area (Broken Hill Lode : X).



**Figure 2** ASTER derived sericite/white mica mosaic for the Curnamona Study Area (Broken Hill Lode : X)



**Figure 3** a) Left: Broken Hill ASTER interpreted sericite/white mica; b) Right: Broken Hill HyMap interpreted sericite/white mica. Broken Hill Main Lode (X) and Broken Hill Block shown.

## CONCLUSIONS

Results to date indicate that large scale ASTER mosaicing has delivered sericite/white mica, MgOH/carbonate and quartz regolith maps. In addition, AIOH compositional maps interpreted from ASTER, show white mica variations between regolith units and also within some metasedimentary units of the Curnamona Province. The discrimination of mineral species by ASTER is limited however by its spectral resolution compared to such airborne systems as HyMap. Greater differentiation between either regolith or outcropping units however appears likely by processing individual ASTER scenes. The processing of key individual scenes, such as those encompassing the Olary 100K mapsheet could be a useful geological product. Further research should also establish the significance of the AIOH compositional variations within outcropping metasedimentary units of the Curnamona.

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# **EXPLORATION WITHOUT HITTING ROCK BOTTOM: A BRIEF GUIDE TO RECENT DEVELOPMENTS IN EXPLORATION IN REGOLITH-DOMINATED TERRAINS OF THE CURNAMONA CRATON AND ADJOINING AREAS**

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## **INTRODUCTION**

The regolith-dominated terrains of the Curnamona Craton and adjacent areas are under-explored in the region's mineral exploration programs. This region includes a wide range of regolith and landscape settings, characterised by a diversity of regolith materials with different relationships with highly prospective bedrock. As a result mineral exploration in these different settings requires different approaches. The relatively recent (since the mid-1990's) research by CRC LEME has aimed to improve our knowledge of the regolith in the region thereby stimulating mineral exploration in these terrains.

Regolith research in the region has taken two main directions:

1. Regional studies utilising a regional landscape evolution context for characterising regolith materials and as a first pass regolith characterisation. This now mostly extends into little explored parts of the region and contributes to the knowledge base for the regional assessment and identification of broad exploration challenges; and,
2. Local (prospect / tenement) scale research dealing with developing specific regolith exploration techniques and characterising the expression of mineralisation in the regolith within case study areas.

Many of the specific highlights of this research are included in the series of oral and poster presentations at this meeting as well as in the field excursion guides. A brief overview is given here.

## **REGIONAL STUDIES**

Initially the regional studies involved broad-scale regolith-landform mapping (e.g. 1:500k scale) of western NSW and the Curnamona Craton in SA, with the objective of providing an overview of major regolith-landform types (Gibson & Wilford, 1996; Gibson, 1996). This form of mapping was a quickly compiled, first pass of the region and has the potential to broadly help exploration companies plan regional exploration strategies and provided a context for more detailed research by the CRC LEME regolith research team. A regional hydrogeochemistry program has also been undertaken across much of this region (see oral presentation by Dirk Kirste & Patrice de Caritat at this conference).

Regional regolith characterisation and mapping has also been undertaken on the scale of 1:100k. This work includes the geochemical analysis of a wide range of regionally significant exploration sampling media such as calcrete, ferricrete, silcrete, and major tree species. Geochemical samples and results are placed into the context of 1:100k regolith maps along with accompanying regolith-landform evolution models. So far this work has been mostly focussed on the area and margins of the Broken Hill Domain, with some work also at Wonaminta (in the Koonenberry Belt) and near the Tibooburra-Milparinka goldfields (see

Tibooburra Au-fields poster presentation by Hill *et al.* at this conference). Work is currently nearing completion on the Teilita 1:100k sheet area and includes regolith-landform mapping, and regional geochemical orientation programs for calcretes, silcretes, white cypress pines, river red gums and groundwater. An integrated GIS package of these results is also being compiled.

Some major discoveries associated with this level of research have included:

- an improved understanding of the use and regional significance of calcrete sampling for Au and polymetallic mineral exploration (see BHEI field excursion guide, plus poster presentation on the Tibooburra Au-fields by Hill *et al.* at this conference);
- a new model for the use of silcretes as a regional exploration sampling medium (see BHEI field excursion guide, plus the Teilita poster presentation by Hill at this conference);
- the potential to use river red gum leaves as a convenient improvement to more traditional stream sediment and shallow groundwater sampling programs (see BHEI field excursion guide, plus poster presentation by Hulme & Hill at this conference);
- the development of exploration models for the palaeo-landscape related dispersion and reconcentration of Au in the Tibooburra area. This suggests a buried primary Au source exists to the S of this area and has been reconcentrated over the course of regolith and landscape evolution (see poster presentation by Hill *et al.* at this conference);
- the use of regional hydrogeochemistry for mineral exploration in areas of basin cover (Caritat *et al.*, 2001, plus see oral presentation by Dirk Kirste at this conference);
- improved use of remote sensing, in particular hyperspectral data sets, for characterising regolith materials used in mineral exploration sampling programs (see oral presentation by Ian Lau at this conference);
- the use of regolith geochemistry in areas of significant transported cover (e.g. Thunderdome case study by Eric Tonui *et al.* in press; Teilita poster presentation by Hill at this conference; and Tibooburra Au-fields poster by Hill *et al.* at this conference); and,
- the development and production of regional regolith-landform maps and associated regolith and landscape evolution models (Hill & Kohn, 1999; Hill, 2000; Hill, 2001).

## **TENEMENT / PROSPECT SCALE STUDIES**

Most of this research has been focussed on areas of known mineralisation near Broken Hill. Detailed regolith-landform mapping of standard geological sheets at 1:25k, plus 1:10k mapping of selected mineralised sites have provided a framework for this work. Exploration sampling media that are significant for tenement scale exploration programs have been characterised and evaluated within these studies. Some of these sampling media include: soils (total and partial leaching analyses of different size fractions), calcretes, and shrubs and small trees (including saltbush, bluebush, and acacias). The 1:25k regolith mapping and associated studies have mostly been conducted on the southern Broken Hill Domain – Murray Basin margins and include the Triple Chance, Balaclava, Redan, Quondong, Kinalung, Pinnacles, Mt Gipps and Wahratta sheets. Associated prospect / mineralisation case studies have been undertaken at Great Goulburn (Cu-Au); Pinnacles (Au and Ag-Pb-Zn; Senior & Hill, 2002); Flying Doctor (Ag-Pb-Zn), Boundary Prospect (unknown mineralisation), Thunderdome (polymetallic, see Tonui *et al.* in press), Luxemburg and White Dam (see poster presentation by Aaron Brown *et al.* at this conference.).

Some major discoveries associated with this level of research have included:

- Refinement of the use of calcretes for mineral exploration programs on the prospect scale. This requires integration with regolith-landform maps, and a record of calcrete morphology and major element chemistry (see BHEI field excursion guide, plus poster presentation by Hill, plus Hill *et al.*, 1999; McQueen *et al.*, 2000);
- Refinement of traditional soil sampling techniques to provide results equivalent to many partial-leaching surveys. This requires a sound knowledge of the regolith-landform setting of soil samples to represent local dispersion pathways. It requires special care to sample comparable material rather than only sampling from a constant depth where a variety of regolith materials may be encountered across the landscape (see Flying Doctor poster presentation by Hill *et al.*, White Dam poster presentation by Aaron Brown *et al.*, plus BHEI field excursion guide);
- The use of vegetation sampling to penetrate shallow transported cover (< 5m depth), where other regolith surface chemistry results provide limited success (see Flying Dr poster presentation by Hill *et al.* at this conference; plus BHEI field excursion guide).
- The development and production of detailed (1:25k and 1:10k) regolith-landform maps, and their use to show the local availability of regolith sampling media and local dispersion pathways (see oral presentation by Kylie Foster, plus PIRSA regolith maps by Alistair Crooks, and the BHEI field excursion guide)
- The development of remote sensing techniques, in particular Hyperspectral data, to characterise regolith materials at the local scale (see poster presentation by Ian Lau *et al.* at this conference).

## EDUCATION, TRAINING & COMMUNICATION

This research program has benefited greatly from the integration of Honours and PhD student research. Research staff have also been responsible for running many undergraduate students field excursions and short courses designed for post-graduate students and professionals (see poster presentation on the regolith mapping courses by Hill & Roach at this conference), developed using many of the results from this research.

## ACKNOWLEDGMENTS

The development of this research program is largely due to the excellent support of NSW DMR and some support by PIRSA.

I would like to thank all team members that have been involved with projects within the Curnamona Craton in NSW and SA for the Cooperative Research Centre for Landscape Environments and Mineral Exploration, including: Richard Barrett, Karin Barovich, Jaclyn Brachmanis, Aaron Brown, Tessa Chamberlain, Alistair Crooks, Rod Dann, Patrice de Caritat, Simon Debenham, Karen Earl, Adrian Fabris, Kylie Foster, George Gouthas, Robert Grzgorek, Graham Heinson, Leanne Hill, Karen Hulme, Pat James, John Keeling, Amy Kenech, Dirk Kirste, Ian Lau, Alan Mauger, Kingsley Mills, Robbie Morris, Brad Pillans, Melissa Quigley, Nigel Radford, Ian Roach, Keith Scott, Andreas Schmidt Mumm, Anthony Senior, Tim Sharp, Martin Smith, Barney Stevens, Matilda Thomas, and Martin Williams.

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# TOWARDS A REGOLITH AND LANDSCAPE EVOLUTION FRAMEWORK FOR MINERAL EXPLORATION PROGRAMS NEAR THE TIBOOBURRA GOLDFIELDS, NW NSW

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## INTRODUCTION

Tibooburra is centred on a bedrock inlier surrounded by sediments of the Eromanga and Lake Eyre Basins. As such it has the potential to provide valuable insights into the regolith and long-term landscape evolution of this part of south-eastern central Australia, particularly relating to the relationships between the evolution of bedrock-dominated uplands and the flanking and overlying basin cover. The region hosts significant Au deposits, most of which are associated with Mesozoic and Cainozoic sediments deposited as a part of the region's landscape development. Although the extensive regolith cover has been traditionally seen as an impediment to mineral exploration, there are few regions where mineralisation and its exploration are so intimately linked with regolith and long-term landscape evolution.

## GEOLOGY

The Tibooburra Inlier is the N-most of several small basement inliers in the NW of NSW. Exposed bedrock of the area consists of early Palaeozoic metasediments and late Silurian to Devonian intrusives. Interestingly none of the bedrock of the Tibooburra Inlier has been found to host extensive Au mineralisation (this is maybe because it does not host Au or else reflects the need for more detailed geological study of the area). Mesozoic sediments of the Eromanga Basin flank and overlie parts of the Tibooburra Inlier, which are then overlain by Cainozoic sediments from the Lake Eyre Basin. Considerable conflict and uncertainty exists in the previous literature relating to the stratigraphic context and recognition of many of these sediments. Recent fossil finds and field mapping associated with this study suggests that there has been extremely liberal lithostratigraphic correlation across the region, with many of the areas of ancient sediments closer to the Tibooburra Inlier pre-dating the Palaeogene Eyre Formation (probable Jurassic-early Cretaceous equivalents) rather than being a part of it.

## REGOLITH-LANDFORMS

The regolith-landforms of the Tibooburra Inlier have been mapped at 1:25k, with more detailed mapping of the Dee Dee Creek catchment headwaters at 1:10k.

Variably **weathered bedrock** is most extensively exposed on the rises and hills throughout the inlier, and in sections where it underlies sedimentary cover. Slightly weathered granodiorite mostly forms erosional rises covered by rounded tors. The metasediments typically form rounded hills and rises with angular slabs of slightly weathered rock. The more arenaceous metasediment lithologies (e.g. quartzites) tend to form the most prominent landscape expressions as strike ridges and hillcrests.

Assorted **alluvial, colluvial, and aeolian sediments** are widespread across the region, particularly flanking the hills and rises of the Tibooburra Inlier. *Ancient sediments* (alluvial and possible marginal marine origins) are widespread around the margins of the inlier, and at

several sites over the central part of the inlier. *Alluvial sediments* are mostly associated with the contemporary drainage network, and as minor eroded exposures in elevated landscape positions. Contemporary alluvial deposition occurs within alluvial channels and flanking depositional plains, drainage depressions, outwash fans and swampy depressions. *Colluvial sediments* are widespread across the area, particularly flanking hills and rises, and extending across the adjacent lowlands. The most widespread colluvial deposits are associated with shallow overland flow and may form a thin cover on erosional hills and rises or extensive sheetflow fans. *Aeolian sediments* are very extensive across the area where they variably mantle most of the landscape and form extensive sand plains and linear dunefields in low lying settings, particularly flanking the inlier.

Regolith carbonate accumulations (**calcretes**) are limited in their distribution, mostly occurring as hardpan coatings along hydromorphic barriers such as the interface between slightly weathered bedrock and transported regolith. Disseminated powder regolith carbonate accumulations are associated with many of the ancient transported regolith materials, particularly in sediments with calcareous cements, and in the overlying aeolian sediments. **Ferruginisation** is associated with some weathered bedrock exposures. **Ferruginised sediments** are very common in the ancient transported regolith and typically form low rises or prominent breaks in slope on hills. Silicified regolith is most prominent on rises and low hills composed of ancient transported regolith, and is a common detrital component of surface lags on sheetflow fans and deposits flanking the inlier.

## **SOME MINERAL EXPLORATION IMPLICATIONS**

The main input of Au to the area has largely been from the deposition of ancient sediments such as those that now immediately flank the inlier. At the time of deposition these sediments were more extensive across the area of the inlier, with the valleys between bedrock rises acting as ideal ‘traps’ for Au deposition. Palaeocurrent indicators in these sediments are highly variable (consistent with their proposed marginal marine to alluvial origins) however in some of the more Au-rich locations there are broad indications of source areas to the S. The occasional occurrence of volcaniclastic bedrock clasts within these sediments may also help define the source of these sediments and associated transported Au. It is very likely that the primary Au source for these sediments is in an area presently covered by regolith and basin sediments. These ancient sediments have since been reworked throughout the landscape history into alluvial and colluvial deposits that in many cases have further concentrated the Au (e.g. The Granites diggings). Cainozoic tectonics are a major component of the regolith and landscape evolution. Tectonic activity along regional structures such as the Warratta Fault to the SW has had important implications for regional palaeogeographic reconstructions and the possible reconstruction of dispersion pathways from areas S of Tibooburra.

Ongoing research in the area is further refining the regional regolith and landscape evolution models closely related to defining the source area and redistribution of Au. The development of suitable exploration tools such as calcrete, silcrete, ferricrete, soil and biogeochemical sampling media are also being developed.



# **REGOLITH GEOSCIENCE EDUCATION & TRAINING WITHIN THE WESTERN NSW TEACHING LABORATORY**

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## **INTRODUCTION**

Regolith science has traditionally been overlooked as a major component of geoscience education in Australia and as such, many professionals and graduating students have a poor background in this discipline. This is unfortunate especially when it is considered that most of Australia is covered by regolith and nearly all of the under-explored parts of regions such as western NSW are in regolith-dominated terrains. Not surprisingly many geologists have struggled to work effectively in regolith-dominated terrains. One of the major objectives of CRC LEME is to help to rectify this problem as a part of its Education & Training Program. Western NSW (and recently the Curnamona Craton of SA) has been a major focus of the activities of this program.

CRC LEME, in conjunction with the Minerals Tertiary Education Council (MTEC), has been developing a program of regolith education and training courses in western NSW, featuring its diverse and widespread regolith cover and the implications of this knowledge for mineral exploration and environmental management practices. This has included:

- the development of shortcourses for professionals and tertiary students (Honours and post-graduate);
- teaching undergraduate university classes in field based activities; and,
- supporting Honours and PhD student research programs and their integration into the larger Western NSW research program of CRC LEME.

## **PROFESSIONAL AND POST-GRADUATE SHORTCOURSE PROGRAM**

CRC LEME through MTEC offers a range of shortcourses, also marketed as a part of the Victorian Institute of Earth and Planetary Sciences (VIEPS) Honours shortcourse program.

The Regolith Mapping and Field Techniques (RMF) Course is designed as a 5 day Honours-level, course that contains a combination of lectures, fieldwork and mapping exercises. In the 5 days the participants develop a regolith map from its fundamental beginnings to approaching the final production of a digital map. In 2002 the course was run at Silverton where accommodation and map production (including setting up a short-term computer laboratory) were at the War Memorial Youth Camp. From this a series of maps were produced along the western edge of the Thackaringa 1:25k geology sheet, near Cockburn. In 2003 the course was run at the University of NSW Arid Zone Research Station at Fowlers Gap, with mapping conducted on the station within the Sandstone Paddock. The Fowlers Gap venue offered accommodation and an immediately adjacent mapping area that featured a diversity of regolith-landforms, as well as being in an ideal central location for field visits to key regolith-landform sites in western NSW. The courses have been well received, with participant numbers of 21 in 2002 and 17 in 2003. Participants come from a wide range of Australian universities, Federal and State government research organisations and private industry.

A Masters-level course of 11 days duration is taught on a rotating basis between Broken Hill and Kalgoorlie and is designed specifically for industry extension and professionals undertaking Masters programs. The course aims to introduce participants to terminology and concepts and teaches introductory regolith mapping and mineral exploration techniques in regolith-dominated terrains. In August 2003, this course will be held at Fowlers Gap.

Field trips catering to professional geoscientists are also run to meet specific demands or as a part of larger meetings such as the Broken Hill Exploration Initiative (BHEI) conference.

### **UNDERGRADUATE TEACHING PROGRAM**

Undergraduate teaching programs originally from ANU and now from the University of Canberra and the University of Adelaide visit western NSW during regolith-related field excursions. As well as visiting many of the key regolith and landscape evolution field sites in the region, students also meet many government survey and mining and exploration geologists in the region. Several days of these field trips are also spent mapping and characterising the regolith of selected areas. This also includes a regolith and biogeochemical sampling program of the area mapped and the eventual integration of these data sets.

In 1999 the National Undergraduate Regolith Geology School (NURGS) was held in Broken Hill and included field visits throughout the Broken Hill region and the Koonenberry Belt. NURGS brought to Broken Hill a nominated 3<sup>rd</sup> year geoscience student from most of the universities within Australia, and introduced them to many of the fundamentals of regolith geology.

### **HONOURS AND POSTGRADUATE STUDENT RESEARCH PROGRAM**

Honours and post-graduate students have been integral to the CRC LEME research program in western NSW. Since 1998 there have been 15 Honours students, one MSc and 4 PhD students working in the region on a diverse range of regolith-related research topics. Copies of all western NSW regolith theses are deposited within the NSW DMR Broken Hill office library.

### **FUTURE OPPORTUNITIES?**

If you would like to participate in a regolith shortcourse, either as an individual or else as a part of a restricted company-specific course please contact the authors of this abstract.

### **Acknowledgments**

The authors gratefully acknowledge the important support of CRC LEME, in particular its core parties the NSW DMR, the MCA, ANU, the University of Adelaide, and previously the University of Canberra, without which these educational opportunities would not be possible.

The participation of Honours students: Kylie Foster, Darryl West, Greg Shirtliff, Michael Holzapfel, Grant Jones, Steven Willis, Simon Debenham, Anthony Senior, Jaclyn Brachmanis, Ben Maly, Rod Dann, Tessa Chamberlain, Robert Grzgorek, Robbie Morris and Jodi Webb; Masters student Melissa Quigley; and, PhD students Lea Hill, Karen Hulme, Martin Smith and Steve Hill, have been greatly rewarding.

# **REGOLITH EXPRESSIONS OF MINERALISATION WITHIN THE FLYING DOCTOR PROSPECT, NORTHERN LEASES, BROKEN HILL, NEW SOUTH WALES**

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The Flying Doctor prospect occurs approximately 8 km E of Broken Hill, within an area referred to as ‘the Northern Leases’, which includes the NE continuation of the Broken Hill lode rocks and extends from the Broken Hill North Mine to the Stephens Creek Reservoir.

## **PHYSICAL FEATURES AND ENVIRONMENT**

The prospect is in the central-E part of the Barrier Ranges, and includes a tributary of Willa Willa Creek, which is a part of the Stephens Creek catchment within the Murray-Darling drainage basin. The drainage pattern of the prospect shows a well-developed trellis pattern reflecting a strong bedrock lithological and structural control. The vegetation of the area consists mostly of open woodlands dominated by *Acacia aneura* (mulga) on hills and rises, and *Acacia victoriae* (prickly wattle) in valleys. Shrubs occur most frequently within a chenopod shrubland dominated by *Mairiana pyramidata* (black bluebush) along valleys and *Sida petrofila* (rock sida) on rises and hills.

## **GEOLOGICAL SETTING**

The bedrock of the area is shown within the Mt Gipps 1:25,000 Geological Sheet (Bradley, 1984). Structurally the Globe Vauxhall Schist Zone extends across the central part of the area from W-E. Stratigraphically the rock units are part of the Early Proterozoic Willyama Supergroup, with most of the psammites and pelites interpreted as being part of the Sundown Group, and most of the other rocks as undifferentiated Purnamoota Subgroup within the Broken Hill Group (Bradley, 1984). Broken Hill type (Ag-Pb-Zn) mineralisation occurs along a NE-trending linear zone within two main lodes: the Main Lode Horizon; and, the Upper Lode Horizon (Burton, 1994). Examples of mineralisation in this area are the Barrier Main Lode, and the Flying Doctor mineralisation, which are both part of the Upper Lode Horizon.

## **REGOLITH**

Slightly weathered bedrock is exposed within low hills and rises, and is buried by up to 3 m of transported regolith within valleys. Alluvial sediments consist of red-brown to brown-grey, quartzose and lithic silts, sands and gravels within depositional plains, alluvial channels, and drainage depressions. Colluvial sediments are widespread as lithic and quartzose sheetflow silts, sands and gravels within depositional plains and on erosional rises. Aeolian silts and fine sands are part of most regolith materials and may form sand sheets and hummocky dunes, particularly on the E slopes of rises and low hills. Mostly hardpan calcretes occur along the bedrock-regolith interface, and are best exposed in creeks. Detailed maps and accounts of the regolith here can be found in Thomas *et al.* (2002) and Lewis *et al.* (2002).

## REGOLITH EXPRESSION OF MINERALISATION

A combination of ICP-MS, ICP-OES, XRF and INAA were performed on regolith and biogeochemical samples, however only results for Cd, Cu, Pb, Zn are directly discussed here.

With the exception of *Sida petrophila* twigs, the assay results for all of the sampling media express the underlying mineralisation in varying degrees and for at least some elements. Two important aspects to consider when interpreting the results are: i) the regolith-landform setting and its relationship to local dispersion pathways (particularly for soil samples); and, ii) that strict comparison of equivalent sampling media is achieved. Dispersion distances mostly depend on the regolith-landform setting of samples (greater in alluvial and less in bedrock-dominated units).

Saprock samples show a large increase in Cd, Cu, Pb and Zn at the mineralisation lode. This sampling media however was not conveniently sampled across the whole area, particularly in alluvial settings where it was buried. Surface soil samples were available across the entire area and conveniently sampled. The two size fractions (<80µm and 80-300µm) show at least some aeolian and other transported components, largely accounting either for their relatively weak chemical expression of mineralisation or else the increase in metal contents (eg. Cd in both size fractions, and Cu, Pb and Zn in the 80-30 µm fraction) in the alluvial depositional plain downslope from mineralisation. This demonstrates the importance of a regolith-landform context for interpreting soil chemistry results, and to distinguish between transported metal contents and those adjacent to mineralisation. A notable exception is that Pb contents in both soil fractions are greatest adjacent to mineralisation, suggesting that it is less mobile in soil fractions.

The biogeochemical results show variable expressions of mineralisation. *Sida petrophila* twigs did not express the presence of underlying mineralisation because it was not available for sampling at those sites. *Acacia victoriae* phyllodes were widespread across the area (particularly in valleys) and the assay results for Cd, Cu, Pb and Zn were perhaps the most outstanding at expressing underlying mineralisation. *Maireana pyramidata* leaves were widely available across the area and showed notable increases in Pb content over mineralisation. *Acacia aneura* phyllodes had greater Cu and Pb contents over the mineralisation zone, however Zn contents were relatively high both over mineralisation and within the alluvial depositional plain downslope of mineralisation. These results suggest that if carefully and consistently sampled (including precise species discrimination and systemised sampling techniques) biogeochemical methods may be better than some soil fractions for expressing mineralisation, particularly in areas of shallow transported regolith. The reason for this could largely be that the plant roots penetrate the shallow transported regolith cover and are at least in part chemically connected to the underlying bedrock.

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# **RIVER RED GUM BIOGEOCHEMISTRY: TOWARDS AN INNOVATIVE NEW TOOL FOR MINERAL EXPLORATION PROGRAMS IN THE CURNAMONA CRATON AND ADJACENT REGIONS**

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## **INTRODUCTION**

Biogeochemistry is a field of research that has the ability to offer a means of delineating local and regional geochemical dispersion patterns associated with mineralisation in regolith-dominated terrains. Until recently its application has not been extensively applied in Australia. Preliminary results from recent research performed by CRC LEME on the use of vegetation as a mineral and environmental chemical sampling media within western NSW however are encouraging for the development of its use within mineral exploration programs. Several years ago an Honours research project conducted a preliminary biogeochemistry survey of river red gums along Stephens Creek (Dann, 2001). Although the results from this reflected mineralisation at Broken Hill and several smaller prospects, this approach needs greater refinement and to be tested for a wider application.

One of the most widely distributed tree species through out the Curnamona Craton and adjacent regions is the river red gum (*Eucalyptus camaldulensis*). They are mostly restricted to the riparian zones of large alluvial channels systems. The widespread prevalence of river red gums in regolith-dominated terrains (in particular the basin margins flanking much highly prospective bedrock-dominated uplands, but also throughout agricultural areas experiencing dryland salinity problems) makes them a strong candidate for development as a biogeochemical sampling media.

River red gums rapidly develop an extensive and deep taproot system. Dexter (1967) established that the dense surface root system of a mature river red gums extends at least 20 m in the horizontal direction and Davies (1953) demonstrated that in the vertical dimension the root system is greater than 10 m. Field observations from western NSW suggest that even these figures are conservative. This however means that river red gums can have a biogeochemical sampling area of  $>4000 \text{ m}^3$ . They have the potential for element uptake via their roots, from the adjacent stream sediments, the shallow ground water aquifers within the alluvial sediments, buried bedrock and saprolite.

This research proposes to:

- Characterise the biogeochemistry of major river red gum organs;
- Assess the spatial and temporal variation of river red gums on a local and regional scale;
- Produce environmental biogeochemical maps using river red gums; and
- Evaluate the application of river red gum biogeochemistry as an environmental and mineral exploration sampling media.

This project commenced in early 2003 and plans to conclude in 2006.

## PROJECT DESIGN

The initial stages of the study will characterise the geochemical signatures of river red gum organs (leaves, roots, twigs, fruit/buds and bark) and compare this with sieved fractions of stream sediments from equivalent sites. Sampling will be conducted for individual trees in 6 key orientation study sites across the Curnamona Craton and adjacent regions. These study sites include: Teilta (Lake Eyre Basin margins / buried Willyama bedrock), Tibooburra Inlier (regolith-hosted Au mineralisation), Flying Doctor prospect (adjacent to Ag-Pb-Zn mineralisation lodes), Williams Creek (Au and diamond mineralisation within the Koonenberry Belt), and Tikalina (eastern Olary) and Yunta (western Olary). Preparation of the recovered samples will involve drying, grinding (vegetation), with sieving, milling (stream sediments). The analytical techniques to be used for the vegetation are INAA, ICP-OES and ICP-MS, while the stream sediments will under go ICP-MS, ICP-OES and AA9 analyses.

These preliminary result will identify and establish a suitable biogeochemical sampling medium and analytical suite, as well as comparing biogeochemical results with stream sediments (a more traditional regolith sampling media which is extensively used by mineral exploration companies in the region).

River red gums will be then sampled along stretches of channels at the 6 key orientation sites, resulting in the collation of local-scale data sets and the initial development of local biogeochemical maps. This will assist in determining the spatial variability and therefore constraining the ideal sampling spacing and local relationships between river red gum biogeochemistry and other landscape-environmental factors such as regolith-architecture, existing regolith chemistry, and existing hydrogeochemistry data sets. On a regional scale sampling of river red gums along major streams throughout the Curnamona Craton and adjacent regions will also result in the collation of a regional data set and development of regional biogeochemical maps.

## ACKNOWLEDGEMENTS

The authors would like to acknowledge the support of CRC LEME and the NSW DMR.

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# GROUNDWATER STUDIES AS AN AID TO MINERAL EXPLORATION IN AREAS OF SEDIMENTARY COVER, BROKEN HILL REGION

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## INTRODUCTION

Mineral exploration in the Broken Hill region has been ongoing for over 120 years. Although extensive, the efforts have focussed primarily on the regions of outcropping Paleo- to Neoproterozoic basement rocks, ie in the Barrier, Olary and, to a lesser extent, Flinders Ranges. Unfortunately, the vast majority of these highly prospective Proterozoic rocks of the Curnamona Province is concealed by up to 200 m of Cainozoic sediments and regolith of the Callabonna Sub-basin. Other margins of the Broken Hill Domain are obscured by sediments from the Murray Basin and Bancannia Trough. The traditional mineral exploration methods used in areas of outcrop are often inadequate when applied to areas of transported cover especially where it is greater than a few meters thick, and developing methods to “see through” the cover is crucial to continued exploration success. To avoid extensive drilling, techniques need to be introduced that allow us an insight into the chemistry of the underlying materials. One medium that is ubiquitous and can, when applied correctly, reveal its physical and chemical history is groundwater. Hydrogeochemistry can be an invaluable tool in identifying buried mineralisation by enabling us to recognise chemical fingerprints of economic minerals in the sediment-covered regions of the Curnamona Province.

Hydrogeochemistry or groundwater geochemistry has been utilised as a successful exploration tool in a number of studies (Taufen, 1997) and is likely to become increasingly popular as technological developments and cost efficiency continue to drive exploration. One distinct advantage of the use of hydrogeochemistry is that considerable research has been undertaken in the study of acid mine drainage, or ‘what happens to water when it encounters mineralisation’. Essentially, the hydrogeochemical problems introduced by the exposure and weathering of mineralisation are precisely those utilised in the search for deposits. We are looking for the unmistakable imprint that ore deposit minerals leave on water chemistry in our regional groundwater study.

## METHODS

We have collected and analysed over 200 groundwater samples from the region surrounding Broken Hill, including the Callabonna Sub-basin, the Bancannia Trough and the Murray Basin, in order to develop and test methodologies for using groundwater as a mineral exploration tool in regolith-dominated terrains. Groundwater interacts with the minerals that occur along its flowpath, and thus it has the potential to be a sampling medium representative of the subsurface from the point of recharge to the sampling site. However we cannot simply look for high base metal concentrations in the water. The concentrations of target elements such as Ag, Zn, Cu, and Pb tend to be very low in natural waters and geochemical maps based on these can be noisy and unreliable. Therefore, one has to look for other clues in the geochemistry of the groundwater in order to detect the presence of concealed mineralisation.

A robust methodology needs to be developed starting from sensible field sampling procedures, followed by a comprehensive analytical protocol and a reliable QA/QC program. Once a methodology (recipe) is proposed and tested, means need to be found to make its uptake by industry as cost-effective as possible. Thus, we have concentrated our efforts on sampling *fresh* groundwater from the aquifers, analysing for an *extensive* suite of major and trace species (using IC, ICP-AES, ICP-MS, ISE) and isotopes (MS, MC-ICP-MS) in order to find the most promising ways to vector towards mineralisation using groundwater.

Many physical, chemical and biological processes influence groundwater composition in the near-surface environment. One has to be able to ‘remove’ quantitatively the effects of the most dominant of these processes in order to assess the often subtle influence of, for instance, a body of sulfide mineralisation encountered some distance from the sampling point. Thus, we need to understand the processes that control dispersion of elements from ore bodies. The aim of this presentation is to propose a methodology to identify the signature of a buried ore deposit using groundwater. We have focussed our efforts on understanding the origins and controls on the  $\text{SO}_4^{2-}$ , Zn, Cu, Pb, and Sr contents of groundwaters. We will discuss what some of those controls are and how we can recognise the potential for determining their origins and, through an understanding of the hydrogeology, vector towards mineralisation.

## DISCUSSION AND CONCLUSIONS

The processes that most significantly change the composition of water as it falls on the landscape as rain and infiltrates the upper layers of the regolith on its way to the aquifer(s) in the Broken Hill region are *evaporation* and *transpiration*. These processes are particularly active in the uplands areas of the Barrier, Olary and Flinders Ranges (*ranges*). They result in the concentration of species contained in the rainwater, commonly by a factor of 100 to more than 5000. Some of the Callabonna Sub-basin waters (*basins*) show evidence for *mixing* with Na-Cl-SO<sub>4</sub> water, in addition to the evapo-transpiration effects. Other processes that we recognise in the Broken Hill groundwaters include mineral *precipitation* and *dissolution* (including primary rock-forming and sulfide minerals, radiogenic minerals and gangue mineral fluorite), *redox reactions*, *cation exchange* and *adsorption* onto Fe-oxyhydroxides and clay minerals (Caritat *et al.*, 2002). These processes affect the groundwater composition in ways that can be recognised and assessed quantitatively. Knowledge of the physical and chemical controls on the water chemistry enables us to determine the more subtle effects on water composition that interaction with mineralisation can cause (Caritat *et al.*, 2001).

We also need to develop a model for the hydrogeology. There appears to be a poor connectivity between the upland areas and the deep basin waters, suggesting the existence of a complex hydrologic system. This system is characterised by distinct aquifers in the elevated areas (unconfined, perched alluvial aquifers in valleys overlying fractured bedrock aquifers) and under the low-relief plains (confined porous sedimentary aquifers). The upland aquifers are more dynamic and responsive to climate inputs (floods/droughts); the basin aquifers are relatively isolated from the upland aquifers and from the surface, and are more sluggish.

The primary types of mineralisation we are looking for are sulfide deposits. Probably the most direct approach is to develop an understanding of the behaviour of S species in the groundwater and use this to recognise where S has been added to the system, potentially through sulfide oxidation (Krouse, 1980; Taylor and Wheeler, 1994). All of the sampled waters have SO<sub>4</sub><sup>2-</sup>/Cl<sup>-</sup> values greater than seawater demonstrating an addition of SO<sub>4</sub><sup>2-</sup> (sulfate) relative to seawater, but this just indicates that the source of the groundwater may have had high SO<sub>4</sub><sup>2-</sup>/Cl<sup>-</sup> ratios. The *ranges* waters have higher SO<sub>4</sub><sup>2-</sup>/Cl<sup>-</sup> ratios than the *basins*, similar to and greater than rainwater in the region (0.36-0.5, molar ratio), while a number of the *basins* waters show slightly elevated SO<sub>4</sub><sup>2-</sup>/Cl<sup>-</sup> ratios. This higher than expected SO<sub>4</sub><sup>2-</sup>/Cl<sup>-</sup> ratio may be the result of sulfide oxidation.

Another method we can add is to study the S isotopic composition of dissolved SO<sub>4</sub><sup>2-</sup> in the groundwater. The S isotopic composition of groundwater SO<sub>4</sub><sup>2-</sup> is influenced by the composition of rainfall, water mixing, and the potential contribution from oxidation of sulfide minerals along the flowpath. The δ<sup>34</sup>S of Broken Hill Type Pb-Zn mineralisation clusters around 0 ‰ (V-CDT) in the Broken Hill Domain and later vein mineralisation in the Olary Domain around +4 to +7 ‰ (Bierlein *et al.*, 1996a). Gypsum samples from the region have δ<sup>34</sup>S values ranging from +14 to +17 ‰, with an average value of +15.2 ‰ (Chivas *et al.*, 1991; Shirliff, 1998). Fractionation between gypsum and dissolved SO<sub>4</sub><sup>2-</sup> is approximately 1.7 ‰, implying that the groundwater from which gypsum precipitated had a δ<sup>34</sup>S of around +13.5 ‰. This value coincides with that of the *basin* groundwater SO<sub>4</sub><sup>2-</sup> isotopic composition and is also assumed to represent average atmospheric precipitation composition. Figure 1 shows a plot of δ<sup>34</sup>S vs 'excess S' (SXS), defined as the concentration of S due neither to evaporation nor to mixing with connate water. Several groundwater samples, particularly from the *ranges*, have both anomalous S concentrations (SXS > 0 mmol/L) and low δ<sup>34</sup>S compositions. Our hypothesis is that oxidation of sulfides and addition of isotopically light SO<sub>4</sub><sup>2-</sup> into the groundwater accounts for the shift to lower δ<sup>34</sup>S values and the increased SO<sub>4</sub><sup>2-</sup>/Cl<sup>-</sup> ratios in the recharge waters and in some basin waters.

Further, we can use the oxygen isotopic composition of the dissolved SO<sub>4</sub><sup>2-</sup> to recognise whether oxidation of sulfides has occurred above or below the water table. The *basin* waters that have slightly lower δ<sup>34</sup>S (<13 ‰) also have lower δ<sup>18</sup>O<sub>SO4</sub> values (Fig. 2), suggesting that these may have a component of isotopically light SO<sub>4</sub><sup>2-</sup> from sulfide oxidation. The δ<sup>18</sup>O<sub>SO4</sub> values of most recharge waters are generally consistent with sulfide oxidation as well (Fig. 2). The low δ<sup>18</sup>O<sub>SO4</sub> (triangle area > 70% H<sub>2</sub>O) values reflect the addition of oxidised S wherein the O is primarily sourced from the H<sub>2</sub>O molecule (in the study area δ<sup>18</sup>O<sub>H2O</sub> values range from -2 and -7 ‰ V-SMOW) and thus oxidation occurs below the water table. The samples with low δ<sup>34</sup>S but high δ<sup>18</sup>O<sub>SO4</sub> (>+8 ‰) values may be the result of sulfide oxidation above the water table with a significant amount of atmospheric O<sub>2</sub> present. This has important implications for the reaction path modelling of this system especially when trying to address the fate of trace metals in the groundwater system.

The Sr isotope results show a wide range in <sup>87</sup>Sr/<sup>86</sup>Sr ratios (nearly 0.0300). The majority of the values are much higher than the <sup>87</sup>Sr/<sup>86</sup>Sr composition of seawater during or since the Proterozoic (0.702 – 0.709; Veizer 1989), indicating an input of radiogenic Sr through water-rock interaction. The Sr isotope data fall into three broad groupings: one group has <sup>87</sup>Sr/<sup>86</sup>Sr ratios around 0.712-0.718, another around 0.721-0.724 and the last one around 0.731-0.737. These correspond broadly to areas in the east, central, and southeast regions, which roughly correlate to the interpreted basement geology and sediments derived therefrom. The less radiogenic Adelaidean rocks of the Flinders Ranges (Foden *et al.*, 2001) and the more radiogenic Willyama Supergroup rocks of the



Olary and southern Barrier Ranges (Pidgeon, 1967) are clearly reflected in groundwater Sr isotopic composition. The Sr data indicate (1) that the groundwaters have interacted with the basement or with bedrock-sourced materials and (2) that fluid flow is sufficiently slow to retain the isotopic signature.

The Pb isotope results plot along the growth curve that extends from the Broken Hill ore signature to the average background Pb signature. Those samples with the lower  $^{206}\text{Pb}/^{204}\text{Pb}$  ratios may either represent a mixing between Broken Hill Type and background signatures, or represent various other local ore types recognised in the Broken Hill district (Thackaringa, Pyrite Hill, Ettlewood; Gulson *et al.*, 1985, Bierlein *et al.*, 1996b). The samples with a low  $\delta^{34}\text{S}$  can have a wide range of  $^{206}\text{Pb}/^{204}\text{Pb}$  values (~16-18.5). All of the recharge samples with  $\delta^{34}\text{S} < 10\text{‰}$  have  $\text{SXS} \geq 0\text{ mmol/L}$ , suggesting possible interaction with a range of different sulfide mineralisation styles as suggested by the Pb isotopic variability.

To predict the behaviour of the trace metals Cu, Pb, and Zn during transport along a flow path, we have generated a 1-D reactive transport model (Kirste and Caritat, 2002). The basic initial assumptions in the model are that

- the transporting fluid is a typical groundwater equilibrated with galena, chalcopyrite and sphalerite, with no secondary mineral precipitation allowing for a maximum metal content,
- the flow path has ion exchange sites and adsorption sites which are equilibrated with the unreacted groundwater, and
- flow and transport occur at 1 m/yr for 4,000 years.

The results show that elevated Cu and Zn concentrations extend to ~150 m down the flowpath, while Pb values are attenuated within ~50 m of the deposit. Perhaps the most important outcome of this exercise is to illustrate that trace metals do not travel far in groundwater systems and that Zn and Cu have a higher mobility than Pb. We cannot expect high metal contents at any great distance from the deposits but where we have higher amounts of specific metals it may indicate proximity to mineralisation, depending on the aquifer mineralogy and the hydrogeology.

Our results were tested on waters collected in the Barrier Ranges proximal to mineralisation and 21 of 23 samples display all or several of the indicators described above for interaction of the groundwater with mineralisation. Applying the criteria to the *basins* waters reveals a number of groundwaters displaying similar potential and, significantly, areas of known mineralisation (eg, Portia) show up as positive anomalies.

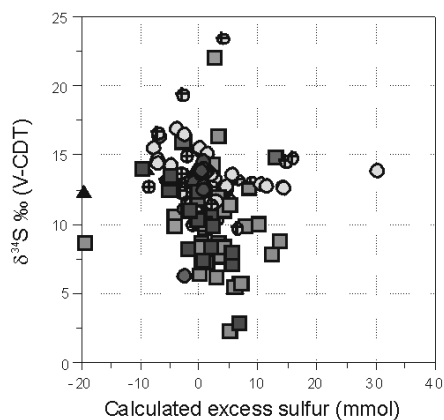
## CONCLUSIONS

Hydrochemistry is a method being utilised in the Broken Hill region to aid mineral exploration in areas of transported and *in situ* regolith cover. A number of techniques have been applied in areas of known mineralisation and positive results have confirmed the capability to recognise metal sulfide oxidation. The same techniques show positive anomalies in parts of the surrounding basins that have thicker sedimentary cover suggesting the presence of mineralisation proximal to the bores. In combination with other exploration methodologies and properly applied, hydrogeochemistry can be an invaluable exploration tool.

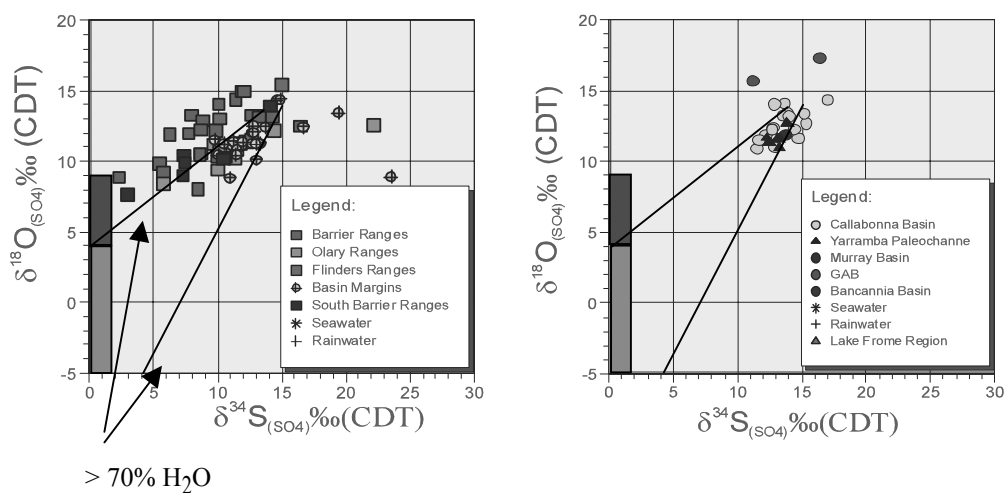
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**Figure 1. Scatter diagram of  $\delta^{34}\text{S}$  vs calculated 'excess S' (Legend below)**



**Figure 2. Oxygen vs sulfur isotopic composition of dissolved sulfate. Framed area represents  $> 70\% \text{ H}_2\text{O}$  oxygen contribution (below water table).**

# AN AIRBORNE GRAVITY GRADIOMETER SURVEY OF BROKEN HILL

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## INTRODUCTION

An airborne gravity gradiometer (AGG) survey has been flown over the Broken Hill region. The survey involved the NSW Department of Mineral Resources in collaboration with the CRC for Predictive Mineral Discovery (*pmd*\*CRC) as principal research project sponsor. Interpretation of these data is expected to assist explorers to locate discrete targets that have anomalous density. This is relevant to exploration for base metal, Fe-Cu-Au and Ni-Cu-Pt-Pl deposits in the region. The data will also provide a significant new data layer for geological mapping and mineral system research, and will provide further insight for exploration across the entire Curnamona Province.

## THE AGG SURVEY

The survey covers a 1,000 square km area and includes the Broken Hill ore deposit, Little Broken Hill, the Pinnacles, Copper Blow and Galena Hill (Figure 1). A total of 5600 line km of data were acquired with a FALCON™ AGG system in February 2003. The lines were spaced at 200 m intervals and oriented at 36 degrees east of north, parallel to the long axis of the survey. The nominal terrain clearance was 80 m except over Broken Hill where this was increased to 120 m. The principal survey outputs were grids of the vertical component of gravity (gD\*) and the vertical gradient of the vertical component of gravity (Gdd). These products contain the same fundamental information about density variations: they are both derived from the same measurements and it is possible to transform from one to the other. They differ in the relative emphasis placed on short and long wavelength components, with the Gdd data having greater emphasis on short wavelengths. As part of the survey, magnetic data and a high-resolution digital elevation model (DEM) were also acquired.

In interpreting AGG data, knowledge of the spatial distribution, 3D geometry and physical properties of geological units is clearly important. The amplitude and wavelength characteristics of the signal and noise fractions of the AGG data must also be kept in mind during interpretation. Spatial resolution was influenced not only by along line sampling and line spacing, but by low pass filtering that was used to reduce the impact of high amplitude noise spikes present in the raw data. The choice of wavelength threshold for this filtering was a tradeoff between improvement in the overall signal to noise level and the degree of aliasing or even elimination of important short wavelength features. The threshold was set between 300 and 600 m depending on the product. The residual broadband rms noise level estimated on other surveys is 5 to 10 Eotvos (Eo) (Dransfield et al., 2001; Christensen et al., 2001; Liu et al., 2001).

There are distinct differences in the long wavelength content of traditional ground gravity measurements and the AGG data. Explorers primarily use AGG data to detect short wavelength anomalies related to discrete sources in the top few hundred metres, but also have an interest in the regional scale implications of any longer wavelength features present in these data. The ground measurements have excellent long wavelength accuracy because of the nature of the instruments and field procedures that tie the data to stations where the absolute value of gravity is known. In contrast, the procedures used to acquire the AGG data give rise to relative measurements, and thus the DC level of the processed gradient data is arbitrary (Dransfield et al., 2001). Since the gD data are a result of integration of the gradient information, the first order trend surface or slope of the gD data is arbitrary. The longest wavelength in the AGG data is determined by the smallest dimension of the survey area because the gD and Gdd data are produced through a transformation of the measured gradients across the entire survey area (Mahanta et al., 2001). The survey edges are likely to have an influence on the very longest wavelengths, so the longest wavelength that is accurately recovered is probably less than the theoretical maximum of 22 km for this survey.

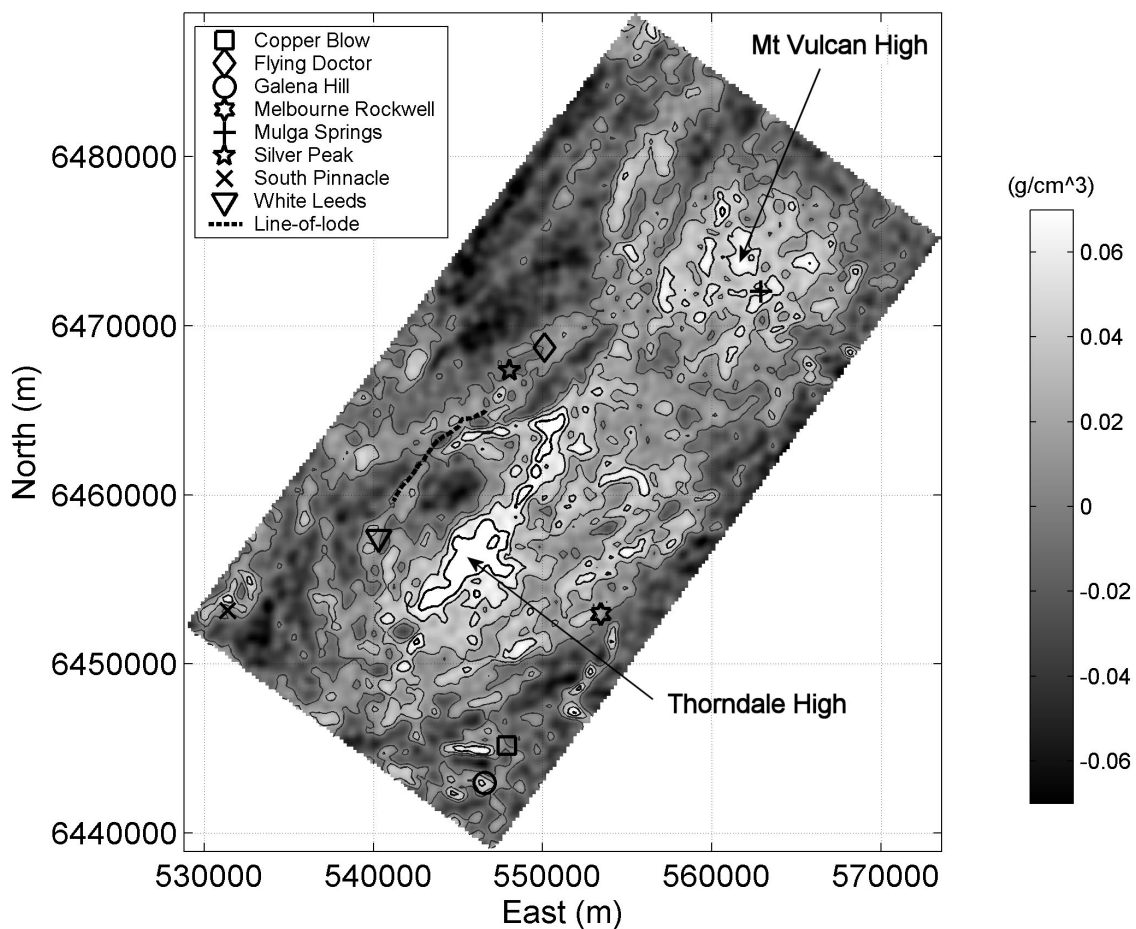
## PREVIOUS GRAVITY INVESTIGATIONS

Previous gravity investigations include work in the mine area by Pecanek (1975), a regional potential field interpretation by Isles (1979, 1983) and a description of the inferences drawn by CRA Exploration from potential field data in the Broken Hill region by Tucker (1983). A 20 by 10 km northeast-trending Bouguer gravity high of

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\* A convention of N, E and D is used with the AGG data, referring to north, east and down directions respectively. gD is the quantity generally measured in ground surveys, whilst Gdd would result from the application of a first vertical derivative (1VD) transformation on gD data. Although the 1VD of ground gD data and airborne Gdd data are measurements of the same type, any numerical comparison of these data needs to take into account the elevation of the observations since the response amplitude decreases with increasing height above the surface.

5 to 10 mGal amplitude to the east of Broken Hill was noted from the earliest surveys. Infill data have resolved this high into two features: the Thorndale high centred on 545000mE 6455000mN and the Mt Vulcan high centred on 560000mE 6475000mN (Figure 1). Both of these features are covered by the AGG survey. The source of these features remains unresolved and continues to intrigue explorers, with Triako drilling a 1224 m hole into the Thorndale high (Collins, 2000). Geological observations and drillcore density measurements from this hole are being used by Stevens and David (in prep.<sup>+</sup>) to constrain a number of density models that attempt to reproduce the gravity high. Mining has virtually eliminated the gravity response of the Broken Hill orebody so the original response must be arrived at through modelling. Simulations by Pecanek (1975), Tucker (1983), Dransfield (1994) and Lane (in prep.<sup>+</sup>) produce a range of anomaly amplitudes depending on the location of the observations, source geometry and excess mass assigned to the orebody. The maximum Gdd anomaly measured at 80 m terrain clearance is estimated to have been in the range 10 to 50 Eo over the central few kilometres of the lode, whilst the ground gravity (gD) anomaly would have been between 0.5 and 1.5 mGal.



**Figure 1.** Density contrast values for a gD inversion model with a single layer of right rectangular prisms of 200 m by 200 m horizontal dimensions extending from surface to 2000 m depth. Contours are at levels of 0, 0.025, 0.05 and 0.075 g/cm<sup>3</sup>. Locations of selected mineral occurrences are shown. Coordinates are for MGA54 projection and GDA94 datum.

## DENSITY MEASUREMENTS

Gravity response is a function of lateral density variations. At Broken Hill, these variations are related to the composition of the host sequence, significant granite gneiss bodies, the presence of amphibolite or pegmatite bodies, local to semi-regional alteration, metamorphic grade, younger mafic and ultramafic intrusions, and of course, base metal sulphide deposit(s). Regolith effects such as variability in the thickness and density of in-situ weathering products and transported cover are an important contributor to gravity response in many parts of the Curnamona (eg the Benagerie Ridge prospect (Godsmark et al., 2003)).

Density measurements of drillcore and outcrop samples held in the BHEI petrophysical database (Maidment et al., 1999) provide useful guidance to the interpretation of the AGG data, notwithstanding the restricted number

<sup>\*</sup> Stevens, B. and David, V., Gravity modelling of the Thorndale gravity anomaly, Broken Hill, NSW: NSW Geological Survey Report (in prep.).

<sup>+</sup> Lane, R., Peljo, M. and Milligan, P., Forward modelling the gravity response of the Broken Hill orebody.

and spatial distribution of the samples. A summary of the density measurements based on mapped units (Table 1) complements the analysis performed on the basis of lithology by Ruszkowski (1998). The majority of the samples are from the Sundown, Broken Hill and Thackaringa Groups, and the median values for each of these Groups\* lie within a small range (2.80 to 2.83 g/cm<sup>3</sup>). These three Groups account for the majority of the outcrop within the survey area, thus a background density of around 2.82 g/cm<sup>3</sup> is appropriate. A small number of samples from the Clevedale Migmatite, as well as measurements reported by Isles (1983), suggest that a negative density contrast may be present between the above mentioned Groups and the older units. The Alma Gneiss and, to a lesser extent, the Rasp Ridge Gneiss have a negative density contrast to the remainder of the Thackaringa Group. Amphibolites have a strong positive density contrast, and the concentration of such units within the Broken Hill and Thackaringa Groups would give rise to an elevated gravity response over these Groups. Pegmatites have a strong negative density contrast and the number of such units within the Sundown Group would be expected to reduce the gravity response over this Group. Iron-rich rocks and the younger mafic and ultramafic intrusions such as the Red Hill Serpentine and Little Broken Hill Gabbro have positive density contrasts that would generate discrete positive gravity anomalies. The retrograde schist zones have a very slight negative density contrast and may generate subtle gravity lows.

In addition to the density measurements given in the BHEI petrophysical database, Kelly and Bell (1992) provide values for ore from the Broken Hill deposit based on extensive mining experience. The density values range from 3.1 g/cm<sup>3</sup> for low grade ore (+3% Pb+Zn) to 3.6 g/cm<sup>3</sup> for high grade ore (+25% Pb+Zn). A density of 3.4 g/cm<sup>3</sup> has been chosen as a typical value in several previous studies (Dransfield, 1994). A base metal deposit with this density would produce a positive gravity anomaly in the Broken Hill area, but this may not be distinguished from the response from an amphibolite, iron-rich rock or younger mafic or ultramafic intrusion without geological input.

**Table 1.** Density values in g/cm<sup>3</sup> derived from measurements given in Maidment et al. (1999). Samples were assigned to the groupings on an exclusive basis from top to bottom. Samples from the Rasp Ridge Gneiss and Alma Gneiss were separated from the remainder of the Thackaringa Group samples. "Contrast" is with respect to a notional background value of 2.82 g/cm<sup>3</sup>. "N" is the number of samples in each grouping.

Grouping	Map symbol from 1:25,000 maps	Contrast	Median	N	Mean	Standard deviation	Minimum	Maximum
Younger mafic and ultramafic intrusions	bp,bx	+0.08	2.895	6	2.870	0.047	2.800	2.910
Retrograde schist	rm	-0.03	2.790	43	2.787	0.087	2.600	2.980
Pegmatite and Quartz	p,rp,q	-0.15	2.670	28	2.717	0.146	2.580	3.260
Iron-rich rocks	bif,qm	+0.48	3.295	16	3.270	0.256	2.690	3.580
Amphibolites	a,ag,ax	+0.23	3.050	67	3.071	0.164	2.760	3.500
Sundown Group	E,M,S,SE,rE,rM	-0.02	2.810	147	2.833	0.104	2.630	3.300
Broken Hill Group	BG,E,EM,FEM,FM,FS,FSE,Lq,M,S,SE,SM,bp,gq,rE,rSE	0.01	2.830	211	2.853	0.135	2.630	3.440
Rasp Ridge Gneiss	BG,BG2,Bc,EM,M,S,SE,rBm	-0.07	2.750	73	2.796	0.143	2.590	3.500
Alma Gneiss	Bc	-0.13	2.690	3	2.903	0.378	2.680	3.340
Thackaringa Group	BG,E,EM,FEM,FM,FS,FSM,M,PI,S,SM,gq,BG2,rBm,rE,rEM,rM	-0.02	2.800	149	2.812	0.165	2.640	4.510
Clevedale Migmatite	Lf,rLF	-0.13	2.690	5	2.686	0.047	2.620	2.750

#### APPARENT DENSITY INVERSION

A simple inversion of the equivalent source gD data was performed to illustrate the level of detail that is present in the AGG data, and to provide a product that was in physical property units (g/cm<sup>3</sup>) rather than measurement units (mGal for gD or Eo for Gdd). This inversion was also a test of the statement by Tucker (1983) that the Broken Hill gravity high could be sourced by material with relatively small density contrast (ie 0.05 g/cm<sup>3</sup>) in the upper 2 km of the subsurface rather than by a deeply buried source. The model consisted of a single layer of right rectangular prisms extending from surface to a depth of 2 km. Each prism had a horizontal extent of 200 m by 200 m, consistent with the lateral resolution of the AGG data. The measurements were subsampled from the gridded data at 200 by 200 m intervals, assigned a constant noise standard deviation of 0.025 mGal and assumed to have been made at a constant terrain clearance of 80 m above a flat land surface. The University of British Columbia program GRAV3D (Li and Oldenburg, 1998) was used for the inversion. The result (Figure 1) shows that Tucker's assertion cannot be immediately dismissed since the contrasts evident in the model are not unreasonable given the measured positive (amphibolite, iron-rich rocks, and younger mafic and ultramafic

\* Excluding the Alma Gneiss and Rasp Ridge Gneiss samples from the Thackaringa Group calculations.

intrusions) and negative (granite gneiss and pegmatite) density contrasts. Several discrete positive density features can be seen, and it remains for explorers to determine whether any are associated with base or precious metal mineralisation.

## **FUTURE WORK**

The *pmd*\*CRC has committed to further work in relation to the AGG survey in collaboration with various partners. Objective estimates of noise levels in the data will be made using a number of methods including analysis of specially acquired repeat line data. This will help to rationalise decisions as to whether features in the survey data are real or due to noise. The AGG data will be integrated with ground data to provide a single data set with optimal long and short wavelength characteristics. To assist in this process, additional ground gravity data were recently acquired by Geoscience Australia to close down the maximum station spacing in the survey area from 7 km to 2 km. The potential for testing and further enhancing the geometry of the Pasminco 3D geological model (Archibald et al., 2000) using the AGG and ground gravity data will also be investigated.

## **ACKNOWLEDGMENTS**

The Broken Hill AGG research project was initiated by the collaboration of the NSW Department of Mineral Resources, *pmd*\*CRC, Geoscience Australia, Gravity Capital and BHP Billiton. This paper is published with the permission of the Chief Executive Officers, Geoscience Australia and *pmd*\*CRC, and the Director General, NSW Department of Mineral Resources.

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# **BHT DEPOSITS: PART OF THE SPECTRUM OF STRATIFORM SEDIMENT HOSTED Zn-Pb-Ag DEPOSITS**

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## **INTRODUCTION**

The genesis of Broken Hill Type (BHT) deposits is poorly understood, principally due to their high metamorphic grade, recrystallisation of the ores and the consequent lack of primary sulfide depositional textures. Previous models include the following:

- Selective strata replacement by granite derived hydrothermal fluids (Gustafson et.al., 1950)
- Metamorphosed syngenetic stratiform sea floor deposit (King and Thompson, 1953; Stanton, 1976; Parr and Plimer, 1993)
- Diagenetic inhalative replacement and in-fill (Haydon and McConachy, 1987)
- Distal skarn (Chapman and Williams, 1998)
- Multi-stage from early syn-sedimentary to late syn-metamorphic (Bodon, 1998; Walters and Bailey, 1998)

In this short discussion I will review the similarities and differences between BHT and SEDEX Zn-Pb-Ag deposits, and speculate upon the nature/source of ore fluids and their depositional environment.

## **WHAT DEFINES A BHT DEPOSIT?**

Based on previous work by Walters (1996) and Beeson (1990) BHT deposits may be defined in the following terms: 1) stratiform or stratabound Zn-Pb-Ag deposits hosted in amphibolite-granulite facies metamorphic terrains, 2) they occur in a rift-related tectonic setting, 3) ore bodies are located at the transition from coarse quartzo-feldspathic to finer pelitic sedimentary facies, 4) meta-volcanics are abundant in the footwall stratigraphy, 5) immediate host sedimentary rocks are dominantly oxidised clastic facies and may include bifs. The basinal setting of BHT deposits compared to SEDEX and Irish type Zn deposits is outlined in Large et. al. (2002).

A major chemical feature of BHT ores that distinguishes them from the general class of SEDEX deposits is their low sulfur/metal ratios. BHT ores are dominated by galena, sphalerite  $\pm$  magnetite, with little pyrite and variable to low pyrrhotite. Other defining chemical features are their high Mn-Ca-Fe composition expressed as garnets, pyroxenes and pyroxenoids, and the commonly anomalous levels of F and P.

Due to their high grade metamorphic setting BHT deposits commonly exhibit structural upgrading and a complex history of metasomatic overprinting. The ores are coarsely recrystallised with annealed textures and may contain zones with complex ductile breccias (Walters and Bailey, 1998).

## **ARE ALL KNOWN BHT DEPOSITS THE SAME?**

The characteristics of BHT deposits outlined above are common to only a few deposit; Broken Hill, Cannington and two deposits in the Aggeneys district of South Africa (Broken Hill SA and Swatzberg). This may be considered a weakness of the BHT model, and suggests that not all examples of previously defined BHT deposits are the same. Other so-called BHT

deposits, including Gamsberg, Zinkgruven and Sullivan, exhibit only a few of the BHT characteristics, and fit comfortably within the general class of SEDEX deposits defined by Goodfellow et. al. (1993). Within the one mineralised district at Aggeneys, there is a range of deposits which vary from typical BHT (Swatzberg and Broken Hill) to metamorphosed SEDEX (Gamsberg). This suggests there maybe a spectrum of stratiform Zn-Pb-Ag deposit types dependent on the local sedimentary environment and redox conditions.

### **WHAT CAN WE LEARN FROM THE ORE MINERALOGY?**

Due to the high grade post-ore metamorphism of both ores and host rocks in BHT deposits it is not possible to use standard techniques such as ore textures, alteration mineralogy and fluid inclusions to make deductions about the nature and source of the ore fluid and the sulfide depositional processes. However simple observations on the mineralogy and chemistry of the ores and host rocks can lead to some reasonable deductions (Stanton, 1983; Large et al., 1996; Cooke et al., 2000).

The following key features of BHT deposits are relevant: 1) The host sediments are commonly oxidised (high  $\text{Fe}^{3+}/\text{Fe}^{2+}$ ), whereas the ore assemblage is reduced, 2) there is a general lack of iron sulfides and barite, 3) gold content of the ores is much high than other Australian SEDEX deposits, 4) Mn-rich minerals are abundant and 5) the ores have a low Cu content. The above observations lead to the following deductions: 1) the ore fluid was reduced ( $\text{H}_2\text{S} > \text{SO}_4$ ) and slightly acidic, 2) dissolved  $\text{Zn} + \text{Pb} > \text{S}$  in ore fluid, 3) moderate temperature of sulfide deposition of 150 to 250°C, 4) the deposition trap environment was partially oxidised, but lacking  $\text{SO}_4$ , and 5) metal deposition was due to fluid oxidation, neutralisation and possibly cooling.

### **EVIDENCE FROM SULFUR AND LEAD ISOTOPES**

Data from Broken Hill and Cannington indicates that the S isotopes of sulfides are fairly uniform and close to zero, suggesting only one sulfur source was involved. The source of sulfur was likely hydrothermal  $\text{H}_2\text{S}$ , with little or no involvement of local seawater sulfate. This is very different to most SEDEX deposits where the S-isotopes commonly show a wide variation to either positive or negative values suggesting a major role for sulfate reduction processes in the generation of the ores. Pb isotopes (Carr and Shen-su Sun, 1996), indicate that the major input of lead (i.e. age of the primary mineralisation), was roughly coincident with sedimentation, and not sometime much later. The Pb isotopes also suggest that the source of the lead is not upper crustal, as with most SEDEX deposits; a mantle or mafic volcanic/intrusive rock source is implicated in their genesis. However although a mafic or mantle source for Pb is suggested by the data, it is recognised that mafic rocks are not a good source for Pb or Ag. Thus a combined mafic-felsic igneous rock source is preferred.

### **ELEMENTS OF THE BASIC GENETIC MODEL**

Based on the above discussion the following basic elements of a genetic model for BHT deposits are proposed:

*Source rocks:* a combination of felsic and mafic volcanics/intrusives derived from the mantle.

*Transport system:* hydrothermal fluid is reduced ( $\text{H}_2\text{S}$  stable), moderate temperature (150 to 250°C), slightly acidic, high salinity with  $a_{\text{Zn}+\text{Pb}} > a_{\text{S}}$

*Trap environment:* mixed oxidised/reduced sedimentary package of argillites, clastics, carbonates and bif. Little or no involvement of marine  $\text{SO}_4$ .



## **EXHALATION OR REPLACEMENT?**

One of the major recent debates concerning stratiform volcanic and sediment hosted ore deposits is whether they form by seafloor exhalation or sub-seafloor replacement. It is now apparent that both processes are important and may lead to major deposits. For example Century and Rosebery most probably formed by sub-seafloor replacement (Broadbent et al, 1998; Allen 1994), whereas McArthur River and Hellyer formed principally by seafloor exhalation (Large et al, 1998; Solomon and Gasper, 2001). These issues have been best resolved by studying primary sulfide depositional textures and sediment diagenesis textures.

Due to the high degree of metamorphism in BHT deposits all primary sulfide and silicate textures have been destroyed and it is not possible to use this approach. King and Thompson (1953) and Stanton (1976) used the fact that the ores at Broken Hill consist of stratiform, stacked ore lenses, which have been folded and metamorphosed with the enclosing sediments, and yet individually display different compositions and metal ratios, to argue for an original syngenetic exhalative genesis. However the lack of barite, the tight S-isotope distribution and the abundant silification associated with some ore lenses could be used to support a sub-seafloor replacement model.

## **WHY IS THERE SO MUCH MANGANESE IN BHT ORES?**

BHT, Zn-skarns, SEDEX and VHMS deposits commonly contain elevated levels of Mn especially at the margins of the ore lenses. However BHT deposits contain an order of magnitude more Mn than the other Zn-Pb ore types. At low metamorphic grades in SEDEX and VHMS deposits Mn is present in carbonate minerals such as rhodochrosite, kutnahorite, Mn-siderite and Fe-Mn-dolomite (e.g. Broadbent et al, 1998; Large et al, 2000, 2002). At higher metamorphic grades, typical of BHT and skarns, the Mn is sited in garnets, pyroxenes and pyroxenoids (e.g., spessartine, johannsenite, bustamite and rhodonite). Thermodynamic studies of Mn stability in hydrothermal systems indicate that Mn is transported in reduced and acidic ore fluids. Mn deposition in carbonates and oxides is commonly related to fluid oxidation and/or pH increase at temperatures below 200°C.

In BHT systems, Mn was probably concentrated in hydrothermal Ca-Mn-Fe-carbonates (kutnahorite and Mn-siderite) within, and particularly at the margins, of the ore lenses. Precipitation of Mn was probably associated with strong redox and pH gradients as the reduced, acidic fluid moved into an oxidised, pH neutral environment. Metamorphism of the ore resulted in Mn being transferred from carbonate hosts to silicate hosts (garnets and pyroxenoids).

## **CONCLUSIONS**

The stratiform nature, discrete stacked, folded and metamorphosed ore lenses, and Pb isotope composition, of BHT deposits, indicate that the main stage Zn-Pb-Ag mineralisation was synsedimentary or syndiagenetic. Mineralogical and chemical associations in the ores indicate the ore fluids were reduced, acidic and low to moderate temperature. The mineralogy of the host meta-sediments suggest that the sedimentary ore environment was a mixed oxidised/reduced seafloor system, and somewhat different to normal SEDEX Zn-Pb-Ag environments.

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# REMOTE SPECTRAL MAPPING OF REGOLITH IN THE OLARY DOMAIN

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## INTRODUCTION

Until recently there has been little activity on the Olary Domain with regard to detailed regolith-landform mapping (Brown & Kernich 2002, Crooks 2002, Lawie 2001), with only regional studies being performed by Gibson (1996 & 1999) and Skwarnecki *et al.* (2001). Over the last decade the adjacent Broken Hill Domain has been the location for a considerable amount of regolith-focused research, including 1:25000 scale mapping (de Caritat *et al.* 2000) and more regional studies (Hill 2001, Gibson & Wilford 1996,). All of these studies have used digital imagery and geophysics to aid interpretation, demonstrating the value of remote sensing assisting in regional to prospect scale mapping projects.

The acquisition of hyperspectral datasets with extensive coverage, such as the Musgrave (Stamoulis *et al.*, 2001; Mauger *et al.* 2002) and Broken Hill (Robson *et al.* 2003) projects has brought an increased opportunity to provide regional mineral maps as a tool to aid company exploration. Robson *et al.* (2003) published preliminary interpretations of lithological mapping with stratigraphic, regolith, alteration, iron oxide distribution and mineral information being extracted from HyMap<sup>TM</sup> imagery over a large area of the Broken Hill Domain. Multispectral ASTER data has also been used to produce mosaiced mineral maps on a regional scale from the Curnamona Province (Hewson *et al.* 2003).

In November 1998 HyVista Corporation acquired five overlapping 30km by 5km strips of HyMap<sup>TM</sup> data commissioned by MIM Exploration over the Olary and Mingary 1:100 000 map sheets. The 300 km<sup>2</sup> of hyperspectral data included the White Dam Cu-Au-Mo Prospect, the Green & Gold and Wilkins Cu-Au workings as well as a range of regolith-landforms and rock types characteristic of the region.

This project aims to investigate the spectral and mineralogical properties of the regolith around the White Dam Prospect using drill and surface material as well as evaluating the mapping potential of the hyperspectral imagery.

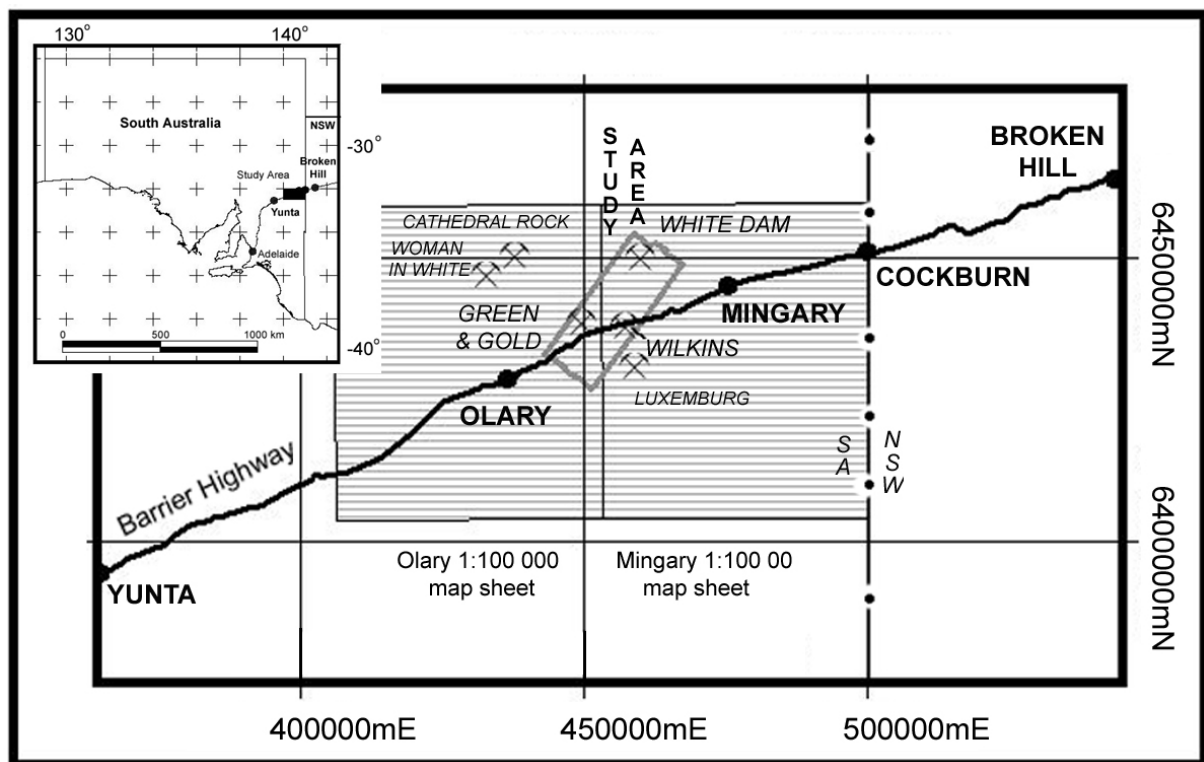
## LOCATION AND GEOLOGY

The region of study is located approximately 25km north-east of Olary and is constrained by the coverage of the hyperspectral imagery (figure 1). The area contains a wide variety of landforms as well as regolith and geological units, extending from basement rocks of the Willyama Supergroup around the White Dam Prospect, south-west over the Barrier Highway to the MacDonald Corridor shear-zone and into a region of younger, Adelaidean rocks. The highly to moderately weathered Palaeoproterozoic Willyama Supergroup metasediments and felsic intrusive rocks have undergone five phases of deformation, whereas the Neoproterozoic to Palaeozoic Adelaidean metasediments in the southern regions of the imagery, are less deformed and generally only slightly weathered. The basement rocks occur as inliers between Tertiary to Recent alluvial and colluvial sediments, which dominate the low lying areas.

## METHOD

BHEI gamma-ray data were used as a preliminary mapping tool to classify suspected lithologies and regolith-landform units. Further analysis of these classes was performed using a 25m digital elevation model (DEM) and digital orthoimagery, commissioned by the South Australian Government, to form part of a regolith-landform interpretation map product.

CSIRO developed HYCORR software was used to atmospherically correct the five strips of HyMap<sup>TM</sup> data. The results from the initial correction were found to be sufficient for lithological discrimination but was not adequate for quantitative analysis of the mineral spectra. An improved atmospheric correction was performed using a combination of model based software (HYCORR) and an Empirical Line method using field and laboratory measurements of samples from bright and dark targets within the imagery. Vegetation and other unwanted pixels in the re-corrected imagery were masked to remove redundant data and to improve the unmixing process.



**FIGURE 1. Locality map of region of study.**

Mineral abundance maps were constructed using mixture tuned match filtering (Harsanyi & Chang, 1994) following CSIRO techniques from the masked imagery (Quigley, 2001). The mineral maps were integrated with the gamma-ray derived data to improve the regolith-landform interpretation map. Field sampling was performed to validate the hyperspectral imagery results by analysing with an Analytical Spectral Devices (ASD) spectrometer and X-ray diffraction (XRD) of selected samples.

## RESULTS

The gamma-ray derived classes were found to discriminate areas of exposed bedrock, which correlated with topographic highs observed in the DEM. The less altered Adelaidean rocks displayed a distinctive subdued radiometric response with little variation between lithological units. The older, deformed Palaeoproterozoic metasediments and intrusive rocks displayed characteristic responses, enabling preliminary lithological mapping and discrimination. Regolith-landform units were also able to be distinguished due to differing moisture content in alluvial regions and the signature strength in relation to the depth of the basement.

Three hundred rock and soil samples were collected from various regolith-landform units found in the study region and spectrally measured using an ASD Fieldspec and a Portable Infrared Mineral Analyser (PIMA) instruments, which were referenced back to the airborne hyperspectral data. Preliminary results from the surface samples have identified kaolinite, white micas, hematite, goethite, smectite and carbonate minerals.

The processed HyMapTM data produced comparable results to field samples. The predominant minerals found in the re-corrected data consisted of kaolinite, illite and muscovite as well as smectite (montmorillonite), hematite and goethite. Carbonate and MgOH minerals were not found due to the dominance of dry vegetation in the region causing broad absorptions in the 2.3µm region and low signal-to-noise over these wavelengths. Geo-rectified mineral maps were produced for the region around the White Dam Prospect for each HyMapTM strip. Difficulties were found with the production of seamless mosaics due to differing scene statistics and characteristics.

## FUTURE RESEARCH

The study provided useful information for targeting field sites for a detailed follow up investigation involving XRD analysis and spectral measurements of subsurface regolith materials of drill-hole material from the White Dam Project area. Ongoing research is required on the relationship of the hyperspectral imagery to the information extracted from the airborne gamma-ray data and their role in understanding the regolith. It is

anticipated that changes in the mineral chemistry observed in the spectra and XRD analysis will be reflected in the radiometric dataset. Further work is required to determine the validity of the atmospheric correction and subsequent results from the HyMap™ imagery through ASD spectrometer and XRD analysis of field samples. Technical difficulties regarding multi-swath hyperspectral data require further attention to allow the generation of seamless mosaiced mineral maps.

## ACKNOWLEDGMENTS

The authors would like to acknowledge the support of the following persons and organisations for their support and collaboration on this project: CSIRO Exploration and Mining, CRC LEME, HyVista Corporation, Primary Industries and Resources of South Australia, the New South Wales Department of Mineral Resources, Geoscience Australia, Mount Isa Mines Exploration and Polymetals Ltd.

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# **THE BROKEN HILL GEOSCIENCE DATAPACKAGE: DISCOVERIES IN THE DATA**

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## **INTRODUCTION**

For the explorer the pre-competitive data supplied by the Geological Survey is an important resource for delineating prospective tracts and possibly even drill targets. During the seventies and eighties larger companies maintained their own regional datasets. The capture and management of these large datasets proved time consuming and a drain on scarce resources. This role is now almost exclusively carried out by the government geoscience agencies. It is now routine for this information to be in a digital (GIS) format, ready for further processing and interpretation by the user. It is only a matter of time before the improvement in 3D software will result in the creation of more models to study and query.

The Broken Hill region is endowed with a wealth of data from a long history of research and exploration. Over the past eight years funding from the Broken Hill Exploration Initiative (BHEI) has been used to capture this material. It provides the ideal base for a company to create a regional dataset. The Department is committed to continuously improving the database by the addition of new material and frequent data releases. In NSW there is a policy of promoting easy access to data and in pricing products at cost of transfer, currently \$A110 for geoscience products.

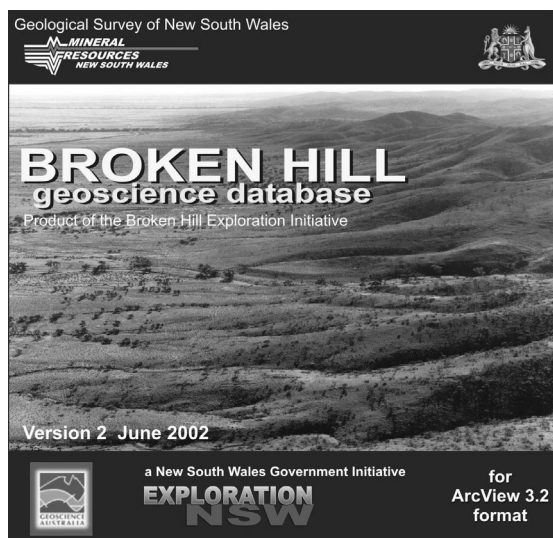
## **THE DATA WAREHOUSE**

For most clients the initial data search is conducted over the web via MinView or DIGS. These are important tools for the serious explorer. MinView holds details of available geoscience data. DIGS is the browser access to scanned images of technical reports including company exploration reports on expired titles.

The extent of material available for explorers is too large to list here. In 2002 the Department released an updated version of the Broken Hill Geoscience Data on CD. It holds a subset of the corporate data on geology, geophysics, RAB and whole rock geochemistry, mineral deposits, expired exploration titles and reports on Cu-Au potential. This CD is a must buy and holds most of the more relevant exploration datasets\* (Note that except for preliminary images and summary details the HyMap and Falcon airborne gravity survey data acquired recently has not been widely released and is not present on the CD). The long term goal of the Department is to hold as much of its data on line as possible, to remove the need for companies to hold separate datasets. In the meantime it is possible to hold a reasonably current set of data by checking the web for new material and adding it to the data provided on CD.

Two important datasets worthy of particular notice are the geochemical data compilations. A whole rock geochemical database, which at present contains in excess of 2200 samples, will eventually include an additional 8000-10000 samples collected from the line of lode. Another key geochemical dataset is the RAB (40,000 holes) and auger (54,000 holes) drilling

compilation. The geochemical values can be imaged and used in conjunction with the other regional data to highlight prospective areas.



**Figure 1.** Cover graphic of the Broken Hill Geoscience Datapackage (Version 2).

## DATA SYNTHESIS AND INTERPRETATION

Synthesis of the data has taken a variety of forms. At a basic level there is a complete index of data sources and reports on Broken Hill, prepared to make background research an easier task. The data has also been used in several studies to find vectors for mineralisation. In one study structural and geophysical features were used to locate sites with potential to host Cu-Au mineralisation. (reference). An earlier study examined the evidence for Cu and Cu-Au deposit styles. More recently the potential for Pb-Zn and Cu-Au mineralisation in sequences underlying the Mundi Mundi Plain has been investigated.

## GAPS IN THE INFORMATION BASE

In the high grade metamorphic zones interpretation of lithologies below cover has been difficult to achieve. Structural elements and units with high magnetic susceptibility (the ubiquitous amphibolites) can be traced but there is a lack of contrast between the most prevalent units. This is an area where detail is lacking and a need for data derived from drilling, detailed gravity or other methods is required.

The geology of Broken Hill is locally complex and it could be argued requires more detailed coverage than many other mineralised terrains. The world class geology maps at 1:25,000 scale, produced over Broken Hill, often lack the detailed structural readings required by explorers. The role of government agencies when presenting data is to provide basic information to enable the researcher to develop and test their ideas. Each explorer has to adopt or find a 'target model'. However the various factual Geological Survey reports, published reference papers and the advice freely given can help in this quest.

## THE FUTURE

A core storage facility? There are plans for the Department to establish and maintain a core storage facility in Broken Hill to provide proper custodial protection for core and cuttings

from the region. The plan still requires proper funding and other assistance but is regarded as an important initiative for preserving vital resource material.

Data held by the Department will be placed online to take advantage of the advances in internet technologies, especially download speeds. The idea is to allow subsets of data to be selected by area, chosen from a map displayed on a (WMS) browser. This has the advantage of being current, available all the time, with no need to save it for future reference. The system has the added advantage that if the data can be downloaded it is free. Note that some large geophysical datasets will be available over the web real soon.

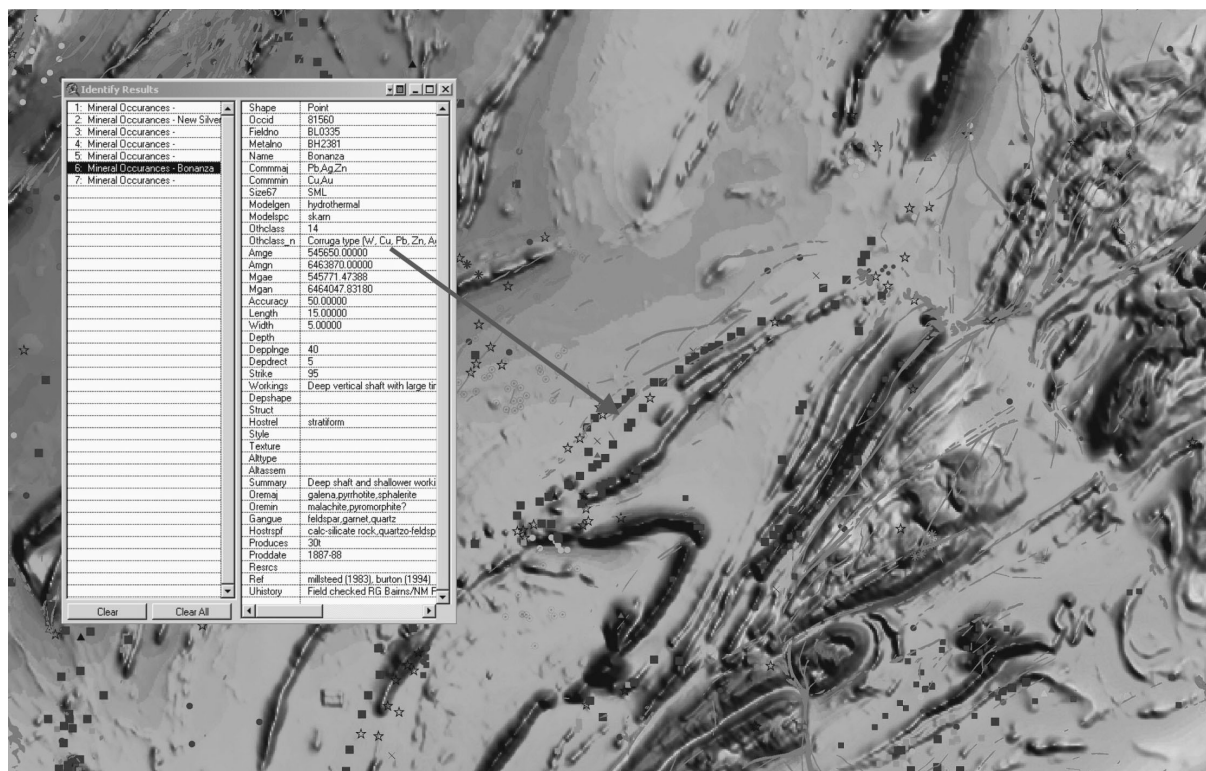
A faster DIGS? We are working on it.

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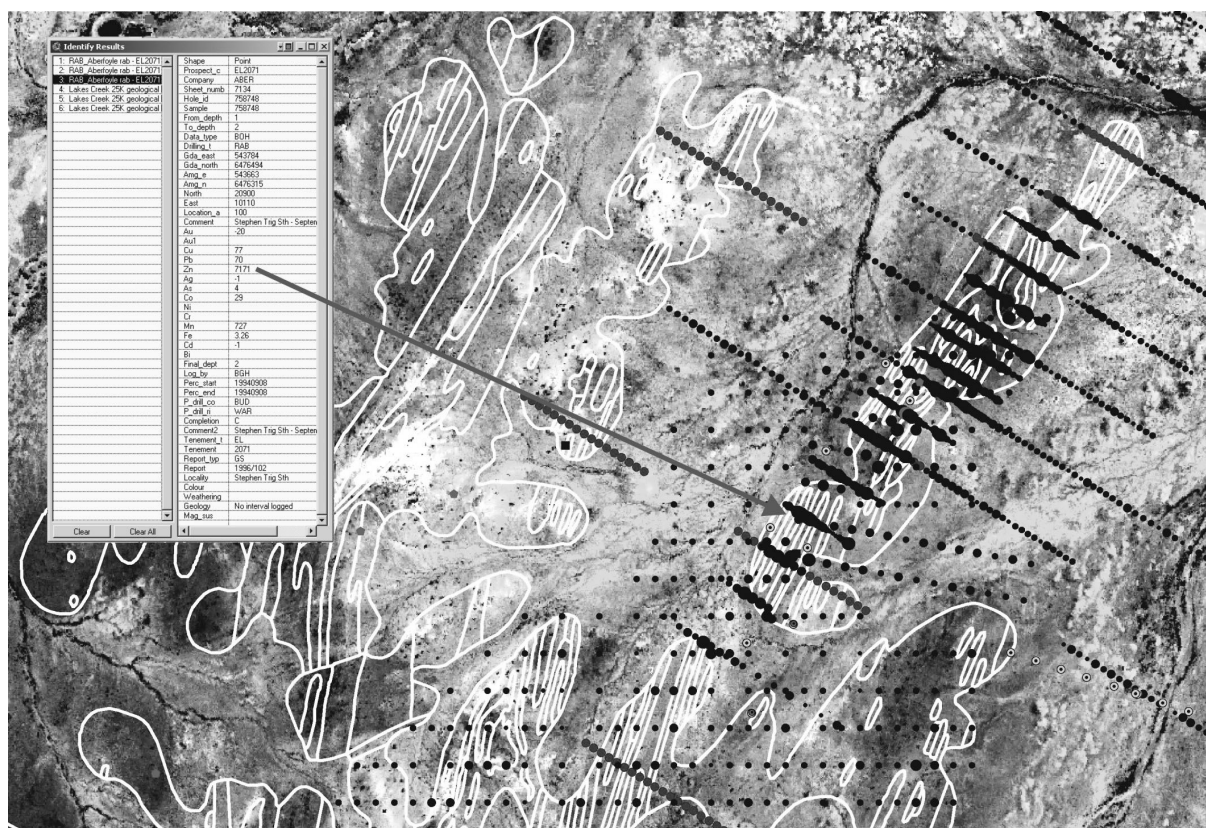
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**Figure 2.** Total Magnetic intensity image of the Broken Hill Line of Lode area. Symbols represent deposits, workings and economic mineral occurrences, each attributed and described as per the example given.



**Figure 3.** Hymap data overlaid with size coded zinc geochemistry derived from RAB drilling (black dots). Each point point represents multi element analysis. White outlines represent attributed polygons derived from 1:25,000 scale geological mapping.

# THE SULLIVAN AND BROKEN HILL DEPOSITS: ARE THERE SIGNIFICANT GENETIC DIFFERENCES?

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## INTRODUCTION

Both the Sullivan and the Broken Hill deposits represent a huge concentration of Pb,-Zn-Ag-in an area that is devoid of other Pb -Zn-Ag deposits of the same magnitude. This would imply that the whatever the process for mobilizing the ore metals, in both areas 90% or more of the ore metal that was mobilized over an area of  $>10^3$  km<sup>2</sup> was focused through a single conduit system. Other similarities between the two deposits, including a geological setting in a volcanically active intracontinental rift, an unusually high Pb;Zn ratio for the Sedex type, and the widespread occurrence of tourmalinite, are therefore likely related to the process that mobilized and focused the ore metals. Differences between the two areas, such as the the tholeiitic magmatism, high pyrrhotite content and low fluorine content at Sullivan compared to the bimodal felsic-mafic volcanism, low iron content and high fluorine content of ores, and the association of banded magnetite iron formation at Broken Hill, emphasize that the mobilization/concentration process did not involve an identical chemical system. Geological relationships in the minimally deformed upper greenschist facies rocks of the Sullivan area are less ambiguous than in the polydeformed granulite facies rocks of Broken Hill, and thus relationships elucidated in the former area may be transferable to interpretations of the latter and other highly metamorphosed areas containing BHT deposits.

## REGIONAL SETTING OF THE SULLIVAN DEPOSIT.

The Sullivan deposit, which contained an original economic resource of  $>160$  million tonnes at 5.9% Zn, 6.1% Pb and 67 g/t Ag, is hosted by a turbidite-sill complex up to 10 km thick. This turbidite-sill complex, called the Aldridge Formation in Canada and the Pritchard Formation in the U.S., forms the lower part of the Mesoproterozoic Belt-Purcell Supergroup, which represents the sedimentation of an intracratonic rift system (Fig. 1). The sills (Moyie sills) are transitional between E-MORB and N-MORB tholeiites and together with the preservation of rift-margin basal sag quartzite, suggest a passive rift developed on attenuated continental crust. A minimum of 50,000 km<sup>3</sup> of magma was emplaced into wet and unconsolidated turbidites over a maximum time span of a few million years around 1468 Ma. Sills locally form 30-40% of the Aldridge sequence but on

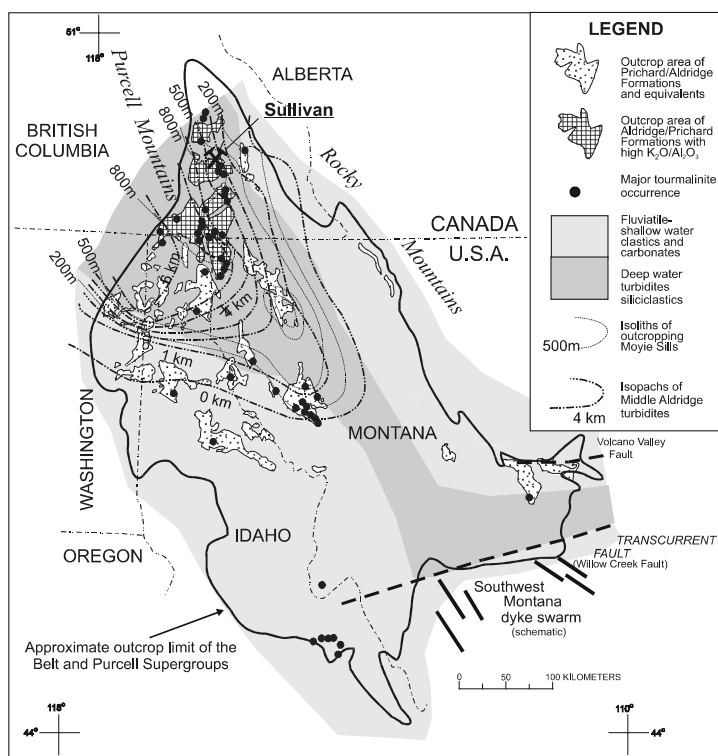


Fig. 1. Map showing:

- the extent of the Belt-Purcell Supergroup;
- the symmetrical distribution of shallow water sedimentary facies on both sides of an axial deep water facies at the time of formation of the Sullivan deposit, reflecting an intracontinental rift;
- isopachs of turbidites of the middle Aldridge formation;
- isoliths of outcropping Moyie sills;
- distribution of major tourmalinite occurrences;
- distribution of K<sub>2</sub>O-enriched turbidites.

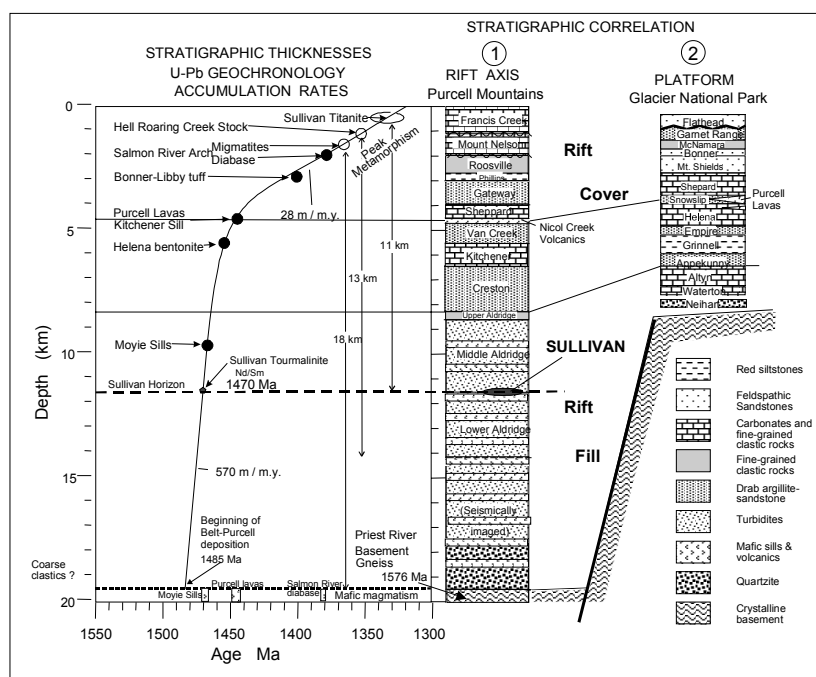


Fig. 2. Stratigraphic correlations between the axial and platform parts of the Belt-Purcell rift and accumulation rates in the axial part based on stratigraphic thicknesses of Hoy (1993) and stratigraphic- or depth-controlled events dated by U/Pb zircon or Pb/Pb titanite methods. Locations of profiles shown in Fig. 1. Geochronological data from Anderson and Parrish, 2000; Evans et al., 2000; Jiang et al., 2000; Schandl and Davis, 2000; Sears et al., 1998. Barometric data from Doughty and Chamberlain, 1996 and De Paoli and Pattison, 2000.

average occupy only about 10-20% of the sequence. A very high average accumulation rate of  $>500$  m/m.y. persisted from the initiation of sedimentation in the rift, which may have been as late as 1485 Ma, until the last major mafic magmatic event at about 1445 Ma involving the eruption of the Nicol Creek volcanics (Fig. 2). This high accumulation rate resulted in a sedimentary pile with unusually high porosity, that was, from time to time, catastrophically dewatered by the emplacement of Moyie sills into unconsolidated sediment. Mud volcano activity associated with these catastrophic dewatering events is expressed both as discordant (vent breccias) and concordant (eruption breccias) bodies of sedimentary fragmental rocks throughout the Aldridge and Pritchard Formations. Tourmalinization (of the argillaceous component of the sedimentary rocks) is spatially associated with these mud volcanos, with most occurrences of tourmalinite being within or adjacent to sedimentary fragmental rocks and about one third of sedimentary fragmental bodies containing zones of tourmalinite (Fig. 1).

Shallow-water stratigraphic equivalents of the Aldridge Formation contain salt clasts, evaporitic nodules, chamosite pellets and syneresis cracks, suggesting that the permanent water column was saline, which combined with the evidence of tidal conditions afforded by herringbone crossbeds and elongated stromatolites, indicate a marine environment of a warm semi-arid climate. High  $K_2O$  (and  $Na_2O$ ) contents of sedimentary rocks in the thickest part of the basin (Fig. 1) is interpreted as indicative of highly saline Mesoproterozoic formational waters, presumably due to the gravitational settling in the deepest part of the basin of evaporitic brines generated on the adjacent platform (Fig. 2). The high organic carbon contents of hemipelagic sediment intercalated with the turbidites, their sulphur:carbon ratios and stratigraphic excursions of the sulphur isotope ratios of disseminated iron sulphides, indicate at least periodic reduction of the marine water column and anoxic bottom conditions.

#### LOCAL SETTING OF THE SULLIVAN DEPOSIT.

The Sullivan deposit occurs at the contact of distal fan, thin-bedded, argillaceous turbidites of the lower Aldridge Formation, and the slope/upper fan, thick-bedded, arenaceous turbidites of the middle Aldridge Formation. On a regional scale, the contact is marked by up to 20 m of carbonaceous laminated argillite, which is interpreted as marking a tectonic downdrop of the basin that caused turbidite starvation. The deposit accumulated in the crater and on the flanks of a collapsing mud volcano, situated in the largest mud volcano field of the Aldridge Formation, a 7 km long, rift-parallel zone called the Sullivan – North Star Corridor. The Corridor is characterized by sedimentary fragmental rocks, sysedimentary faulting and hydrothermal alteration, the latter being dominated by “muscovite” (dominantly hydrolysis and sulphidation) and tourmaline types. The tectonic activity and the immense amount of fluid upflow that caused the sediment disruption and alteration within the Corridor, was likely coincident with the onset of magmatism and the emplacement of sills at depth, because the Nd/Sm age of tourmalinite alteration in the immediate footwall of the Sullivan deposit is 1470 Ma (Jiang et al.,

2000), close to the 1468-1469 Ma U/Pb ages of the Moyie sills. The occurrence of Sullivan in the rift-fill sequence is anomalous compared to the setting of most other SEDEX deposits, which preferentially occur in the sag sequence of intracontinental or epicontinental sedimented rifts.

The Sullivan deposit consists of a stratiform body of pyrrhotite-pyrite-sphalerite-galena that is up to 100 m thick (Fig. 3) and whose economic part is about 2,000 m by 1,600 m in area. The thickest (Vent Complex) part of the deposit overlies a subvertical alteration pipe of tourmalinite about 1 km in diameter. Tourmalinite is cut by a network of thin sulphide veins that is interpreted as the zone of upflow for the ore fluids. The deposit is strongly zoned, with grades of ore, Pb:Zn ratios and pyrrhotite:pyrite ratios decreasing away from the central part of the Vent Complex. Contours of Pb:Zn ratios cross-cut bedded sulphides at a high angle and are a main line of evidence that the Sullivan deposit was formed by the shallow subsurface replacement of a pyritic sedimentary sulphide body by pyrrhotite, galena and sphalerite, the process being accompanied by chloritization of the siliclastic component of the ores. Albitite-chlorite-pyrite alteration is most prominent in the hanging wall to the Vent Complex and together with pyrite-carbonate alteration of pyrrhotitic massive sulphide in the core of the Vent Complex, are associated with the post-ore emplacement of the Mine sill at 1468 Ma. The mud volcano conduit at Sullivan therefore seems to have been the conduit for at least four different episodes of hydrothermal upflow over a period of several million years, each producing a different hydrothermal alteration: 1) sericite (accompanying mud volcano activity); 2) tourmaline; 3) pyrrhotite-chlorite; 4) albite-chlorite-pyrite.

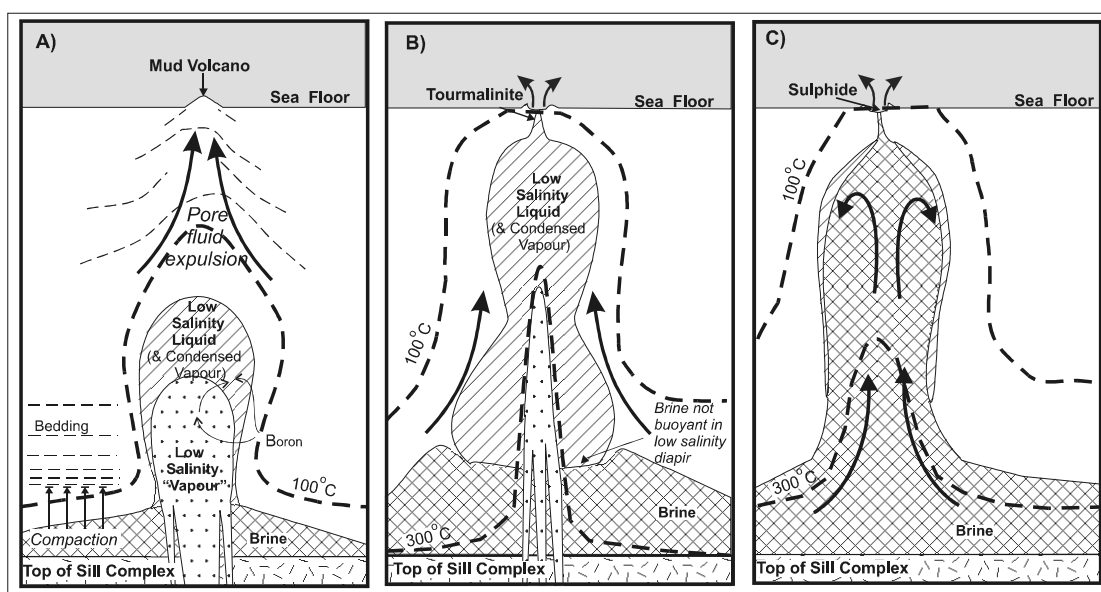


Fig. 3. Diagrammatic representation of the time sequence link between mud volcano, tourmalinization and sulphide accumulation at the Sullivan deposit.

**A.** Sill emplacement causes rapid compaction of sediment and heating of saline pore fluids to  $>600^{\circ}\text{C}$ , which separates into aqueous vapour, low density low salinity liquid and high density high salinity liquid. Volume expansion of pore fluid to vapour / low density liquid causes very high overpressures that blasts a conduit to the surface and allow the expulsion of over-pressured pore fluids, fragmented and slurried sediment to the surface to form a mud volcano.

**B.** Induration of sediment by heating of pore fluids causes release of boron which partitions into the low salinity liquid, in part by vapor condensation. The low density low salinity liquid rises as a diapir centred on the cross-stratal permeability cause by mud volcano eruption. Tourmalinization occurs due to temperature decrease along conduit to sea floor.

**C.** With evacuation of low salinity diapir, high salinity formational waters become buoyant and rises to the sea floor.

## DISCUSSION

The sequence and timing of hydrothermal upflow at Sullivan, coupled with the regional relationship of mud volcanos and tourmalinization to sill emplacement, can be explained by a single model of hydrothermal segregation in a hydrothermal diapir (Fig. 3). The recurrence of hydrothermal upflow along the same conduit by fluids with different alteration effects, and hence compositions, suggests that the cross-stratal conduit through un- or semi-consolidated sediment provided by a column of hydrothermally indurated rock, such as the Sullivan conduit, is semi-permanent. The volume of fluid required to mobilize the quantity of ore metal alone represents dewatering of  $>200 \text{ km}^3$  of semi-consolidated turbidites, which, consistent with the absence of any other contemporaneous cross-stratal upflow zone of major proportions in the northern part of the Belt-Purcell Basin, suggests that a single cross-stratal upflow zone can relieve over-pressuring of a sedimentary basin on a regional scale.

The relatively high Pb:Zn ratios of the Sullivan ores compared to other Sedex deposits can be explained by a higher chlorinity or higher temperature of the ore fluids (the Pb:Zn ratio of chloride fluids saturated with galena and sphalerite increases with increasing temperature and chloride content), or by a limited supply of reduced sulphur at the depositional site (the nucleation of galena is lower than that of sphalerite so  $Pb^{++}$  preferentially captures dissolved sulphide). Metalliferous brines of modern sedimentary basins are generated by leaching during the smectite-illite transformation, which under normal geothermal gradients mainly takes place over the range of 90-110°C and produces fluids with Pb:Zn ratios of 1:5 to 1:3. It is speculated that in the Belt-Purcell Basin, the smectite-illite transformation was driven by the sudden temperature increase associated with sill emplacement and took place at higher temperature to produce a higher Pb:Zn ratio in the formational brine.

## CONCLUSION

The geological characteristics of the Sullivan deposit that are intimately related to the catastrophic dewatering and sudden heating of >5 km of rapidly deposited turbidites triggered by the emplacement of tholeiitic sills into the semi-consolidated sediments, include its large size, lone occurrence, relatively high Pb:Zn ratio, and stratigraphic position in a rift-fill sequence. Broken Hill shares these characteristics and thus also may represent a similar catastrophic dewatering. Differences between the deposits can largely be explained by differences in the sea floor environment and the composition of contemporaneous magmatism.

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(Note: The above is largely the author's condensation of selected conclusions by various authors contained in the Sullivan Volume (*The Geological Environment of the Sullivan deposit, British Columbia*, J.W. Lydon, T. Höy, J.F. Slack and M.E. Knapp editors, *Special Publication No. 1, Geological Association of Canada Mineral Deposits Division*, 834p). In the interests of conserving space, citations to papers contained in this volume have not been made in the text).

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# CURNAMONA AUDIT AND GAPS ANALYSIS

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## INTRODUCTION

The NSW and SA Geological Surveys in conjunction with Geoscience Australia wish to re-invigorate the Broken Hill Exploration Initiative (BHEI). This initiative which commenced some 8 years ago seeks to increase mineral exploration in the Curnamona Province (Figure 1), leading to new discoveries and the generation of wealth for Australia. It is considered that one of the best ways to re-invigorate mineral exploration is to provide precompetitive data and information. However, considerable precompetitive data have already been provided by the surveys and GA, so the main question is what kind of future information and data is the most appropriate and not only scientifically sound but also attractive for potential mineral explorers. To this end an audit is required of what information, knowledge and data exist and whether there are gaps in this coverage that could and should be filled. A 10 month-long audit and gaps analysis comprising various fractions of our time commenced in March 2003 and here we present a progress report. Results of an industry survey about its view of data and knowledge coverage, and impediments to exploration in the Curnamona Province will also be presented.

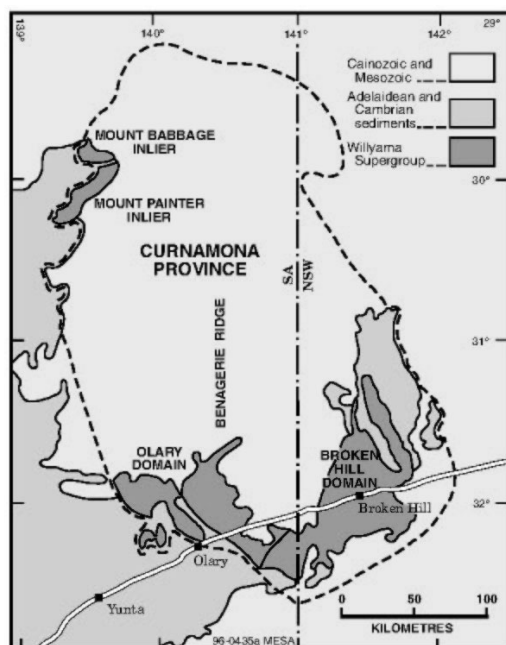


Fig. 1 Curnamona Province locality map

## KEY DRIVERS

- Investment focus on high impact initiatives. The BHEI will continue but where should resources be focussed to provide the maximum impact.
- Data and information are provided by government on a pre-competitive basis. Beyond this point it becomes exploration and the domain of industry.
- Build upon and utilize existing resources and expertise in the pmd\*CRc and elsewhere.

## **METHODS**

1. Catalogue existing data and information, including state and federal data sets and company data where appropriate.
2. Assess the existing data and information coverage. For example, where are the gaps in coverage? Assess the integrity of data sets e.g.: surveys (what, where and how), magnetic, seismic, electromagnetic, gravity; age dating-coverage, stratigraphy, methods used, applicability; geochemical compilations (e.g., drainage, RAB, soil, rock, ground water, whole rock, alteration and isotope geochemistry); regolith coverage; depth to basement and "ease" of exploration; drilling coverage; open file reports and university theses; models (2D, 3D, "soft" conceptual); coverage by "new" techniques assessing their potential applications (e.g., HyMap)
3. The project is also including an analysis of knowledge gaps as well as the data gaps. Examples of knowledge gaps include the coverage of age dating in the Curnamona. Are there gaps in the current coverage, and, if so, how might they be filled? What structural models have been used and how useful are they?
4. Questionnaire-ask what the industry sees as its priority for pre-competitive data and technical impediments to exploration in the Curnamona area.

Possible spin offs of the audit and gaps analysis will be revised assessments of the potential for new styles of mineralisation, and further advancement and understanding on the growing similarities between the metallogenic evolution of Curnamona and Mt Isa.

The outputs of the study will comprise a report, maps and CD copy.

## **PRELIMINARY RESULTS**

We have been highly impressed by the sheer volume of data that exists for the Curnamona Province. The volume of data covering the Broken Hill Block is far greater than for the Olary and Mt Painter Blocks. This reflects the location of the Broken Hill ore body in NSW, the Broken Hill Block's perceived high prospectivity and a long exploration history, and the establishment by the NSW DMR of a regional office in Broken Hill, from which detailed regional mapping and data compilation and integration have been ongoing for the past 27 years. Many workers have detailed knowledge of many facets of the data coverage but very few workers admit to a clear, comprehensive overview. The state surveys have welcomed the opportunity to check their own data retrieval ability and are well aware of gaps in data and knowledge. Geochemical databases are proving to be complex to audit and to understand due to the large volume of data and various degrees of validation (e.g., Stockfeld, 2002). A number of unpublished reports also contain valuable information and have been helpful resources (e.g., Capnerhurst, 1995, 1998; Webster, 2001). A summary of preliminary results is listed in Table 1.

**Table 1.** Summary of Preliminary Results of Curnamona Audit and Gaps Analysis

		NSW	SA	Comment
<b>Geology</b>		Completed maps to 1: 25 000 scale-world class coverage	Work in progress mapping selected areas at 1:25 000 scale. Previous mapping compiled but not systematic, spatially inaccurate and incomplete at various scales	No absolute seamless coverage, though mapping in Olary uses same stratigraphic framework as Broken Hill, but not in Mt Painter. Good 1:500 000 compilation of province
<b>Geophysics</b>	<b>Gravity</b>	Innovative airborne gravity completed with good detail, assessment ongoing	~260 000 stations. SARIG-PIRSA working on depth to basement using Intrepid software	Depth to basement needs assessment. Forward modelling requires better rock property attributes
	<b>Magnetics</b>	Good coverage, no obvious gaps at this stage	Overall good coverage mostly at 100m line spacing in outcrop areas, 400m in deeper cover. Some exceptions include Mt. Painter. Working on depth to basement using Intrepid software and combining with drillhole data.	Depth to Willyama basement interpretation difficult using magnetics, e.g., BIF in the near surface Adelaidean geology
	<b>Radiometrics</b>	Good coverage, no obvious gaps, down to 150m line spacing	Not as complete as gravity and magnetics	Gaps in high quality data across the Curnamona though regridding has improved quality and location accuracy in places
<b>Geochemistry</b>		Whole rock: ~14 000 analyses in total but only 2500 have been completely validated. ~10 000 samples from Line of Lode, lithologies assigned to 8500 samples and 4000 samples assigned to stratigraphic units. ~1300 new samples from BHP-Pasminco-C. Stanley study. Assay data 95% complete for open file RAB, auger holes. No assay data captured for diamond or percussion holes.	All exploration geochemistry and while rock on SA-Geodata. 150 000 geochemical samples but only 12% (~17 000) validated, 88% (~133 000) remain to be captured.	Geochemical databases are complex due to large number of samples and variable quality of metadata (subsets, overlap). No merger of diamond drill hole locations and assay data.
<b>Rock properties</b>		Some datasets are known to exist	Some datasets are known to exist.	Datasets have been requested from individuals.
<b>Alteration</b>		pmd*CRC has gained access to BHP-Pasminco study of Line-of-Lode. Very limited regional interpretation (ASTER and HyMap data useful, ongoing gaps due to cloud cover)	Limited regional interpretation only. PIRSA vision to create regional alteration maps based on geology, remote sensing and radiometrics. Further ASTER acquisition is awaited, especially for Olary 100K map sheet.	Line-of-lode alteration geochemistry is well characterised, with similar conclusions from 3 different studies. Regional studies underway.
<b>Drill core</b>		Line-of-Lode and regional core stored at 9 different locations on mine leases, (up to May 2001). All diamond holes that had been retained by North and ZC, and subsequently Pasminco (~14180) are in retrievable system. Number of holes not recorded for Northern leases (Webster, 2001)	Considerable amount of core stored at PIRSA Glenside Core Library Unspecified amount of company core stored at various sites in Broken Hill. Space limited in PIRSA core shed near Adelaide	No current central storage location for Curnamona drill core, but planning continues.
<b>Regolith</b>		CRC LEME covered 40% of Broken Hill Block	Work on going via PIRSA and CRCLEME. PIRSA plans to use regolith mapping as basis for geochemical strategic maps for use by explorers.	CRC LEME using different regolith mapping scheme from the RED (residual erosional depositional) scheme of PIRSA.
<b>Drill Holes</b>		>54 000 auger holes >40 000 RAB holes >2000 diamond & percussion holes, ~95% complete for	Of ~44 000 holes, ~20% (8227) captured on SA Geodata. ~90% (4294 of 4800)	Capture of these data are labour intensive, ongoing but with limited resources. No capture of down hole surveys for diamond holes.



	NSW	SA	Comment
	regional exploration but line-of-lode diamond drill holes (>14 180) not included.	captured of diamond core and deeper RC, percussion and rotary . ~10% (3933 of ~39 000) captured of shallow RAB, auger, percussion holes.	Stratigraphic units not assigned to RAB holes in NSW.

Notes: This summary is preliminary only and incomplete, subject to amendment. Evaluation of other data sets such as water geochemistry, stream sediments, petrology, isotope geochemistry is underway.

## CONCLUSION

The audit and gaps analysis has so far revealed voluminous data sets in various stages of completeness. Further compilation and analysis will ultimately assist government on where and how it should best allocate its resources in the future to achieve its goal of re-invigorating mineral exploration and maximising potential for discovery in the Curnamona Province.

## ACKNOWLEDGEMENTS

PIRSA, NSW DMR and GA are thanked for their support to undertake this project through pmd\*CRC. Fruitful discussions have been held with a number of people from these agencies, in particular Stuart Robertson, Colin Conor, Kevin Capnerhurst, Peter Lewis, and Lesley Wyborn. We also acknowledge guidance provided by Lindsay Gilligan, Paul Heithersay, Russell Korsch and Chris Pigram; and assistance from CSIRO's Glass Earth initiative, led by Joan Esterle.

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# RESOLUTION OF THE STRUCTURAL GEOMETRY OF THE LINE OF LODE AND THE BROKEN HILL BLOCK: A 3D MODEL

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## INTRODUCTION

The geometry and structural evolution of the Line of Lode containing the Broken Hill Pb-Zn-Ag ore bodies has long been a subject of contention (e.g. Andrews 1922; Gustafson 1950; Lewis et al. 1965; Archibald 1978; Laing et al. 1978; Haydon and McConachy 1987; Rothery 2001). Many workers accept the litho-sequences containing the mineralization is downward facing (e.g. Laing 1978) but disagree as to the deformation sequence and gross geometry. Particularly contentious has been the apparent lack of evidence for a Broken Hill Antiform which is supposed to separate the Hangingwall Synform and the Broken Hill Synform. Common geometric solutions to this problem invoke D<sub>2</sub> slides (complex zones of very high strain which developed at or near peak metamorphic conditions) that have displaced the antiform.

We have developed one potentially valid geometric solution to the distribution of rock units mapped both at surface and in the subsurface in an area including the Line of Lode. The digital model is highly constrained by surface and subsurface mapping and a series of 21 drilled cross-sections (Pasminco Line of Lode Study). To investigate these implications at a regional scale a 3D digital model of the entire Broken Hill block (some 150km x 90km) was constructed. This regional model was based on a new interpretation of 1:50 000 scale maps by the Geological Survey of NSW, mapping by Archibald (1978), and observations by Pasminco exploration geologists. This interpretation makes use of available geophysical data including gravity, magnetics and reflection seismic. These models have important implications for exploration both at a mine scale and at a regional scale.

## KEY ASSUMPTIONS UNDERPINNING MODEL CONSTRUCTION

The geometry of the Broken Hill ore bodies was investigated in an attempt to determine structural controls on the location of the orebodies and to establish whether the geometry in the Line of Lode area is unique to the Broken Hill Block. As such there is an assumption that the Broken Hill ore bodies have some tectono-stratigraphic control.

In order to develop a geometric model a number of key assumptions were made, namely:

1. There are consistently ordered time-stratigraphic packages of rock suites that can be traced across the Broken Hill block. Going from oldest to youngest, these are equivalent to the Clevedale, Thorndale, Redan/Thackaringa, Broken Hill, Sundown and Paragon Groups/Formations (Willis et al., 1983).
2. The structure is dominated by superposed folding with some early shear zones (slides) and late retrograde shear zones.
3. The Alma Gneiss and the Rasp Ridge Gneiss occur at different time-stratigraphic intervals. This is supported by age dating (Page et al., 2000).

4. The Hores Gneiss occurs at the top of the Broken Hill Group and forms a single time-stratigraphic horizon (albeit somewhat discontinuous) rather than multiple stratigraphic levels of the same lithology. This has very important implications for interpreting structural complexity within the environment of the Line of Lode.

## **MODEL CONSTRUCTION**

The Pasminco Line of Lode study was the primary data set used for interpretation. The study data comprised two map (flitch) interpretations at the 9700 RL and the 9400 RL and 21 cross-section interpretations (with drill hole and underground mapping control), all at 1:5000 scale. These cross sections were extended to cover part of the Broken Hill Synform to the east and the Sundown area to the west.

The digital model of the Line of Lode was constructed using Vulcan 3D CAD software. 50 digital cross sections were constructed on 200m centers and the cross sections stitched together to form 3D triangulations.

Modeled geological entities were:

Hores Gneiss, Rasp Ridge Gneiss, Sundown Group, high strain zones that envelop the Pb-Zn-Ag mineralization, and retrograde shear zones.

The Line of Lode model was partly used as a template for constructing a larger model of the Broken Hill Block. The regional model was based on 17 key cross-sections at approximately 5km spacing and incorporated the two ANSIR seismic lines and a drill hole data base of regional drilling compiled by Pasminco.

The new interpretive map is constrained by the mapped distribution of defined time-stratigraphic units and by the notions of fold superposition. Such ideas constrain overprinting of fold generations, distribution of areas of upward and downward facing and together imply a rigid topology that must be adhered to for the geometric model to be valid. To demonstrate geometric compatibility we have interpreted cross-sections and the model above the current topographic surface.

Modeled entities included:

Retrograde shear zones, base and top of the Thackaringa Group, top of the Broken Hill Group and the Sundown Group.

## **GEOMETRY OF LINE OF LODE**

The 3D model has clarified the structural geometry of the Line of Lode. The most important observation is that the Line of Lode mineralization is contained within a high strain domain that broadly marks the transition from downward facing sequences of Thackaringa and Broken Hill Group to upward facing sequences of the Sundown Group. This high strain domain, as well as containing the Pb-Zn-Ag mineralization, also has multiple lenticular bodies of Hores Gneiss that we explain as representing remnants of a single horizon that has been strongly deformed.

The Broken Hill Antiform is located between the Hangingwall and Broken Hill synforms however, its identification has been problematic. The enigma of the Broken Hill Antiform can be better understood by examining the change in morphology of mesoscopic folds going north

to south. In the north folds exposed in the Sundown Group are relatively open and generally upward facing whereas in the main exposure of the Line of Lode folding becomes very complex as a result of near coaxial refolding of very tight flat lying folds formed during the development of the high strain domain. We contend that the antiform is present but has been difficult to pin-point on a mesoscopic scale because of the structural complexity arising from the near coaxial superimposition of flat plunging later folds on an early-developed high strain domain in which the folds are strongly flattened and dismembered with vergence and younging directions complicated by both earlier and later generation folds.

Changes in geometry of the Line of Lode mineralization are due, in part, to its location within an envelope of highly strained rocks. In particular, the change to a steep geometry at the northern end of the Line of Lode has been attributed to interaction with the De Bavay and Globe Vauxhall retrograde shears. However, we suggest that the change is the result of refolding an elongate but folded zone of mineralization that formed during the development of the Line of Lode high strain domain, about more open folds that formed the Hangingwall and Broken Hill synforms. It is possible that the Potosi mineralization on the western flank of the Round Hill Synform is a continuation of the main Line of Lode mineralization.

### **REGIONAL BROKEN HILL MODEL**

A number of observations arise from the regional 3D model that have important implications for the tectonic evolution of the Broken Hill Block, and in turn, controls to Broken Hill style mineralization. These are:

- Contrary to most previous interpretations for the Broken Hill Block, the areas of downward facing sequences are much more restricted than most workers would interpret.
- Some areas of downward facing stratigraphy comprise sequences lower in the stratigraphy that appear to be thrust over thick sequences of younger Sundown Group.
- It is difficult to impose more than one geometric model on the data used in this analysis.

### **3D MODEL: IMPLICATIONS FOR BROKEN HILL STYLE MINERALIZATION**

The observation that the Broken Hill mineralization occurs within a high strain zone that separates downward facing sequences from upward facing sequences of younger sediments has important implications for the controls on mineralization. A possible interpretation for this observation is that the mineralization developed adjacent to a growth fault that controlled late clastic basin development (thick accumulations of Sundown Group sediments) and formed a locus for later strong compressional deformation. The early stages of compressional deformation inverted this fault and became a zone of high strain and deformation with mineralization strongly elongate. Later folding further deformed these high strain zones.

Exploration should therefore focus on high strain belts separating areas of limited downward facing stratigraphy adjacent to thick sequences of younger clastic sequences. Within the Line of Lode environment, the 3D model suggests that there is potential for deep mineralization under the synform in the vicinity of Round Hill. This zone might connect the deep (Fitzpatrick/A1 area) mineralization with the Potosi mineralization.

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# COMPOSITION AND STRUCTURE OF THE KOONENBERRY REGION

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## INTRODUCTION

In the broad sense the Koonenberry region extends from Scrope Range in the south to Tibooburra in the north and lies to the east of the Bancannia Plain. This region has a structural framework underpinned by the Middle to Late Cambrian Delamerian Koonenberry Fold and Thrust Belt that hugs the eastern margin of the Curnamona Craton. The general grain of the country reflecting the trend of the Koonenberry Fold and Thrust Belt is obvious on many regional maps, particularly aeromagnetic images. From Wertago to Camerons Corner and beyond, the fold belt trends uniformly at about 320°. To the south of Wertago, in the vicinity of Grasmere and Wilandra, the near vertical cleavage and rock unit trends become folded on all scales about late stage vertical axes in a zone (Grasmere Knee Zone) influenced by major faults trending 300°. The rocks emerge from this zone with a north-south trend near Comarto and then rotate to 220° further south to form the Scrope Range trend that continues subsurface into South Australia. The overall effect is for the Koonenberry Fold and Thrust Belt to take an 80° bend near Grasmere. The Delamerian slaty cleavage remains vertical throughout and appears to be folded about vertical axes on all scales in the Grasmere Knee Zone.

The vertical rotation in the Grasmere Knee Zone, and the timing of this event, are two problems that have yet to be fully explained. The aeromagnetic coverage has been particularly valuable in revealing the presence of various types of igneous intrusions and in tracing some magnetite-bearing sedimentary beds within the folded sequence that otherwise would not be distinctive. Gutters cut along the sides of the Nundora-Wonnaminta road provide a semi-continuous cross-section 40 km in length across the northern part of the main exposure of the fold belt (Mills, 1992). An apparent cumulative sedimentary thickness of 16 000 m seemed to demand the presence of at least several thrust faults repeating the sequence. Thrusts have been suggested by geophysical interpretation but few have been verified in outcrop due to paucity of exposure.

## ROCK UNITS PRESENT DURING THE DELAMERIAN OROGENY

Subdivision of the older basement rocks into four rock units based on lithology (Mills, 1992) has stood the test of later detailed mapping. The oldest rock unit, named the Kara beds, underlies much of the western part of the Koonenberry region. It is a thick sequence of well-bedded and laminated slates and siltstones with occasional clean quartzites in the lower part, and dolomitic shales and bedded dolomites in the upper part. Metamorphic grade is chlorite zone. There are no established fossils. The transitional alkaline Mt Arrowsmith Volcanics, consisting of basic pillow basalts and pyroclastics and lesser trachytic derivatives (Edwards, 1978), occupy the centre of the section. The volcanics show some evidence of sub-aerial emergence and indicate that the Kara beds were laid out on a shallow water shelf environment. The sequence is correlated with the upper part of the Late Proterozoic Adelaidean succession in the Fowlers Gap-Sturts Meadows area on the basis of lithological similarity although rock units in the Kara beds are more disrupted by deformation and may have been deposited in a more distal environment. Several thin basalt units have been found near Fowlers Gap suggesting a possible tie across the Bancannia Trough, although this discovery needs to be investigated further. The volcanics may be related to an extensional event that occurred during the deposition of the Kara beds on a slowly subsiding shelf.

The laminated traction current deposited sandstones of the Kara beds are overlain conformably by turbidity current deposited sandstones of the Teltawongee beds at Teltawongee Tank on Nundora station as the shelf foundered. This exposure is in the westernmost of three belts of Teltawongee beds. The western belt is cut out by faulting to the south but continues northwest for at least 15 km beyond Packsaddle. The central belt of Teltawongee beds is about 5 km wide and extends 70 km from Wertago through Nuntherungie and Wonnaminta homesteads. The central belt is bounded to the west and east against Kara beds and Ponto Group respectively by steep thrust faults. These thrust fault boundaries have been subjected to tight folding. Further segments of this central belt occur at Wilandra and east of Scrope Range. An eastern belt of Teltawongee beds occupies a zone at least 50 km wide and 200 km long east of the Koonenberry Fault. The Teltawongee beds are interpreted as turbidity current slope deposits. Rare brachiopods, sponges, sponge spicules and a variety of worm tubes have been found, suggesting a Lower or Middle Cambrian age. Metamorphic grade is chlorite zone.

The Ponto Group is largely composed of phyllites and fine-grained indurated sandstones of distal turbiditic character. Lesser components include tholeiitic volcanic units (pillow lavas, sills and tuffs), laminated chert-like felsic tuffs and minor calcareous phyllites. Rocks of the Ponto Group are usually metamorphosed to the biotite zone but rocks of higher grade are found near Cymbric Vale. The Ponto Group occupies a narrow zone up to 5 km wide immediately west of the Koonenberry Fault, except in the Grasmere Knee Zone where it appears to be more widespread. The Ponto Group is everywhere fault-bounded against other pre-Delamerian rock units, but the group is overlain unconformably by post-Delamerian Late Cambrian sediments at Bilpa and Cymbric Vale. Limited isotopic dating and the stratigraphic relationships indicate that the Ponto Group is Middle Cambrian in age, although no fossils have been found.

The Lower to Middle Cambrian Gnalt Group is confined to the Gnalt-Mutawintji area with a possible equivalent Middle Cambrian section west of Mount Arrowsmith. The Mount Wright Volcanics and the Cymbric Vale Formation are calc-alkaline units in the base of the exposed sequence (Crawford et al. 1997). These volcanics are overlain by the shale–limestone facies of the Coonigan Formation. The age of the weakly deformed sequence is well-constrained by fossils that occupied a warm near-shore facies in a foreland setting to the Koonenberry Fold and Thrust Belt on the eastern outer edge of a calc-alkaline volcanic arc.

### THE KOONENBERRY DEEP SEISMIC LINE

In 1999 a seismic line was run for 160 km from the Adelaidean sequence on Sturts Meadows northeast across the Bancannia Trough and the whole of the Koonenberry Fold and Thrust Belt to Yancannia. This line provided some excellent images of the Bancannia Trough and of some major fault zones and deep structure within the fold belt. Modelling of gravity and magnetic signatures along the seismic line has provided further insight into the structure of the fold belt (Direen, 1998). The western end the seismic line crosses a broadly folded and weakly metamorphosed Adelaidean sequence of shales, siltstones and occasional quartz sandstones with a weak steeply dipping slaty cleavage. Modelling of the gravity here indicates that the Adelaidean thins to the west and is underlain by a denser metamorphic basement of presumed Willyama gneisses.

The Bancannia section displays a gently dipping well-layered sequence up to 6 km thick sitting on a solid basement. Intervals that may be equated with the Late Cambrian to Early Ordovician Mootwingee Group, Early to Middle Devonian Snake Cave Sandstone, Late Devonian Ravendale Formation and the Mesozoic Rolling Downs Group may be seen in the section. Low gravity over the Bancannia section reflects the thick porous sandstone fill while the strong deep magnetic signatures reflect thick volcanic parcels. It is proposed here that the Bancannia Trough was the site of a major calc-alkaline volcanic arc in Early to Middle Cambrian time and that this volcanic arc may be followed northwards into the Gidgealpa Volcanics and southwards into the southeast of South Australia.

Bedded units within the Koonenberry Fold and Thrust Belt are tightly folded and steeply dipping and are not readily detected in the seismic section. The Koonenberry Fault can be traced in outcrop for 225 km from Pulgamurtie, north of Koonenberry Mountain, to the southern end of Scrope Range as a high-level crush zone. This fault shows in the seismic record as a shear zone dipping about 55° west. Near the seismic line it slices obliquely through Delamerian structures at the surface indicating its late (Carboniferous?) origin at the present level of erosion, but it may be a reactivated earlier structure at depth. The seismic section shows a series of planar shear zones that penetrate well into the crust and either dip east or west. One of these zones comes to the surface at the mapped position of the Koonenberry Fault and it can be reasonably concluded that the Koonenberry Fault is a reverse fault dipping about 55° west. The fact that mapped early Delamerian thrusts in the stacked sequence west of the Koonenberry Fault show evidence of folding on various scales indicates that the planar shear zone we observe in the seismic section must have developed when the crust was solid and not readily deformed by folding. It is proposed here that this shear zone, along with others seen in the seismic section to the east and west, were produced under severe compression in the middle Devonian Tabberabberan tectonic event. In the Carboniferous Kanimblan-Alice Springs orogeny the Koonenberry region was subjected to an extensional or transtensional event that opened the Koonenberry Fault structure and generated a series of south-east curving branch faults, some of which acted as conduits for diatremes in the Permian. This extensional event explains the structure of Koonenberry Mountain and also accounts for the commonly observed vertical dips on surface exposures of the Koonenberry Fault and its branches.

To the east of the Koonenberry Fault the Teltawongee beds extend up to 50 km until they disappear under Mesozoic cover. Gravity modelling indicates that a large body of low-density rock is required in this area and it has been interpreted as a granitic sheet. Small granite occurrences are known to occur widely in this area.

## THE DELAMERIAN OROGENY

The grand unconformity between dipping Late Cambrian Mootwingee Group beds and tightly folded and cleaved Kara beds is well exposed east of the Turkaro Range and can leave no doubt about the magnitude of the Delamerian orogeny in this region. Other segments of this post-Delamerian unconformity are well displayed near Kayrunnera, Nuntherungie, Churinga and beneath the eastern edge of the westerly dipping Scrope Range. Near Gnalta the unconformity between the gently deformed Gnalta Group and the Mootwingee Group is lithologically clear but less spectacular structurally.

Running northeast along the seismic line the pre-Delamerian rock units are met with in order of Gnalta Group, Kara beds, Teltawongee beds and Ponto Group and this is believed to be the layout of the depositional environments at the margin of continental Australia in the Late Proterozoic and Cambrian. These rock units were not contemporaneous, the Gnalta Group and the Teltawongee beds were probably laid in part above the Kara beds. The Gnalta Group was accumulated near-shore on the eastern side of a major volcanic arc, the Kara beds were deposited on an extensive continental shelf, the Teltawongee beds were deposited on the continental slope and the Ponto Group are viewed as distal foot of slope deposits. A subduction zone was active beneath this continental margin accretionary wedge assemblage in the Early and Middle Cambrian. Eventual collision in the late Middle Cambrian resulted in cessation of the subduction and volcanic activity, telescoping by thrusting and foreshortening of the major rock units and the intense upright folding and vertical cleavage characteristic of the Koonenberry Fold and Thrust Belt. Through the Late Cambrian the fold belt was eroded by the sea from east to west to approximately the present level of erosion and two important aspects of the fold belt were revealed. Firstly the generally low-grade greenschist character right across the fold belt despite the apparent great thickness of sequence, although there are higher-grade more uplifted areas of Ponto Group near Cymbric Vale. And secondly, the intensification of fold structure from west to east with important thrusting throughout the sequence. The Gnalta Group shows open gentle folding, the Kara beds show closed to tight folding with strong slaty cleavage, the Teltawongee beds show tight to isoclinal folding and the Ponto Group has been multiply deformed with intense isoclinal folding of not only bedding but also the early slaty cleavage and quartz veins. Steep dipping thrusts with large displacement, such as the Mount Wright Fault and the various faults bounding the major rock units, were active at this time. The generally low metamorphic grade over a wide area is characteristic of an accretionary prism where successive rock packages are stacked up progressively by underthrusting towards the arc. Good examples are the accretionary prism forming above the Lesser Antilles subduction zone (Biju-Duval et al., 1982) or the Makran accretionary prism in the Gulf of Oman (Platt et al., 1985). While mineralisation associated with the pre-Delamerian rock units is not obvious traces of copper mineralisation are commonly associated with the tholeiitic volcanic units within the Ponto Group, and it has been claimed that the copper deposits mined at the Grasmere and Ponto Mines had a syngenetic origin.

## POST-DELAMERIAN EVENTS

In the Late Cambrian and Early Ordovician the shallow marine Mootwingee Group and equivalents were deposited over a marine eroded unconformity across the fold belt. Deposition began in the east (Kayrunnera) in the Mindyallan Stage of earliest Late Cambrian but may not have begun in the west until the latest Late Cambrian (Mount Arrowsmith). Some excellent marine fossils and trace fossils have been found in this sequence. The Mootwingee Group and equivalents were presumably the near shore facies of the thicker and deeper water sediments accumulating in the Wagga Trough and the Thompson Fold Belt to the east and northeast, although the possibility of exotic movements of blocks to the east of the Koonenberry Fold and Thrust Belt cannot be ruled out. The absence of Late Ordovician and Silurian rocks in the region suggests general uplift and erosion while the Silurian Benambran event produced folding, a strong cleavage and granite intrusions to the northeast of the Koonenberry Fold and Thrust Belt under northeast-southwest compression. Local intramontane basins accumulated fluvial sediments and volcanics (Mt Daubeny Formation) in the east during a latest Silurian and Early Devonian extensional event. Pebbly quartz sands of the Snake Cave Sandstone blanketed the region in the Middle Devonian, with minor marine intervals in a dominantly fluvial sequence. Major thrusting and uplift occurred after Snake Cave time, resulting in the removal of all the Snake Cave Sandstone and much of the Mootwingee Group from the central region between the Lawrence Fault and the Koonenberry Fault. A further blanketing of fluvial quartz sands occurred across the region in the Upper Devonian. The Carboniferous Kanimblan or Alice Springs orogeny brought transtension and extensional tectonics to the area with rejuvenation of movement on some earlier faults such as the Mount Wright and Koonenberry structures. Widespread steep northerly to northeasterly faults were developed at this time and are associated with Ag, Pb and Cu mineralisation at Wertago and Au mineralisation at Milparinka. There are several interesting targets and areas for investigation of mineralisation throughout the area.



## ACKNOWLEDGEMENTS

The author began working in the Koonenberry region 20 years ago under the auspices of the University of Sydney and has been involved with the Broken Hill Exploration Initiative and the NSW Department of Mineral Resources Koonenberry Mapping Program since 1995. Over this period the author has worked with numerous people who have helped to build up knowledge of this region. In the early days Evan Leitch, Barry Webby and Peter Kolbe encouraged interest in the Koonenberry region and students David Collins, Bo Zhou and Jolanta Pahl made important contributions. Since 1995 Department of Mineral Resources colleagues Barney Stevens, Michael Hicks, Ian Cooper, Peter Buckley, Joseph Ogierman, Timothy Sharp, Ian Percival, David Robson, Peter Lewis and Lindsay Gilligan have all helped build up an extensive body of knowledge. Nick Direen broke new ground in attempting a synthesis, building models of the Koonenberry Fold and Thrust Belt and making comparisons of this belt with other regions in South Australia, Victoria and Tasmania. David Gibson is acknowledged for his discussions about Mesozoic to Recent events.

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# **HIGH TEMPERATURE SHEAR ZONES OF THE CURNAMONA PROVINCE**

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## **INTRODUCTION**

The structural evolution and pre-orogenic thermal evolution in poly-deformed geological provinces impact on the timing and distribution of basin-hosted massive sulphide Pb-Zn deposits. The thermal architecture (e.g., geothermal gradient and heat distribution) influences basinal fluid migration, and the basin architecture may influence fluid pathways and chemical traps. Structural studies throughout the Curnamona Province have typically focused on the Olarian and Delamerian orogenies, and until recently there have been few studies little emphasis on the importance of pre-orogenic structures (although see Gibson, 2000; Noble and Lister, 2001; Hills et al., 2001). The oldest structures throughout the Curnamona Province have been ascribed to an episode of nappe development during the earliest stages of the Olarian Orogeny (eg. Majoribanks et al., 1980; Hobbs et al., 1984; Stevens et al., 1988). However, detailed structural analysis in the Broken Hill and Olary sub-domains has revealed the presence of high temperature shear zones that were active before the onset of regional fold development. The timing of shear zone movement is conjectural. Gibson (2000) and Noble and Lister (2001) suggest movement during basin development and deposition of the Willyama Supergroup. Alternatively, extensional shear zones may post-date deposition of the Willyama Supergroup with movement and lithospheric extension occurring shortly before the onset of crustal shortening.

Determining the timing of movement, distribution, and kinematics of these early high-temperature shear zones is critical as they may have influenced the basin architecture or the style of basin inversion and metamorphism during the Olarian Orogeny. Extensional shear zones may be associated with elevated geothermal gradients, enhanced fluid flow, and the incision of stratigraphic packages (e.g., Raetz et al., 2002).

## **COMPARISON OF HIGH TEMPERATURE SHEAR ZONES IN THE BROKEN HILL SYNFORM AND THE OLARY SUB-DOMAIN**

The structural geometry of the Broken Hill Synform area is dominated by a regional north-northeast trending, steeply south plunging fold, the Broken Hill Synform. This fold is defined by an enveloping surface that contains a high temperature shear zone. These shear zones occur within quartz-sillimanite-magnetite-rich lithologies and psammo-pelitic units of the Cues Formation and the Broken Hill Group. The shear zones are characterised by a penetrative sillimanite foliation and mineral lineation. S-C fabrics and isoclinal rootless folds comprising migmatitic melts are preserved within pelite units. There is a close spatial association between the shear zones and the distribution of pre-orogenic amphibolites.

The timing of the shear zones cannot be equivocally determined in the absence of detailed integrated structural geology and in situ, which is subject to ongoing research. However, there are several lines of evidence that support an extensional orogen for the shear zones. This evidence includes the layer parallel geometry of the shear zones, the absence of large regional fold generations associated with them, the spatial association with c. 1710-1680 Ma bimodal magmatism, which is synchronous with widespread lithospheric extension across the North Australian Craton (Giles et al., 2002).

In the Olary Sub-domain numerous high-temperature shear zones have been identified within the Wipieraminga Group (Conor, 2000) in the lower parts of the stratigraphy. These shear

zones occur within migmatitic horizons intercalated with quartzite and quartz sandstone successions. The shear zones are characterised by a well developed biotite foliation, attenuation and boudinage of competent sandstone and quartzite units, the development of asymmetric isoclinal and rootless folds, rotation of melt segregations, the development of shear bands and S-C foliations. The migmatites are characterised by a strong biotite mineral lineation and quartz stretching lineation. These shear zones are folded by the first generation of folding in the Olary sub-province, suggesting a pre-orogenic origin. The timing of shear zone movement is poorly constrained, and they may have moved during early crustal extension associated with basin development or just before the Olarian Orogeny.

## DISCUSSION

The role of high-temperature shear zones in the evolution of the Curnamona Province is still subject to much debate. The present exposure, complex overprint of later deformation and limited understanding of the distribution of the shear zones (at the scale of the province) prevents assessment of the lithospheric architecture of the province during the extension.

If the extensional movement occurred during basin development (e.g., c. 1710-1680 Ma), rapid burial of basinal sediments would be required. Lithospheric extension may have elevated geothermal gradients resulting exhumation and thermal uplift of the crust, possibly leading to depositional hiatus. However, if the high temperature shear zones were active after basin development and before the onset of the Olarian Orogeny, there is no requirement of rapid burial. Furthermore, a pre-orogenic extensional event may explain the high-temperature, low-pressure metamorphic signature of the Olarian Orogeny (Stüwe and Ehlers, 1997), which may have been inherited from the thermal regime associated with the earlier lithospheric extensional event.

## ACKNOWLEDGMENTS

This research was partly funded by the AGCRC and collaborative ARC Linkage grant between Monash University and PIRSA. We thank Martin Hand, Wolfgang Preiss, and Colin Connor for fruitful discussion about models for basin development in the Curnamona Province.

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# SHRIMP U-Pb GEOCHRONOLOGY IN THE CURNAMONA PROVINCE: IMPROVING THE FRAMEWORK FOR MINERAL EXPLORATION

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## INTRODUCTION

The acquisition of useful ages through U-Pb zircon geochronology can have cogent geological outcomes, providing that it is integrated with unequivocal field constraints, and that the assumptions behind the isotopic dating method are validated. Although we commonly think of zircon as a physically and geochemically robust mineral, imposition of closely spaced high-grade metamorphic events, such as occurred in the Curnamona Province in the Mesoproterozoic and Delamerian, can induce open-system behaviour and partial to complete loss of radiogenic Pb. Zircon that initially crystallised during protolith formation and was subsequently partly recrystallised (perhaps more than once) can develop complex isotopic characteristics. These can lead to *minimum* ages of protolith formation, *maximum* ages of metamorphic event(s), or 'blended' ages of little geological worth.

This paper broaches some of those issues. It is an attempt to enhance our understanding of the complex history of the Curnamona Province. We review recent findings, outline the objectives of our current investigations, and report initial results from a new research module begun in late 2002 as a contribution to the Predictive Minerals Discovery (pmd) CRC. Understanding the time dimension is prerequisite to a better understanding of the region's mineral deposits and formulation of predictive mineral exploration strategies.

## OUTLINE OF PREVIOUS GEOCHRONOLOGY AND OUTSTANDING ISSUES

The Broken Hill Pb-Zn-Ag orebody, the age of its host sequence, and the search for stratigraphic and metallogenic correlatives, both in NSW and SA, are a particular focus for geochronological efforts in the Curnamona Province. The overall stratigraphic integrity of the Willyama Supergroup during its depositional history between 1720-1640 Ma is confirmed by recent work (Page et al., in preparation-a). The nexus between upper Broken Hill Group depositional ages (eg. Hores Gneiss 1685±3 Ma) and model ages derived from the ore Pb growth curve for the Broken Hill orebody (Carr and Sun, 1996) is being pursued in this and other current studies (Parr et al., this volume). This connection is apparently of a stratigraphic nature, and the data so far accord with a syngenetic or diagenetic origin for the ore in the upper Broken Hill Group.

Stratigraphic correlations across the southern Curnamona Province between Broken Hill and Olary Domains are corroborated by geochronology on several units within the Willyama Supergroup (Page et al., in preparation-b). Deposition of the ca. 1710-1720 Ma Thackaringa Group rocks near Broken Hill is correlated with Curnamona Group sedimentation and igneous activity (ca. 1720-1705 Ma) in the Olary Domain. Although it appears that much of the Broken Hill Group (ca. 1695-1685 Ma) was eroded or not deposited in the Olary Domain, there remain convincing age and stratigraphic correlations between the base of the Broken

Hill Group (Ettlewood Calc-Silicate Member:  $1693 \pm 4$  Ma) and the base of the Strathearn Group (Bimba Formation and Plumbago Formation:  $1693 \pm 3$  Ma). Furthermore, in the upper Willyama Supergroup, the upper Paragon Group ( $1657 \pm 4$  Ma,  $1655 \pm 4$  Ma, and  $1642 \pm 5$  Ma) and upper Mount Howden Subgroup ( $1651 \pm 7$  Ma) can be well correlated across the Curnamona Province on the basis of lithostratigraphy and depositional ages. Much of this younger basin development in the Willyama Supergroup has age, lithostratigraphic, and sequence stratigraphic parallels with sequences in northern Australia that host the Mount Isa and McArthur River orebodies.

Irrespective of stratigraphic position, regional evidence from metamorphic zircon rims and recrystallised zircons indicates high-grade metamorphism occurred at close to 1590-1600 Ma across the Curnamona Province. This closely corresponds with the age(s) of D<sub>2</sub> and D<sub>3</sub> deformations, as reflected in emplacement ages of several dated granitoid intrusions that bracket particular deformation events. In the Olary Domain, however, evidence derived from molybdenite and monazite alteration ages in mineralised sequences suggests additional, earlier deformation and metamorphism: pre- ~1620 Ma (Skirrow et al., 2000) and pre-1630 Ma (Teale and Fanning, 2000).

Many issues remain to be resolved, and the new geochronological research addresses the following:

- Firmer age constraints for the Thackaringa and Curnamona Groups are being sought using high-grade felsic rocks to date the Cues Formation near Broken Hill and stratigraphically controlled felsic units to date the Wiperaminga and Ethiudna Subgroups in the Olary Domain. This should show whether different, stratigraphically consistent, depositional ages can be resolved within the lower Willyama Supergroup, and whether any significant time breaks are recorded. It is hoped to link Cues Formation stratigraphic ages with Pb isotope studies, particularly those on the Pinnacles mineralisation.
- Several granitic gneiss bodies (eg. Rasp Ridge Gneiss, Alma Gneiss) that may have contributed to the heat source and circulation cells at the time of formation of the Broken Hill orebody are being examined, as are amphibolites associated with base-metal mineralisation at Silver King, and possible Broken Hill Group equivalents (Potosi gneiss lithologies) in the east Mingary region of South Australia.
- Metasiltstones in the lower Paragon Group (Cartwrights Creek Metasediments) are being dated to fill a major gap in knowledge of the Willyama Supergroup, especially in relation to comparisons with Mount Isa and other northern Australian sequences.
- Further work on paragneisses in the southern Redan Block, which is reported below.
- Additional dating of younger granites in the Broken Hill Domain (Umberumberka- and Champion-type) and various granites in the Olary Domain (Lady Louise Suite, Poodla Hill, Rock Wallaby, Antro, etc.) is aimed at refining their emplacement ages. These granite ages are to be utilised to provide local 'age control points' for Pb isotope evolution, so that the timing of hydrothermal events in the Curnamona Province may be better evaluated (eg. Parr et al., this volume).
- A distinctive, biotite-speckled psammite immediately below the Bimba Formation is being examined to determine whether the Bimba, a regionally important mineralised marker, belongs within the Curnamona (>1700 Ma) or Strathearn Group (<1693 Ma).
- Dating of structurally early (D<sub>1</sub>) migmatitic melt phases in the Curnamona Group, should resolve whether these melts formed during the ~1600 Ma Olarian orogeny or (as proposed by some) much earlier in the basin evolution.

## NEW GEOCHRONOLOGICAL RESULTS

Redan zone. Layered paragneisses in the eastern Redan Block (southeastern Broken Hill Domain) have been interpreted as “trondhjemitic” gneisses representing an original ~2650 Ma protolith that was basement to the Willyama Supergroup (Nutman & Ehlers, 1998). Our work, however, indicates complex spectra of zircon provenance ages typical of most ~1700 Ma metasediments in the Curnamona Province and other Australian Palaeoproterozoic settings.

Further zircon SHRIMP results from calc-albititic gneisses in the southern Redan area tighten those constraints. We confirm that these layered paragneisses (quartz-plagioclase-amphibole-epidote-magnetite-sphene) were deposited about 1705-1710 Ma ago – and hence are of the same age as the Thackaringa Group. This conclusion is based on reinterpretation of data collected by Love (1992) and new data on other calc-albititic gneisses, some of which we interpret as metavolcaniclastic rocks and immature metasediments. This allows us to directly date the sequence, and demonstrates lithostratigraphic and age equivalence between gneisses of the Redan Block and ca. 1710 Ma calc-albititic metasediments and metavolcanics of the Ethiudna Subgroup in the Olary Domain. A felsic intrusive in the eastern Redan Block near Farmcote has ages ( $1703 \pm 3$  Ma and  $1704 \pm 3$  Ma) that are in accord with the age of its ca. 1710 Ma host sequence, and provides a further parallel with A-type magmatism of this age in the Olary Domain.

Lower Strathearn Group metasediments. If immature sediments immediately below the Bimba Formation in the Olary Domain are in part volcanoclastic, zircon dating should better constrain the age of this regionally important mineralised marker. However, no volcanoclastic component has yet been found to reliably date this part of the sequence. Preliminary results from the youngest detrital zircons indicate that this immature psammite horizon is no older than 1705-1700 Ma. Given the well constrained age of volcanoclastic rocks in the Plumbago Formation, both the Bimba Formation and this underlying immature psammite package must have depositional ages between 1705-1700 Ma and  $1693 \pm 3$  Ma.

Granitic magmatism across the Curnamona Province. Effort to understand granite ages is focussed on intrusions that are thought to exemplify the range of magmatic history in the Olary Domain, and a few late granitoids in the Broken Hill Domain. The well known ~1710 Ma Basso Suite 'A-type suite' (Ashley et al., 1996) in the Olary Domain has coeval counterparts near Broken Hill (Alma Gneiss, etc.) and in the Redan Block. The youngest (~1590 Ma) S-type anatectic granites in the Olary Domain are comparable in age to the Mundi Mundi Suite at Broken Hill. Our new SHRIMP zircon ages confirm this division of ~1710 Ma and ~1590 Ma granite ages in the Olary Domain, but offer no support for the I-type felsic magmatism reported by Fanning et al. (1998) at between 1640 and 1620 Ma.

The new work extends the ~1710 Ma-Basso suite components to include granitoid bodies in the northern Walparuta Inlier and the deformed part of the Rock Wallaby granite complex southeast of Triangle Hill. Additionally, at least part of the supposed I-type Poodla Hill granite has a Basso Suite crystallisation age (like the nearby Poodla Dam granite reported by Ashley et al. (1996) at  $1717 \pm 14$  Ma). Other designated I-type granitoids, hitherto considered to be 1640-1620 Ma old and canvassed as possible heat sources for Olary Cu-Au mineralisation, have been found to be part of either the 1685 Ma-Lady Louise suite (eg. Antro 'adamellite') or part of the younger, 1580-1590 Ma Mundi-Mundi type (younger, undeformed granite of the Rock Wallaby granite complex). Similarly young ages, comparable to the 1580

Ma ages reported by Ludwig and Cooper (1984) at Crocker Well, are determined for undeformed granitoids in the southeastern Walparuta Inlier. Dating of these various granitic types thus extends the geographic spread and significance in the Olary Domain of Lady Louise suite ages (akin to Broken Hill Group ages) but offers no geochronological support for a metallogenically significant phase of 1640-1620 Ma felsic granitoid intrusion.

## ACKNOWLEDGEMENTS

Published with approval of the Director-General, NSWDMR, the Executive Officer, MER-PIRSA, and the Chief Executive Officer, GA.

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# TIMING OF MULTIPLE HYDROTHERMAL EVENTS IN THE BROKEN HILL TERRANE - EVIDENCE FROM LEAD ISOTOPES

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## INTRODUCTION

Lead isotopes can be used in metalliferous exploration to distinguish and characterise different hydrothermal events. Interpretation of the timing of mineralisation in relation to the host rock lithologies is most effective where data are measured for geologically well-constrained samples. By using Pb isotopic data for “granites” in the region we can also construct a growth curve that allows us to give meaningful ages to the ore deposits.

The aims of this project are to distinguish and characterise different hydrothermal events for the Curnamona Province and to place those events in a regional geochronological framework based on a new Pb isotope growth curve. In the Curnamona Province there already exists a moderate-sized database of Pb isotope analyses (~250 samples), mostly from the Broken Hill line of Lode and gathered over ~20 years (Carr and Sun, 1996). We have significantly expanded this database with geologically and geographically well-constrained samples. We have also sampled granites with known U-Pb zircon ages in order to determine a Pb isotope growth curve. The new model will be released at the BHEI meeting.

A major development in the Pb isotope analysis has been the introduction of a double spike technique. This technique, which is being further developed at CSIRO, uses the rare <sup>202</sup>Pb and <sup>205</sup>Pb isotopes to spike samples and obtain data with a high degree of accuracy (Figure 1). Consequently, it has great potential to differentiate between more subtle ore-forming signatures and, combined with the new growth model, to give accurate Pb-Pb ages for mineralisation. New double spike analyses will be presented and discussed at the BHEI meeting.

## LEAD ISOTOPE DATA

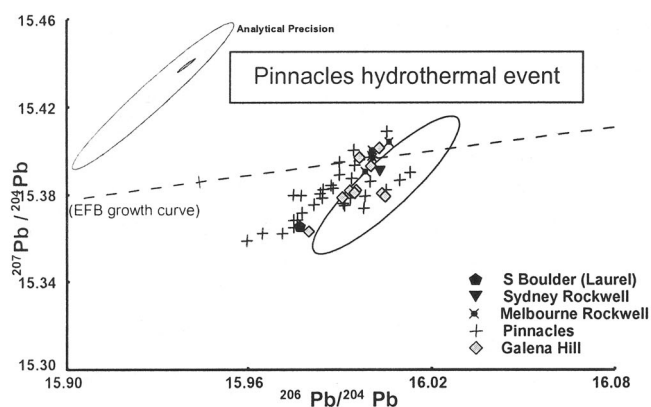
Over 80 new Pb isotope data presented here include 6 double spike analyses. Galena has been sampled from a wide variety of ore deposits in the Broken Hill Block. Conventional and double spike Pb isotope analyses were measured using a VG354/S mass spectrometer.

The data are shown on <sup>207</sup>Pb/<sup>204</sup>Pb vs. <sup>206</sup>Pb/<sup>204</sup>Pb plots (Figures 1 to 3). They can be grouped according to their radiogenic <sup>206</sup>Pb/<sup>204</sup>Pb content. The growth curve used on these plots is that derived for the Mount Isa Eastern Fold Belt (Carr et al., *in prep.*) since, until a Curnamona-specific one is derived, this is probably a best approximation.

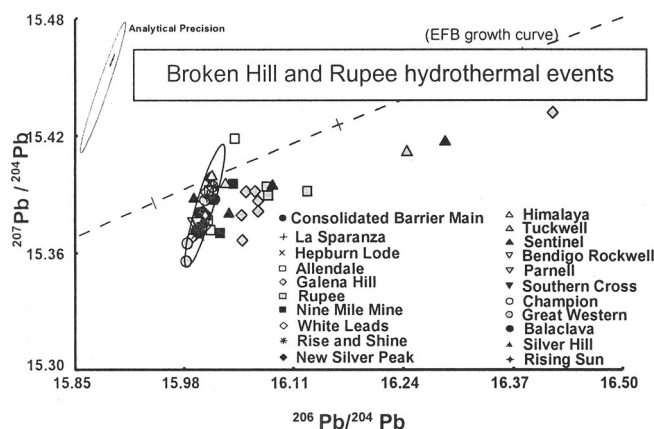
Overall, the spread of data indicate that the Broken Hill Block was characterised by a long history of episodic hydrothermal activity. The main hydrothermal events that can be identified are listed in Table 1 and the stratigraphic distribution of the deposits analysed shown in Figure 4.

The Pinnacles orebody has an isotopic signature that suggests formation of the orebody ~10Ma before the Broken Hill orebody (Figure 1). Representatives of the **Pinnacles hydrothermal event** are also found in the Broken Hill Group (Melbourne Rockwell, Sydney Rockwell and Laurel). One possible model to explain this distribution is the inhalative formation of the Pinnacles deposit synchronous with exhalative mineralisation in the other deposits during deposition of the Allendale Metasediments (1691 ±3 Ma; Page et al., 2000).

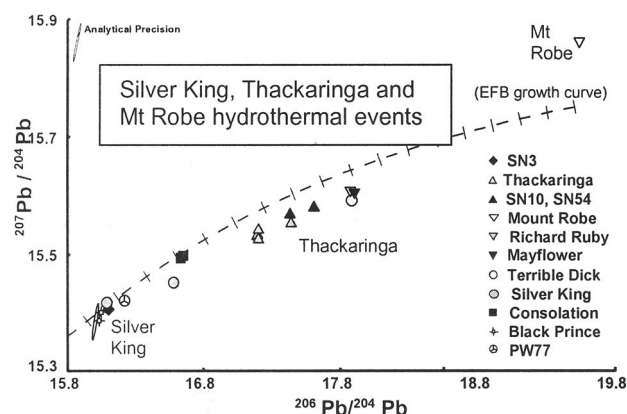




**Figure 1.** Lead isotope ratio plots showing data for deposits with a Pinnacles hydrothermal event signature. Analytical precision for conventional Pb isotope analyses is shown top left; the much smaller ellipse inside that is the analytical precision for double spike analyses. The growth curve is the CSIRO model curve for the Mount Isa Eastern Fold Belt and the ellipse is the Broken Hill orebody signature.



**Figure 2.** Lead isotope ratio plots showing data for deposits with a Broken Hill hydrothermal event signature. The ellipse is the Broken Hill orebody signature.



**Figure 3.** Lead isotope ratio plots showing data for deposits with Silver King, Thackaringa and Mt Robe hydrothermal event signatures. The ellipse is the Broken Hill orebody signature.

In addition to Broken Hill itself, deposits with a BH-type isotopic signature (Broken Hill event, Figure 2) are stratigraphically equivalent and below the main Broken Hill orebody (Hores Gneiss:  $1686 \pm 3\text{Ma}$ ; Page et al., 2000). This scatter of deposits throughout the Broken Hill Group associated with one hydrothermal event suggests that the hydrothermal system that provided Pb for the Broken Hill orebody was long lived and/or permeated sediments in the underlying rocks. Deposits with both Broken Hill and Pinnacles signatures have all been classified by the survey as BH-type (Barnes, 1988, Burton, 1994) - that is stratiform Pb-Ag-Zn sulfide mineralisation in quartz-gahnite, garnet-quartz rocks.

The Broken Hill orebody itself has always been described as isotopically homogeneous (eg Carr and Sun, 1996). However, preliminary double spike analyses have identified isotopic variation between the stratiform lenses and the dropper zone (No. 1 lens), which has a slightly elevated  $^{206}\text{Pb}/^{204}\text{Pb}$ . The data suggest that the dropper zone either represents:

An isolated hydrothermal event,  $\sim 7$  my later, with Pb from a slightly younger crustal(?) source,  
Mixing and overprinting of Broken Hill Pb with younger Pb during a subsequent hydrothermal event (Rupee hydrothermal event?),  
Minor mixing and overprinting of Broken Hill Pb with significantly younger Pb during deformation and metamorphism.

The Rupee hydrothermal event is characterised by a group of deposits that have slightly more radiogenic signature than the Broken Hill orebody (Figure 2). In effect they form a "tail" to the BH signature and may therefore represent the gradual petering out of the dominant BH event.

Samples from Galena Hill (galena hosted in quartz veins) have a bimodal signature (Figures 1 and 2). The less radiogenic signature is similar to that of the Pinnacles hydrothermal event, whilst the more radiogenic signature is similar to the Rupee event. The spread of data could represent later remobilisation and mixing with younger Pb (crustal source?), or overprinting of the existing mineralisation by the younger Rupee event.

The **Silver King Hydrothermal event** is characterised by a variety of ore deposits scattered throughout the Broken Hill Group (Figure 4), which include examples of Silver King, Broken Hill, Sisters, Corruga and Ettlewood calc-silicate type deposits (Barnes 1979). The isotopic signature

covers a range of  $^{206}\text{Pb}/^{204}\text{Pb}$  ratios (Figure 3) and probably represent a hydrothermal event that involved mixing of Broken Hill age Pb and younger Pb. Given the spread of data parallel to the growth curve (even if the Consolation deposit is not included, Figure 3), it is likely that hydrothermal fluids associated with this later event leached BH-type Pb from the rocks to varying degrees and this was mixed with a more radiogenic Pb source from low-Pb source rocks during the younger hydrothermal event. We cannot yet constrain the age of this event.

Thackaringa and Mt Robe vein-type deposits associated with retrograde shear zones (Barnes, 1979) have the most radiogenic Pb isotope signature (Thackaringa and Mt Robe hydrothermal events, Figure 3). However, the data still lie along a linear array suggesting that these late stage veins also derived some of their Pb from pre-existing mineralisation.

**Table 1.** Summary of hydrothermal events as defined by Pb isotope signatures

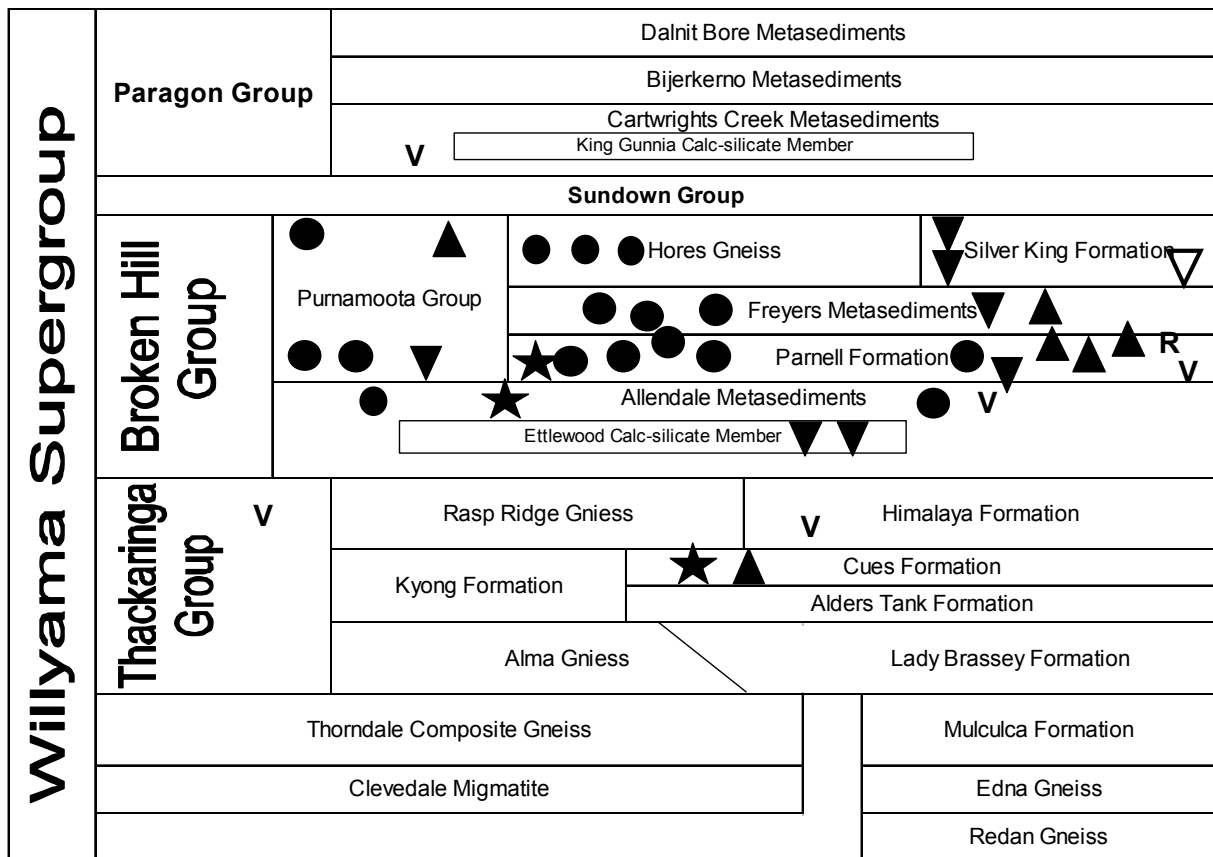
HYDROTHERMAL EVENT	COMMENTS	STRATIGRAPHIC DISTRIBUTION
<i>Pinnacles Event</i>	Pre-dates BH event by ~10 Ma, dominated by Pinnacles deposit	Cues Fm (Pinnacles) to Parnell Fm. Galena Hill vein system has dual Pinnacles-Rupee signature.
<i>Broken Hill event</i>	Homogeneous signature (except for Dropper zone –see below)	Broken Hill group (exclusively).
<i>Rupee Event</i>	“tail” to the BH event – gradual weakening of the main hydrothermal event?	Mostly Freyers Metasediments and Parnell Fm, with one (Sentinel quartz-magnetite) in the Cues Fm.
<i>Silver King Event</i>	Spread over a significant range – mixing of Pb sources?	Allendal Metasediments to Silver King Fm (not in Hores Gneiss). Variety of deposit style including Ettlewood Calc-silicates.
<i>Consolation Event</i>	Single deposit – possible mixing	Silver King Fm.
<i>Thackaringa Vein Event</i>	Consistently elevated $^{206}\text{Pb}/^{204}\text{Pb}$ ratios consistent with formation after the peak of deformation and metamorphism	Thackaringa Group, Broken Hill Group and Paragon Group. All vein-type deposits, except Curruga-type Esmeralda
<i>Mount Robe Event</i>	Highly radiogenic Pb isotope signatures – consistent with post Adelaidean age	Late stage veins in Parnell Fm.

## ACKNOWLEDGEMENTS

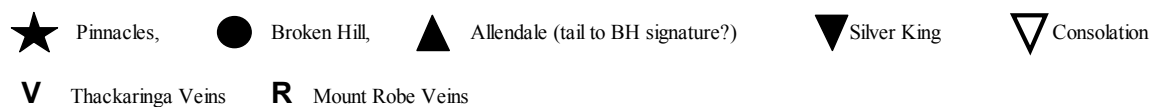
We thank Tony Webster (University of Tasmania) and Jane Murray (Perilya) for providing samples from the Broken Hill Orebody and the Line of Lode. Published with permission of the Director of the Predictive Mineral Deposits Cooperative Research Centre (pmd\*CR) and the Director General of the New South Wales Department of Mineral Resources.

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**Figure 4.** Stratigraphic diagram with deposits analysed in this study as characterised by their Pb isotope signature



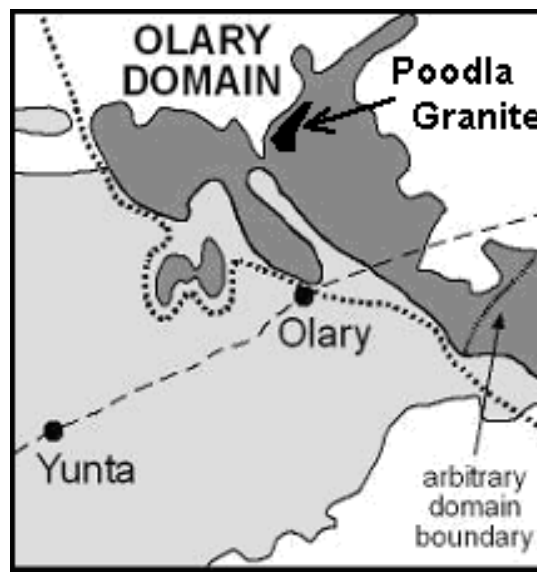
# FLUID MIGRATION – ALTERATION – MINERALISATION OF THE POODLA GRANITE IN THE TECTONOTHERMAL FRAMEWORK OF THE OLARY DOMAIN

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Granitic magmatism in the Olary Domain is an important facet of the tectonic evolution of this Late Palaeoproterozoic Terrain. Whilst some granite suites (the Bimbowrie Suite) are clearly intra-crustal (S-types) and reflect the prevailing thermal regime, others are at least partly mantle-derived and are part of the primary cause of crustal metamorphism. These latter granites are conventionally referred to as I-types and as yet are not well characterised in this setting. The object of this study has been to improve this understanding, enabling us to confidently place these suites in their correct context within the tectonothermal framework of the Olary Domain. Most of this work has dwelt on the Poodla Granite that is located on the south-eastern edge of the Telechie Valley, approximately 8km NNE of the Bimbowrie homestead (Figure 1). The I-type affinities (Benton, 1994) of this granite are similar to bodies at Tonga Hill and in the Antro Woolshed area, with which it is grouped.

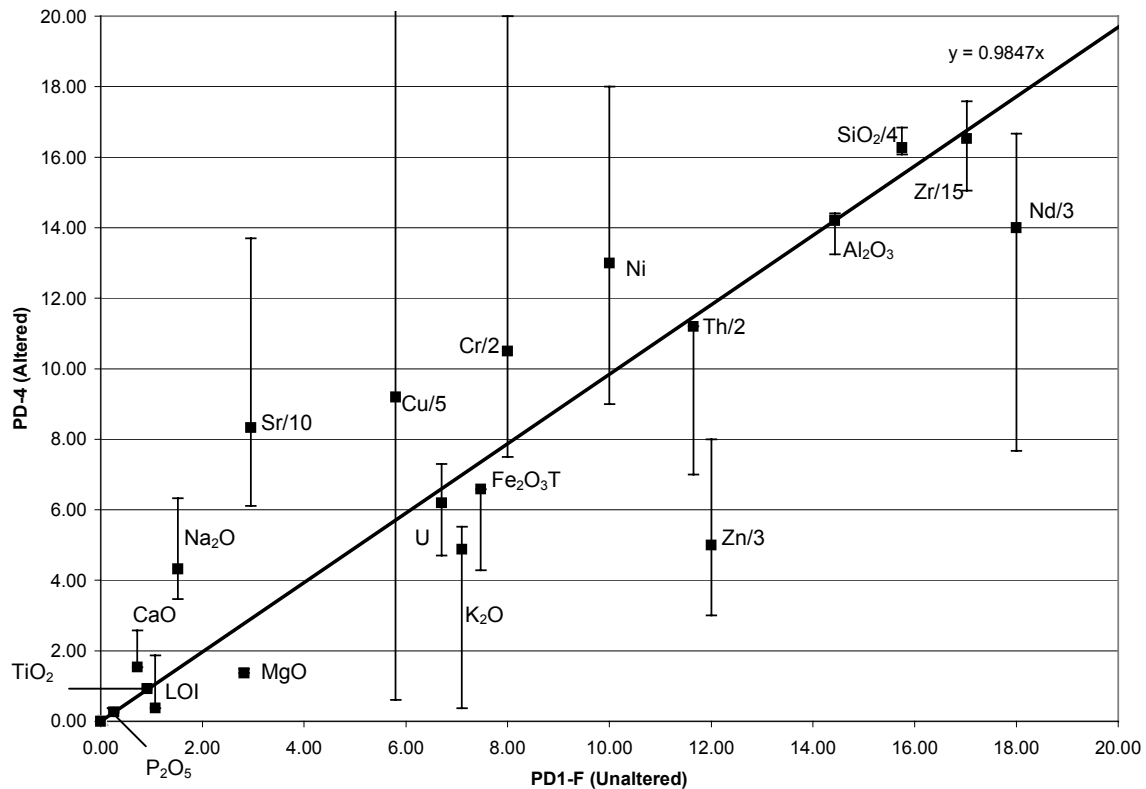


**Figure 1** – Map of Curnamona Province showing location of Poodla Granite (Modified from Robertson *et al.*, 1998)

By investigation of the relative timing of alteration, mineralisation and structural/microstructural characteristics of the granite and its host metasedimentary sequences, we have erected a framework of the timing of intrusion and ensuing hydrothermal events. The Poodla Granite has undergone alkali (Na, K) and calc-silicate alteration, and localised brecciation. Characterisation of these alteration events has been based upon mass balance, fluid inclusion and petrographical investigations. These studies have established links between mineralization and brecciation.

Pearce Element Ratio (PER) diagrams are used to determine mass balance during the alteration of the Poodla Granite. This has allowed to distinguish between the geochemical variation due to alteration from magmatic differentiation processes. Application of the Isocon approach (Grant, 1986) provides further quantitative information about mass transfer during alteration for all elements analysed. Figure 2 shows the isocon diagram for an unaltered sample (PD-1F), and a sample that has undergone sodic alteration (PD-4), error bars indicate the range of compositional variation in all samples. This shows an increase in Na, Ca, Sr and SiO<sub>2</sub> concentrations and a decrease in K, Mg, Fe, Zn and Nd as a result of alteration. Some elements, such as Cr, show variation due to alteration that readily distinguishes the types of

alteration undergone by a sample. In the case of Cr, alkali alteration results in an addition of Cr, while calc-silicate alteration removes Cr. Indicators such as this are combined with petrographical observations to characterise the effects of individual types of alteration within the granite.



**Figure 2** – Isocon Diagram of Unaltered (PD1-F) and Altered (PD-4)  
Error bars show range of all analysed altered samples

The tectonothermal setting of the granite can then be inferred from the relationships between the alteration and deformation. This is expected to lead to indications of possible fluid sources and fluid movement mechanisms which can be applied on a regional scale.

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## **CML 7 (THE SOUTH MINE), BROKEN HILL, AUSTRALIA**

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### **INTRODUCTION**

The Palaeoproterozoic Willyama Supergroup at Broken Hill comprises a rift sequence dominated by metasediments. Felsic magmatism occurred at 1700-1710 Ma and bimodal felsic-mafic magmatism at 1680-1690 Ma was coeval with ore deposition. The sequence has undergone intense nappe-style folding (F1) coeval with granulite facies metamorphism at 1590-1600 Ma and isoclinal folding coeval with granulite facies metamorphism at 1590-1600 Ma. Retrogression and minor folding (F3) occurred after 1570 Ma, with a thermal resurgence at 1100-1200 Ma, dolerite dyke intrusion and retrogression at 830 Ma and retrogression, shearing and refolding (D4, D5) at 470-505 Ma. Uplift, brittle deformation and deep weathering occurred in the Cretaceous and Tertiary during which time 80 Mt of the Broken Hill orebody was removed from a mass that was originally >300 Mt of massive sulphides. The Broken Hill orebody comprises Lead Lodes (No 3 and No 2 lens) and Zinc Lodes (Upper and Lower No 1 Lens, A Lode, B Lode and C Lode) associated with garnet, blue quartz, quartz-spessartine, quartz-gahnite and plumbian orthoclase rocks termed lode horizon rocks.

The original discovery of 'the broken hill' was in the centre of CML7 and since that time in 1883, some 57Mt of Lead Lode ore has been removed. Consolidated Broken Hill Ltd has undertaken a diamond drilling program of the Zinc Lodes and Lead Lodes at South Hill (5000 series drilling), the Western Mineralisation (4000 series drilling) and Lead Lodes at Browne-Marsh Shafts (2000 series drilling). The Zinc Lodes in Kintore and Blackwood Pits and the Lead Lodes in Kintore, BHP and Block 14 Open Pits have been evaluated.

### **THE WESTERN MINERALISATION**

The Western Mineralisation was discovered in 1913 and comprises an unmined mass of Zn-Pb-Ag sulphide ore of strike length at least 2.2 km. A systematic program to upgrade resources along a 1.1 km strike length of the Western Mineralisation has been completed. The resource calculated on a 1.7 km strike length using some earlier CRAE drilling has now been upgraded to 16.7 Mt of 3.2% Zn, 2.2% Pb and 26g/t Ag (at a 2% [Zn+Pb] cutoff) from 4.6 Mt at 4.1% Zn, 2.8% Pb and 33 g/t Ag (at a 2% [Zn+Pb] cutoff). The latest drilling supports earlier widely-spaced historical drilling that outlined more than 28 Mt of mineralisation to a vertical depth of 850 m. Drilling of the Western Mineralisation showed a southerly-plunging mass that pinches and swells at 100-350 m below surface in the north and 600-850 m below surface in the south. The Western Mineralisation is open up dip, down dip, to the north and to the south. Geological interpretation of the latest drilling data shows that the Western Mineralisation occurs in the stratigraphic position of the Zinc Lodes. On CML7 the Zinc Lodes are unmined, exposed in Kintore and Blackwood Open Pits, mapped as gossans and have been intersected in the 5000 series drilling. This interpretation suggests that there is a zone of unmined and undrilled Zinc Lodes from the surface to 300 m depth over a strike length of at least 2.5 km on CML7. Weathering of the Zinc Lodes is to a depth of 30 m. The Tonnage of the Western Mineralisation is controlled by stratigraphy and elevated grades probably result from dilation created by W-plunging F3 antiforms.

Oriented drilling and resultant lithological logging, stratigraphic and structural studies show that the Western Mineralization occurs on the overturned limb of an F1 structure on the western limb of the Broken Hill Antiform. Rocks from the upper part of the Thackaringa Group and the Broken Hill Group were intersected in drilling as well as transgressive retrograde schist zones, dolerite dykes and carbonate-filled fractures. The Western Mineralisation is predictable, it occurs 20-40m above the stratigraphic top of the distinctive Unit 4.6 Pelite. It occurs in upward coarsening psammopelites of the Hores Gneiss. Stratigraphically beneath the Western Mineralisation are garnet-bearing amphibolite, plagioclase psammite and felsic gneiss. These garnet-bearing rocks, commonly called Potosi Gneiss and 'potobolite' at Broken Hill, transgress stratigraphy, garnet amphibolite is better developed on the stratigraphic top of amphibolite masses and garnet amphibolite merges into brecciated calc-silicate rock. It is interpreted that these garnet-bearing rocks derive from pore-metamorphic hydrothermal alteration resulting from the intrusion of mafic tholeiitic volcanics into wet sediments. This alteration is probably coeval with ore deposition. No syn-D1 alteration was recognised although it is acknowledged that layer parallel garnet-, quartz- and quartz-gahnite rich rocks may represent syn-D1 alteration. Syn- or post-peak D2 spessartine-quartz  $\pm$  pyrite alteration has overprinted crenulated sillimanite and varies from slight to complete replacement of metasediments in the structural hanging wall (i.e. stratigraphic footwall). It occurs sporadically in the structural footwall. Isocon diagrams show the addition of Mn, Fe, F and S during post-peak D2 alteration. This post peak-D2 alteration is equivalent to a similar but more oxidised alteration event in the Olary Block (e.g. Cathedral Rock). Pseudomorphous and shear zone controlled retrogression overprints the Western Mineralisation.

The Western Mineralisation is a stratabound zinc-rich sulphide mass, comprising three units, a quartz-gahnite-bearing unit (equivalent to C Lode), a hedenbergite-rich unit (equivalent to B Lode) and a spessartine  $\pm$  rhodonite-rich unit (equivalent to A Lode). Sulphide rocks occur as stringers, disseminations, remobilised breccia ore and in syn-metamorphic quartz veins. High grade metamorphism (D1, D2) has produced coarse grained assemblages comprising granoblastic undulose blue quartz with fracture-controlled galena inclusion trails; poikiloblastic euhedral pyrrhotite garnet with quartz, sillimanite and sulphide inclusions; granoblastic ferroan sphalerite with hexagonal pyrrhotite and chalcopyrite exsolution lamellae; granoblastic argentian galena; poikiloblastic ferroan gahnite with inclusions of quartz and sulphides; ferroan biotite with minor zircon and apatite inclusions that define both S1 and S2; layer-parallel sillimanite (S1) crenulated during D2; and rare plumbian orthoclase.

During D3 and later retrograde events, minerals in the Western Mineralization have undergone partial replacement and retexturing. Galena has been partially replaced by phyllosilicates and biotite and chlorite have been partially replaced by galena. Galena  $\pm$  pyrrhotite veinlets transgress garnet, sphalerite and plumbian orthoclase. Sphalerite has been partially replaced by gahnite and phyllosilicates, gahnite has been partially replaced by phyllosilicates and sphalerite, especially where in contact with sulphides, and pyrrhotite garnet rims grew on ferroan gahnite. Hexagonal pyrrhotite was partially inverted to monoclinic pyrrhotite, galena cleavages were deformed, galena was retextured into a subgrain pattern and argentian tetrahedrite has decomposed to chalcopyrite and gudmundite. Pseudomorphous sericite replacement of sillimanite, biotite and feldspar occurred during retrogression. Brittle deformation, possibly of Tertiary age, has produced transgressive veinlets of siderite-neotocite-argentian galena that contain carbon of biological origin. Lead isotopes of the Western Mineralisation fall in the same range as lead isotopes from the Main

Line of Lode. The Western Mineralisation chemistry suggests that there is no clastic component to the ore and the REE geochemistry of the Western Mineralization is similar to that of modern submarine hydrothermal metalliferous precipitates. However, the abundance of Fe-dominated pre-metamorphic alteration and the paucity of S in Broken Hill ores suggest that the ore fluids contained little or no seawater, a source of Mg and S during submarine hydrothermal alteration. The textural, mineralogical and chemical re-equilibration of Broken Hill sulphide rocks during a long history of multiphase deformation and metamorphism has allowed syn- and post-D1 genetic models to thrive in the absence of drill core, underground and field data.

### **THE ZINC LODES**

The Zinc Lodes on South Hill intersected in the 5000 series oriented drilling comprise the downward-facing limb of an F1 fold of the western limb of the Broken Hill Antiform. C Lode comprises a number of stratabound quartz-gahnite masses within which higher grade Zn>Pb ore occurs (possibly along S2) and B Lode comprises thickened masses of high grade breccia ore in a S-plunging S2 monocline, the up-plunge extension of the antiformal B Lode bulge. Stringers of sulphides may represent the stratigraphic equivalents of A Lode and 1 Lens. In Kintore Pit, A Lode crops out as a mass of high grade sulphide rock showing spessartine-quartz clasts. The Zinc Lodes show a long history of textural re-equilibration, remobilisation on all scales from thickened fold hinges to micro-scale and slight partial replacement of sulphides, silicates and spinel by sulphides and phyllosilicates. The Zinc Lode chemistry suggests that there is a clastic component to C Lode suggesting either replacement or competing chemical and clastic sedimentation and the REE geochemistry is similar to that of modern submarine hydrothermal metalliferous precipitates

### **THE LEAD LODES**

On CML7, the Lead Lodes have been weathered to a depth of 120 m and have been mined for cerussite, anglesite, silver halides and native silver. The No 2 Lens (Lead Lode) was intersected in drilling at South Hill and in the Browne-Marsh Shaft areas and both No 2 and No 3 Lenses occur as fresh sulphide masses in Block 14 Open Pit. In drill holes, the No 2 lens ore comprises coarse grained galena>sphalerite>calcite which, near the margins of sulphide masses, is brecciated and contains clasts of spessartine-rich rocks. In Block 14 Pit, No 2 Lens contains abundant rhodonite and No 3 Lens contains abundant spessartine. The No 3 Lens is stratigraphically overlain by spessartine-quartz-chalcopryite-löllingite rocks of possible alteration origin, the No 2 Lens is enveloped by plagioclase psammite and quartz-spessartine boudins are common in the No 3 Lens.

In Block 14, the Broken Hill Antiform is well exposed. Lead Lode ore occurs on the western and eastern limb (Eastern Mineralisation) of a F2 structure, the high metamorphic grade Main Lode Shear which transects the eastern limb of the Broken Hill Antiform is coplanar with S2 and S2 axial plane galena droppers have been mined. Galena droppers, presumably S2, have been intersected in drilling on the 1000' level beneath the floor of the Block 14 Open Pit. The Broken Hill Antiform has been overprinted by open F3 structures with axial plane cracking and quartz veins. The floor of Block 14 show an egg carton structure with F2 folds plunging both south and north and the F3 folds plunging both east and west. In Blackwood Pit, the Main Lode Shear has been intersected by a high grade shear zone and in Block 14 Pit, the Main Lode Shear has been intersected by a quartz-galena-spessartine-bearing shear zone. In Kintore Pit, the Main Lode Shear comprises a retrograde mineral assemblage.



Where the Lead Lodes have been transposed into the Main Lode Shear, the margins of the Lead Lodes comprise a garnet rim enveloped by retrograde silicate mineral assemblage and the high metamorphic grade Main Lode Shear has bifurcated into sulphide-bearing retrograde shear zones. In proximity to the Zinc Lodes, evidence for D1 and D2 is universal whereas within 10 m of the Lead Lodes, there is not only evidence of D1 and D2 but there is a long history of sulphide rock remobilization and associated retrogression unrelated to mine- or regional-scale structures suggesting that the rheological properties of the galena-rich Lead Lodes during deformation created local structures. The Lead Lodes show a complex history recrystallisation, textural re-equilibration, inversion of hexagonal to monoclinic pyrrhotite, remobilisation of galena, chalcopyrite and pyrrhotite and slight partial replacement of sulphides and silicates by sulphides and phyllosilicates. Tetrahedrite has invariably decomposed to chalcopyrite and gudmundite and rare sulphosalts were observed. The Lead Lode chemistry suggests that there is no clastic component and the REE geochemistry is similar to that of modern submarine hydrothermal metalliferous precipitates.

#### **ACKNOWLEDGMENTS**

This project has been supported by Consolidated Broken Hill Ltd with additional geological input provided Mike Barr, Bob Besley, David Groombridge, Charlie Georgees, Kate Kitchen, Pete Kitto, Colin Lutherborrow, Tim Sproal and Richard Tully.

# **THE NACKARA ARC: GEOLOGICAL FRAMEWORK AND MINERAL POTENTIAL**

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The Nackara Arc (NA), an arcuate belt of folds in Neoproterozoic and Cambrian sediments of the Adelaide Geosyncline (AG), formed during the 0.5 Ga Delamerian Orogeny (Preiss, 1987, 2000), as part of a larger orogenic system extending from the Transantarctic Mountains to the Koonen-berry Belt of NSW and beyond. Widespread gold and copper occurrences of various associations, including skarn mineralisation, numerous kimberlites and diamond indicator minerals, as well as several industrial mineral commodities, all point to the economic potential of the Nackara Arc.

## **MINERAL POTENTIAL OF THE NACKARA ARC**

Historical gold mines are scattered along the NA, commonly associated with but not restricted to particular stratigraphic horizons, but whether these reflect sedimentary accumulations or hydrothermal mineralisation in favourable structural and lithological sites is uncertain. There are also alluvial gold deposits in Cainozoic sediments. The Wadnaminga Goldfield may be related to hydrothermal fluids associated with the nearby Anabama Granite. At the Blue Rose prospect, ~3 km north of the granite, mineralisation has been described as 'skarn type'; follow-up drilling is planned by Giralia Ltd, after promising intersections of '41m @ 1.62% Cu from 9 m' and '48 m @ 1.01 gpt Au and 0.82% Cu from 84 m' (Mining News, 31 March 2003).

The 'axial zone' (point of maximum curvature) of the NA has recently seen renewed exploration interest, with Range River Gold, Novec, and AngloGold holding ELs. Range River Gold have reported 'a large mineralised alteration system with potential to produce sediment-hosted gold, and intrusion-related sediment-hosted iron oxide copper gold deposits' (Mining News, 31 March 2003). Connor (1987) identified sericite alteration associated with gold mineralisation in the Appila Tillite at Mount Grainger in this 'axial zone'.

Curtis (2003) outlined the Nackara Regional Diamond Indicator Mineral Anomaly, a zone of known kimberlites and indicator minerals identified in surficial sediments in the NA, and related kimberlites to NW-trending fractures and strike-parallel 'macrofaults'. Primary control of kimberlite distribution may well be the deep-seated fracturing and attenuation of the basement associated with the earliest rifts (now deeply buried) in the AG. An understanding of the tectonics of the NA will be essential for effective exploration.

## **TECTONIC FRAMEWORK**

The NA is gradationally separated from the dome-and-basin fold style characteristic of the central Flinders Ranges to the north, and from the Fleurieu Arc (FA) to the south. Together, the NA and FA form an apparently continuous sigmoidal belt of long anticlines and synclines of variable plunge stretching from Kangaroo Island to the NSW border. The tectonics of the NA can be inferred only after consideration of its pre-sedimentary, syn-sedimentary and post-depositional deformation history, as its tectonic controls are deep-seated and not immediately apparent from present fold trends.

The *Gawler Craton* (GC) is the stable Precambrian sialic crust lying to the west of the NA. Long after cratonisation (by ~1.5 Ga), the mafic Gairdner Dyke Swarm (827 Ma) was intruded during the first Neoproterozoic extension event. Platform sedimentation of the Stuart Shelf commenced later (~0.7 Ga). The *Torrens Hinge Zone* (THZ) is a meridional zone of tectonic transition between the stable GC and the folded sediments of the AG, with intermediate sediment thicknesses and degrees of deformation. The NNW-SSE trending G2 corridor, possibly a zone of basement fracturing, runs obliquely across the eastern GC, (localising Olympic Dam, Mount Gunson and Emmie Bluff mineralisation), and thence across the THZ and AG to the Padthaway Ridge in the southeast of SA.

The *Curnamona Province* (CP) of late Palaeoproterozoic to early Mesoproterozoic basement lying to the northeast was overlapped by various Neoproterozoic units of the AG. Unconformable and faulted contacts define the newly rifted boundaries of the CP.

## THE ADELAIDE GEOSYNCLINE

The AG is a complex of rift and sag basins between the GC and CP which accumulated great thicknesses of Neoproterozoic (Adelaidean) to Cambrian, mainly sedimentary, rocks that were folded to form the NA. Much tectonic information is provided by the well understood stratigraphic record of the AG. The earliest rifts (of *Willouran* age, ~830-800 Ma) are completely buried and can be deduced only from the distribution of evaporitic Callanna Group sediments and mafic rocks rafted to the surface in diapirs. The limits of these troughs are defined by the rift shoulders where Callanna Group is absent and younger Adelaidean sediments directly overlie basement. The buried G2 Corridor, where it crosses the AG, is likely to define the western margin of Willouran troughs in the south, inferred to trend NNW-SSE. They reflect NE-SW extension, also represented by the Gairdner Dyke Swarm on the eastern GC.

Rifting of *Torrensian* age encroached further west and defined the present, N-S trending eastern margin of unattenuated GC crust along the THZ. Great thicknesses of fluvial arkose accumulated in the rifted trough adjacent to the THZ, and there are local thin basalt flows and dolerite dykes, plugs and sills. The bimodal Boucaut Volcanics (~780 Ma) in the eastern Nackara Arc may also have resulted from this rift event.

*Sturtian* age troughs (~700 Ma) resulted from rifting around the perimeter of the CP during a major glaciation, and defined the limits of the CP. Northwest-trending half-grabens developed at the southwestern (in SA) and northeastern (in NSW) margins of the CP. Iron-rich facies of thick diamictite and siltstone deposited in the SA half-grabens are responsible for the very high magnetic intensity zones evident on TMI images. Contemporaneous E-W rifts north of Mount Painter define the northern limits of the CP.

While the timing of continental separation is controversial, stratigraphic and tectonic evidence favours break-up of the supercontinent Rodinia soon after Sturtian glaciation and rifting. Sag-phase sedimentation predominated in the younger Neoproterozoic deposits of the AG, until the onset of renewed rifting along SE-dipping extensional faults in the Early Cambrian to form the Kanmantoo Trough at the southern extremity of the NA. From there the Kanmantoo Trough continues along the outer FA, possibly forming a Cambrian failed rift between Australia and Antarctica at a high angle to the Neoproterozoic continental margin.

## DELAMERIAN OROGENY

The expression of the Delamerian Orogeny differs in the various subdivisions of the orogen. Whereas the inner (western) FA is dominated by gently dipping, northwest-vergent thrusts and associated folds, the NA has mainly relatively upright folds (which also continue southward into the outer FA), with vergence varying from mostly westerly in the west to mostly easterly in the east. Synclines are dominant, and are more commonly separated by faults than by anticlines. These faults are steep and display both dip-slip and strike-slip movement; in places they are slightly oblique to fold axes. Mapping in the poorly exposed region east of the main highlands of the Mid-North has shown that stratigraphic units cannot be directly matched between isolated exposed E-W transects along major streams. Aeromagnetic interpretation shows that this region is cut obliquely by such faults (Preiss, 1997). Similarly, Curtis (2002) has interpreted segmentation of the northeastern portion of the Nackara Arc by oblique 'macrofaults'.

## INTERPRETATION

Any interpretation of the formation of the Nackara Arc during the Delamerian Orogeny must take into account the following constraints:

- The unconformable relationships of Adelaidean cover on basement inliers means that the cover is autochthonous with respect to its basement.
- The Neoproterozoic-Cambrian continental margin, formed during the Rodinia breakup, must lie southeast of the presently exposed rocks of the Nackara Arc.
- The Darling Lineament, expressed in SA by the Anabama Shear Zone, probably originated as a transform fault during Neoproterozoic rifting; it was the locus of bimodal volcanism in earliest Torrensian time, and was perpendicular to the Sturtian rifts bounding the CP, as first envisaged by Scheibner (1973).
- At the 'axial zone' (point of maximum curvature of the NA), there is a NW-trending zone of fracturing (in part the 'Teetulpa Fracture Zone' of Forbes, 1990) and structural anomalies such as the N-S trending Mount Grainger Anticline, which Connor (1987) reinterpreted as a 'kink of regional dimension'.
- Major Delamerian syn-orogenic igneous intrusions (mostly highly magnetic I-type granites, variably contaminated with sediment) run along the eastern edge of the exposed NA and FA and post-date at least some of the deformation.
- New mapping confirms that diapiric intrusions of brecciated Willouran rocks, so prominent in the central Flinders Ranges, extend southward into the less well exposed regions of the NA.
- The overall convergence direction during the Delamerian Orogeny was from the southeast to the northwest, though local structures vary greatly in orientation.

The preferred interpretation is that the NA portion of the AG represents a passive continental margin, and the Central Flinders Zone an associated intracratonic rift. Following episodes of intracontinental rifting in Willouran, Torrensian and early Sturtian times, continental separation from Laurentia occurred at ~700 Ma. Early Cambrian rifting forming the Kanmantoo Trough cut across earlier rifts at a high angle to the Australo-Antarctic eastern margin. Delamerian plate convergence involved a Cambrian island arc now lying beneath the Murray Basin, and possibly Proterozoic continental ribbons, parts of which may be represented in Tasmania. These colliders impinged against the continental margin from the SE, first coming into contact with the projecting SE corner of the GC and causing severe crustal shortening (using basement-rooted thrusts that had probably originated as Cambrian

normal faults) in the FA, while sediments to the north remained unaffected; the age of this deformation is estimated at ~510 Ma, probably correlating with the obduction of ophiolite in Tasmania. With continued NW-directed plate convergence, sediments of the NA started to buckle but here deformation was controlled by pre-existing NNW-trending rift structures in the basement. Thick evaporitic Callanna Group in the Willouran troughs, bounded to the W by down-stepping faults of the G2 corridor, permitted décollement between basement and cover and diapiric intrusion of breccia into higher strati-graphic levels. Sinistral transpression of the cover formed upright folds and faults of the southern NA and eastern FA at ~500 Ma. The NE arm of the NA developed as the NW-directed deformation front migrated northward, and formed local interference structures. The arcuate shape of the belt results from NW tectonic transport, but influenced by the pre-existing shape of the continental margin and deep fracturing in the basement imposed during various rift episodes.

## PROBLEMS AND FURTHER WORK

Much remains to be learned about the NA. What is the origin of the late NW-trending fractures and anomalous structures such as the Mt Grainger Anticline? What are the ages and origins of various mafic intrusives known from this region? Are the breccia cores of some anticlines similar to the diapirs of the Flinders Ranges? Do the early, possibly mantle-tapping rift faults of the AG control the distribution of kimberlites? What is the origin and age of the felsic igneous rocks recently discovered during mineral exploration at Oodlawirra (R. Burke, pers. comm., 2002)? During April 2003, the Geological Survey Branch has mapped a small area at Oodlawirra in detail, with isolated, variously orientated blocks of felsic rocks, silicified carbonate, sandstone and siltstone. The new mapping evidence is not inconsistent with diapiric emplacement. Volcaniclastic layers and ignimbrites show that the felsic rocks are extrusive and steeply dipping. This, and the low-grade metamorphic overprint observed in thin section (Mason, 2002), argues against a post-Delamerian age for the volcanics. If they are diapiric xenoclasts, then the volcanics probably originated from lower Adelaidean stratigraphy that is otherwise not exposed in the region. Unexposed areas between blocks are expected to be underlain by diapiric breccia.

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## **TERTIARY URANIUM EXPLORATION – NEW DEVELOPMENTS IN PALAEOCHANNEL DEFINITION AND DEPOSIT EVALUATION**

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The Honeymoon uranium deposit was discovered in 1972 and was very nearly brought into production when, in 1983, it was stopped by a change in government. The project is similarly poised to commence production pending improvements in equity markets and uranium price (Hunter and Randell, 2002).

The deposit is located at a depth of 100 to 120 metres in an Eocene palaeochannel (Eyre Formation) which itself is buried under 70 metres of Miocene clay (Namba Formation). Although geophysical methods, including ground resistivity, gravity and radiometrics were trialled, the Honeymoon mineralisation was essentially discovered by drilling (Bampton *et al*, 2001). Downhole geophysics including gamma, resistivity and self potential were crucial to early definition and evaluation of the deposit.

The advent of reliable airborne EM prompted a trial of several widely spaced lines across the Yarramba Palaeochannel in 2001. Encouraged by the success of this trial, Southern Cross Resources (SXR) completed surveys over all of its tenements in the Curnamona in 2002. Integration of this survey with other drilling and geophysical datasets has produced a model of uranium deposition and has highlighted other promising targets.

### **AIRBORNE ELECTROMAGNETICS**

In August 2001 Fugro flew an orientation survey using their *TEMPEST*<sup>TM</sup> 25 Hz EM system. Eighteen lines totalling 237 line kilometres were flown at a nominal terrain clearance of 115 metres. The processed AEM data showed a remarkable correlation between increased conductivity at 100 m depth with the boundary of the Yarramba Palaeochannel as defined by drilling. It is thought that the increase in conductivity is due to the presence of highly saline groundwater in aquifers at the base of the channel. Typically, basal sand groundwater contains 20,000 g/l TDS. Due to the flat lying nature of saline aquifers it was resolved to survey tenements at Honeymoon and Goulds Dam at one kilometre line spacing using the *TEMPEST*<sup>TM</sup> system.

The final survey was flown in May-June 2002 and comprised 2,077 line kilometres at a nominal height of 120 metres. Raw data was processed and inverted by Fugro using *EMFLOW*<sup>TM</sup> to produce conductivity depth images at 5 metre increments from the surface to a depth of 350 metres. Due to the wide spacing of the flight lines, only very coarse gridding of the CDI datapoints was possible. However, whilst crude, the resulting images clearly identified and mapped palaeo drainage through conductors in both overlying Namba Formation and underlying Willyama basement. To optimize the mapping of the palaeo drainage the AEM dataset was manually interpreted using individual thematic CDI datapoints superimposed on a variety of other geophysical and drilling datasets. This refined interpretation not only picks out the margins of the main palaeochannels, but also shows internal heterogeneity and numerous subtle tributaries entering the main system. The significance of these tributaries and the role that they may play in uranium deposition is discussed later.

## **DIRECT MEASUREMENT OF *IN SITU* URANIUM GRADES**

Uranium mineralisation in roll-front type deposits is very often out of radiometric equilibrium due to the physical separation of uranium from its daughter products. This is caused by the dissolution of uranium by oxidizing groundwater and the (re)precipitation of that uranium at sites of chemical reduction. These sites generally contain organic debris and pyrite thought to be generated by bacterial action on iron sulphates. A further mechanism causing disequilibrium is the “plating out” of insoluble radon daughter products on aquifer/aquiclude interfaces. The daughter products are “left behind” by the passage of dissolved uranium in the aquifer. Dickson (1983) suggested that high salinity in the Yarramba Palaeochannel may cause dissolution of radium as chloride complexes which can then migrate in moving groundwater away from parent radioisotopes. Disequilibrium in a uranium occurrence is a function of its age: if there is no physical separation of daughters for ca 1 MA then radiometric equilibrium is restored.

Disequilibrium has an important impact on deposit evaluation, particularly as most downhole geophysical methods rely on measuring gamma radiation to estimate equivalent uranium grade. Radiation read by these tools predominantly comes from  $^{214}\text{Bi}$  and  $^{214}\text{Pb}$  which are toward the end of the radioactive decay series. High gamma counts (particularly at sand/clay boundaries) may not be due to uranium and, more importantly low gamma counts in pyritic/carbon rich grey sands may not reflect the presence of significant uranium mineralisation!

In the 1970's a new generation of downhole tools was developed in US and elsewhere to overcome the disequilibrium issue. The tools used pulsed neutron sources to stimulate fission from  $^{235}\text{U}$  which may be present in formations surrounding the tool. Fission produces high energy epithermal neutrons which lose energy through collision to join the thermal neutrons from the source. Measuring the ratio of epithermal to thermal neutrons provides a measure of uranium grade. A simpler method developed in Central Asia records the rate of thermal neutron decay which is also proportional to the fissionable uranium present.

Tools of the latter type are being used in Kazakhstan and it is hoped that they will be put to use at the Honeymoon Project during future exploration and development drilling.

## **INTEGRATION OF ALL DISCIPLINES TO FOCUS TARGET GENERATION**

Previous base metal exploration on the Curnamona map sheet has generated a wealth of geophysical, geochemical and geological data. Due to the paucity of outcrop and highly weathered nature of basement rocks intersected in most palaeochannel drilling, it has been necessary to resort to remotely gathered datasets to generate interpreted basement geology. These datasets include ground gravity, airborne magnetics and, most recently, airborne EM.

Gravity has been collected by government agencies at 1 kilometre spacings across the whole of SXR's Yarramba Palaeochannel tenements and in the late 1990's Rio Tinto Exploration infilled some 140 km<sup>2</sup> to 100 x 500 metre coverage over the most prospective areas. Computer manipulation and imaging of the gravity clearly identifies high level granites and the Willyama stratigraphy. A prominent linear gravity high occurs at the base of the pelitic Strathearn Group. Drilling by Rio Tinto confirmed that this gravity high is caused by shallower cover and reduced saprolite development in basement rocks compared to adjacent areas. There is no evidence of the Yarramba Palaeochannel in current gravity datasets.

Airborne magnetic surveys also characterise the Willyama stratigraphy, particularly the strong magnetic contrast between Curnamona Group and overlying units. Granites seen as gravity depressions are confirmed in magnetic imagery and structural folds/breaks are readily mapped. The Yarramba Palaeochannel and modern surface drainage have no detectable expression in the aerial magnetics. However a subtle sinuous anomaly, trending north west in the vicinity of Honeymoon, can be seen. This is believed to be a shallow palaeo drainage feature probably in Quaternary terrestrial sediments. It has not been mapped in drilling to date.

Numerous interpretations of basement geology have been produced in the past but most are recorded in unpublished company reports. Many variations are seen although basic elements are common. SXR geologists now recognise a broad circular disposition of high level granites which appear to mark the perimeter of a deep seated granitic batholith (Skidmore 2002). Doming of overlying rocks has generated folding, faulting and fault repetitions in the Willyama stratigraphy.

Superimposition of the Yarramba Palaeochannel (as defined by drilling and AEM) on interpreted basement geology reveals some striking correlations. The course of the palaeochannel appears to have deflected some twelve kilometres down a palaeo-ridge (as defined by gravity) and passed through a stricture before widening out and continuing northwards. A modern analogy, but with greater relief, might be Heavitree Gap at Alice Springs where the Todd River breaks through the MacDonnell Ranges. The deflected palaeochannel appears to follow the Bimba Horizon. This is most likely due to enhanced chemical weathering of the Bimba due to its exotic composition including sulphide components. Tributaries to the main channel as defined by drilling and AEM are seen shedding off interpreted granites which have contributed to the base load of sediments in the channel. The granites could also have contributed detrital uranium minerals to the channel system. SXR drilled a rotary mud hole into the headwaters of one tributary at an interpreted granite position. The hole was drilled to blade refusal (142 metres) and diamond cored for a further one metre. The rock intersected was indeed granite and an assay of its uranium content returned a value of 76 ppm U.

The Honeymoon and East Kalkaroo uranium deposits are located exactly where two significant tributaries enter the main Yarramba Palaeochannel and where the channel narrows and changes course. It is probable that this interplay of tributaries and channel stricture has played an important role in deposit genesis. Perhaps there was an accumulation of organic debris at these sites which in turn lead to areas with reducing potential. As noted above, oxidizing groundwater dissolves uranium and carries it to sites of deposition at redox boundaries. This may have happened contemporaneously with Eyre Formation sedimentation but is most likely to have continued right up to the present. Measurement of potentiometric surfaces in the buried aquifers indicates that the present highly saline groundwater is moving slowly in a northerly direction. There is no reason to believe that the process of uranium dissolution and precipitation is not continuing and measurement of radiometric equilibrium supports this premise. Using the model described above other promising sites of deposition have been identified and drilling of these targets is planned in the near future.

SXR has also flown AEM over tenements covering the Billeroo and Curnamona Palaeochannels. The survey identified elevated conductivity at the depth of known saline



groundwaters and this has allowed preparation of an interpreted palaeochannel, once again showing a sinuous braided stream environment with numerous tributaries. The coverage of other geophysical datasets in the area is notably poor and contributes little to revealing basement influences to deposition. However, limited deep drilling has indicated that palaeo drainage is incised into Adelaidean sequences which overly Willyama basement to depths in excess of 400 metres. Further drilling is planned to advance this project.

## CONCLUSIONS

The integration of geophysical datasets has lead to a fuller understanding of the geology and genesis of uranium deposits in the Yarramba, Curnamona and Billeroo Palaeochannels. The challenge now is to exploit this knowledge to locate additional resources.

## ACKNOWLEDGEMENT

Southern Cross Resources Australia Pty Ltd is thanked for permission to publish.

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# **EXPLORING THE CURNAMONA or (LOOKING FOR BIG ELEPHANTS IN A BIG JUNGLE NEEDS BIG DOLLARS)**

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PlatSearch NL

Here we are again at the fourth BHEI, within the huge Curnamona Province, an area of 150,000 square kilometres, home of the mighty Broken Hill orebody, thousands of minor base and precious metals occurrences, thousands of strike kilometres of highly metalliferous rocks, a detailed and an extensive geoscientific database, yet the discovery of another major deposit eludes us still. Why is this so?

Not for lack of interest. Approximately 70% of the Curnamona is covered with over 100 exploration licences and what's not covered is probably too deep to be of interest. A review of the tenement holders shows that the majority are junior and medium size companies, although some of these (such as PlatSearch) have joint venture arrangements with majors that are funding exploration.

Not for lack of encouragement and assistance. We have the benefit of enthusiastic and committed state and federal government agencies that have provided one of the best geoscientific databases in the world, available to all, at minimal cost.

Not for lack of prospectivity. In terms of current understanding of mineralisation processes for lead-zinc and copper-gold developed in Proterozoic domains elsewhere in Australia and the world, the Curnamona meets all the criteria required for the existence of major base and precious metal deposits, demonstrated convincingly by the presence of Broken Hill itself. In the Curnamona, a drillhole without a mineralised intersection is more the exception than the rule. However there is a findability issue:

- Within the area of the Broken Hill Block the geology is highly complex and tightly folded. Conditions change rapidly over short distances.
- The lead-zinc orebodies are generally steeply dipping and have a small, or non-existent, surface footprint and are not particularly responsive geophysically.
- In the surrounding areas, including the Curnamona Craton over the border, pervasive soil cover up to 400 metres in thickness adds another degree of difficulty.

Of course, part of the reason for such a low discovery rate over the past few years is the substantial reduction in exploration expenditure. Exploration spending for gold and base metals deposits in Australia has been declining steeply since 1999 and in 2002 reached its lowest level since 1980 (ABS).

In these lean times how can we maximise the effectiveness of the fewer dollars at our disposal and improve the discovery rate? This issue must be addressed, in order to fill the looming gap between metal supply and demand that will inevitably occur in 10-12 years time. We need to be making major discoveries now.

What is lacking is serious commitment by explorers - read DRILLHOLES, and then MORE DRILLHOLES. All the data, research, new exploration technology and talk-fests are useless unless explorers commit to planned long term programmes in the area, undertake good quality exploration work and serious drilling.

Currently, the industry appears to be afflicted with a condition called “the one hole syndrome”. Explorers with this malaise will be heard to say things like:

- ‘The orebodies we’re looking for are so big we really don’t have to fine-tune our drill targets.’
- ‘There’s no outcrop, but this geophysical anomaly looks pretty simple - one drill hole should be enough to “test” it
- ‘If we haven’t hit 50m of ore grade in the first hole, then it’s not a world class orebody and we may as well move on.’

How naïve can we be – haven’t we learned anything from the last 50 years of exploration? Well, what have we learned?

- Most base metals mineralised systems are complex and difficult drilling targets. They can be missed easily.
- Even for a system the size of Olympic Dam many holes may be required before we can be confident of a discovery.
- Although the geophysical anomaly may look like a simple target, particularly when it is blurred by 200 metres of cover, the basement geology is just as complex as it is where there is outcrop.
- Geophysical anomalies are only reflecting those components of the system that happen to have physical property contrasts, size and attitude characteristics to produce an anomaly. The actual ore zone may be, and often is, somewhere else in the system.
- It’s a mistake to get too smart and too blinkered by rigid models. In my experience all the big discoveries are usually surprises. Keep it simple – look for the right geological provenance, evidence of a large plumbing system, structure, geochemistry if you can get it and in some cases lots of iron.
- If the first hole identifies at least some of the characteristics that are associated with a major deposit, such as appropriate host rocks, brecciation, the right alteration, the right indicator minerals, evidence of size, perhaps some anomalous metal values, then KEEP DRILLING. Dare I say it – even a fence of holes.

So how successful has PlatSearch been in pursuing this strategy?

We see ourselves as a new frontier explorer, prepared to try the occasional ‘left field’ approach and see where this leads us. Of course our limited funding limits how far we can go and we are then dependent on joint venture partners for the serious expensive part of exploration. Time and space don’t permit me to describe everything that PlatSearch is doing in the Curnamona, so I have selected some interesting areas where we have made advances and identified new opportunities and directions, but which still require substantial further expenditure to progress.

## **THUNDERDOME, BROKEN HILL, NSW**

PlatSearch's first drillhole at Dome 5 prospect discovered one of the thickest and most prospective packages encountered in the Broken Hill area.

"The very thick Broken Hill Group lode zone intersection, contains abundant mineralised BIF and spessartine garnet quartzite, and represents a classical Broken Hill type lode sequence only rarely found outside the immediate environment of the Broken Hill Orebody. It contains in excess of 120m true thickness of stacked mineralised garnet quartzite and BIF layers (up to 19 units). A comprehensive comparison of the prospective lode zone with iron formation related lead-zinc-silver ores on a world-wide basis, and more significantly the Broken Hill and Cannington deposits, strongly suggests that the drilling at this anomaly has intersected a proximal-to-ore host rock package which is unequalled anywhere within the Willyama Complex. It represents an extremely encouraging result from a single attempt." (Wolf Leyh, Eaglehawk Geological Consulting Pty Ltd, 1996).

The mineralised package is deep (600-800m) but consider what it would cost to locate such a setting starting from scratch. The nature of the intersections to date indicates that we could be very close to a major BHT lead-zinc orebody. In this context the depth is of little consequence. All the hard work has been done. This is a "walk up and drill" opportunity to discover a major lead-zinc deposit, but majors are shying away because of some arbitrary depth limit. "We don't explore below X metres depth"

## **MUNDI MUNDI, BROKEN HILL, NSW**

Adjacent to Thunderdome, the Mundi Mundi area has had several campaigns of exploration starting with CRA in the early eighties. This is one of those areas where every drill-hole encounters significant mineralisation.

PlatSearch's first hole (funded by Savage Resources) intersected 1.8m @ 7.5% Cu, 6.2 g/t Au and 6 g/t Ag. More recently drilling on two sections 500m apart, funded by Inco, has intersected a zinc-rich massive sulphide horizon in the Bimba Formation with assays up to 3.8m @ 9.25% Pb+Zn. Further drilling will be undertaken this year.

## **QUINYAMBIE, SA**

PlatSearch' first hole at the Dolores East prospect, a lonely magnetic anomaly in the north of the Curnamona Craton, has discovered a spectacular haematite altered volcanic vent structure, highly anomalous in copper averaging 630 ppm copper over the entire 200m basement intersection from 300m to 500m. This is one of those situations where a fence of holes could turn up anything.

## **CALLABONNA, SA**

Within this vast area covering approximately 3,000 sq kms and containing at least fifteen large ironstone systems, there are only two basement holes targeted on these systems. Both holes were funded by PlatSearch joint venture partners, the first on Anomaly 4 by BHP and the second on Anomaly 5 by Inco. Both holes intersected large highly altered and brecciated ironstone (predominantly magnetite) bodies. The Anomaly 5 hole has wide intervals of moderately anomalous base metals up to 766ppm Cu, 783ppm Pb and 1,143ppm Zn. Gravity

surveys suggest that the Anomaly 5 magnetic body is only a small component of a much larger system approximately 4 kms in diameter.

The available gravity coverage over the area is wide spaced and requires more detail. PlatSearch has undertaken detailed surveys in some locations and the results indicate that the entire area really needs coverage at 1,000m spacing and 500m spacing in parts. One gravity feature for which we are currently seeking funding is the Pudding Lake anomaly. This is the strongest localised gravity anomaly in the northern Curnamona.

### **ZIGGYS, BROKEN HILL, NSW**

The Ziggys tenement covers a major NS structure located approximately 30 kms due east of Broken Hill and apparent in the aeromagnetic data. This structure appears to mark the boundary between Broken Hill Group rocks to the west and Thackaringa Group to the east. Previous RAB drilling by North Broken Hill shows strong C-horizon lead and zinc closely associated with this structure, up to 3,000 ppm lead and 1,500 ppm zinc. PlatSearch has completed further RAB drilling to better define this anomaly and map its full strike extent. Work so far shows a zone of strongly anomalous lead and zinc that appears to be directly coincident with the north south structure over a strike length of at least four kms. Following further fill-in RAB, selected anomalies will be tested with RC drilling.

### **YANCO GLEN, BROKEN HILL, NSW**

Wolf Leyh has undertaken some very detailed mapping over a large area to unravel the complexity around the old Allendale Mine, one of the larger early producers. Funded by Inco, PlatSearch is completing currently two inclined core holes to look for down-plunge extensions to surface lodes.

### **HOLLIS TANK, BROKEN HILL, NSW**

In the Hollis Tank tenement, government mapping has identified sporadic gossan outcrops over a wide area with shallow soil cover south of Cockburn near the state border. Rock chip sampling of gossans by Eaglehawk for PlatSearch shows many anomalous values up to 2,400ppm Zn, 2,400ppm Cu, 1,200ppm Pb, 1,400Co and 280ppb Au. This sampling combined with data from earlier RAB drilling now available in the DMR geochemistry database, has been used to plan follow-up RAB drilling currently in progress.

At the old Great Goulburn Mine workings, PlatSearch experimented with calcrete geochemistry covering an area of 1,000 x 1,400 metres and with a sample interval of 100 metres. The calcrete gold defined a strong and coherent anomaly that mapped a folded horizon under cover and with a strike length of at least one kilometre. RC drilling intersected a weakly gold bearing siliceous, pyritic horizon with maximum gold values up to several metres at 0.2 – 0.4 g/t. Disappointing drilling results, but the technique worked.

# **THE CURNAMONA PROVINCE IN SOUTH AUSTRALIA: RECENT DEVELOPMENTS, IDEAS OLD AND NEW, FUTURE DIRECTIONS**

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## **INTRODUCTION**

The Curnamona Province in SA is a region of highly prospective Palaeo-Mesoproterozoic rocks. Company exploration has located extensive and significant Cu, Au, Pb, Zn and U mineralisation but has not so far been successful in locating large, new economic deposits in basement rocks, although economic sedimentary uranium deposits have been found in Tertiary palaeochannels draining basement.

Since the mid 1990's the SA, NSW and Federal Governments have cooperated in the Broken Hill Exploration Initiative (BHEI) to facilitate the discovery of new orebodies in the region. Following earlier phases of acquisition of high resolution geophysical datasets, BHEI activities have been reoriented to emphasise cooperative research on key geological and exploration problems in the region. Detailed mapping by PIRSA and research partners is complementing and adding value to the geophysical data. Ultimate goal is delineation of prospective regions for particular mineralisation styles and of favourable structural and stratigraphic features. This paper summarises some aspects of these activities.

Regolith and sedimentary cover is a feature of much of the region and, although not discussed further here, understanding and use of the regolith in exploration is a key to success in the region.

## **PROVINCE ARCHITECTURE**

Major features of the Palaeoproterozoic to Mesoproterozoic Curnamona Province are described in Robertson et al. (2002). A large area of covered basement occurs between outcrop in the Willyama Inliers in the south and Mt Painter Inliers in the northwest. Cover depths are variable but large areas of the Benagerie Ridge in the south and centre are explorable. Reinterpretation of province solid geology and tectonic architecture using improved geophysical imagery by PIRSA and Monash ACRC is focusing on these areas and the Willyama Inliers.

The reinterpretation shows that large relatively undeformed igneous suites are more prevalent than previously inferred. A broad correlation of the widespread ~1600-1580Ma Bimbawrie Suite granitoids and Benagerie volcanics with the Hiltaba Suite granitoids and Gawler Range Volcanics of the Gawler Craton is known from geochronology. In the centre of the province the Benagerie Volcanics show a similar geophysical signature to the Gawler Range Volcanics. Large plutonic bodies, possibly genetically related, can be imaged beneath the volcanics.

The imagery and study of outcrop shows the presence of both variably magnetic and non-magnetic suites of syn- to post-deformation granites (both Bimbawrie Suite?). The non-

magnetic plutons are significant due to their close spatial relationship to the Portia and Kalkaroo prospects. Some granite plutons appear to be associated with gravity lows and such a pluton is the likely source of an intense gravity low extending north from the Crocker's Well area. This anomaly is part of a much larger feature interpreted by Knaak et al (2002) as a huge syn-Olarian Orogeny (Bimbowrie Suite) pluton underlying the Cambrian Moorowie Sub-Basin.

Barovich and Foden (2002) studied Bimbowrie Suite granitoids across the Olary Domain of the Willyama Inliers and on the basis of petrological, geochemical and Nd isotope differences suggest a distinction between the two-mica S-Type granites in the eastern OD and the more compositionally diverse granites in the western OD. They suggest a significant mantle input to the western granitoids which host uranium mineralisation at Crocker's Well. Further research is underway at the University of Adelaide on aspects of the tectonothermal history and provenance of sediments and igneous suites using geochemical and isotopic methods. A major program of U-Pb dating is currently underway in conjunction with NSW DMR, Geoscience Australia and PMD CRC to provide improved age constraints on intrusive history, the sedimentary and volcanic sequence and mineralising events (see Page, this volume).

## **WILLYAMA SUPERGROUP MAPPING**

Mapping by PIRSA, Geoscience Australia, and Monash and Adelaide Universities is focusing on understanding stratigraphy, basin architecture, structural features and tectonic history to provide an improved framework for exploration for basin-related large Pb-Zn sulphide deposits and for epigenetic Cu-Au deposits.

Conor (2000) has revised the stratigraphic framework for the Olary Domain utilising new mapping and new U-Pb geochronological information (Page et al., 2000). Dating of the ~1710Ma Basso Suite felsic intrusives and volcanics has clarified correlation of the magnetite bearing and albite altered Curnamona Group with the Thackaringa Group in the Broken Hill Domain (BHD). The mineralised, sulphide-rich, calcareous Bimba Formation is now tentatively assigned to the base of the overlying, non-magnetic pelitic and psammitic Strathearn Group. Dating of the immediately overlying volcanoclastic Plumbago Formation at ~1692Ma has confirmed the long assumed correlation with the Ettlewood Calcsilicate in the lower Broken Hill Group (BHG). Further mapping is also indicating the possible presence of some upper BHG rocks in the Olary Domain. The BHD bi-modal intrusive and extrusive 1690-1680Ma igneous suite that includes the Hores Gneiss ( $1686 \pm 3$ Ma) is represented in the OD by the intrusive Lady Louise Suite ( $1685 \pm 4$ Ma). Metabasalts mapped in the OD may belong to this suite or to the lower Basso Suite. A depositional model is suggested for the Willyama Supergroup with thinning and lapping out of units above the Plumbago Formation from southeast to northwest (Conor, 2002).

Mapping on the Mingary area encompasses the BHD in S.A., an area previously lacking any detailed mapping. Outcrop mapping combined with interpretation of magnetic imagery, is now at a stage where distribution of lithostratigraphic units and structural elements is reasonably well understood. Although in general terms the presence of BHG rocks, including quartz-gahnite 'lode horizon' and lead-zinc sulphides, has long been recognised by explorers, mapping has shown a wider distribution and significant unexplored areas. Similar BHG and associated mafic intrusives occur on both sides of the northeast trending magnetic low, previously interpreted as the BHD-OD boundary. Compilation and interpretation of

petrological data relevant to the metamorphic history of the OD and BHD has supported this observation with isograds, including a zone of granulite grade metamorphism, corresponding with those interpreted for NSW but not with the magnetic feature. Bimbowrie Suite granitoids only occur outside the granulite zone in the northwest of Mingary indicating these bodies are limited to a higher crustal level with melting in the deeper granulite zone as a possible source.

Interpretations of the tectonic significance of the earliest deformation event throughout the province remains controversial. In addition to an interpretation of an early nappe-forming event responsible for regional stratigraphic overturning, the earliest stages of regional deformation have recently been interpreted in the context of extensional tectonics. Gibson (2000) proposed that the oldest high-temperature foliation throughout the province is related to an extensional event during the development of the basin. Alternatively, the early high-temperature foliation may be related to regional extension immediately preceding the Olarian Orogeny. This extensional event and consequent lithospheric thinning may have been responsible for the pre-orogenic migmatisation and high-temperature metamorphism at ca.1600 Ma. Understanding the thermal history and architecture of the Curnamona Province will impact on understanding the distribution of metalliferous fluids in the Curnamona crust during mineralisation episodes.

Areas of angular discordance, pre-dating Olarian Orogeny folding, are interpreted in covered areas of the northern Olary Domain. The discordance may be related to regional unconformity development or stratigraphic incision during extensional faulting. A third possible explanation is that the discordant lower boundary is a hydrothermal (magnetite) alteration front crosscutting stratigraphy.

## **MINERALISATION**

Exploration over the last 10 years has revealed significant new potential in the southern Curnamona Province, particularly with the discovery of extensive Cu-Au-(Mo) mineralisation at Benagerie (Portia, North Portia, Shylock etc.), Kalkaroo and White Dam, all beneath varying depths of transported cover. Although grouped as FeO-Cu-Au type, the deposits show a range of mineralisation styles including high-grade Au-rich veins at Portia and other Benagerie prospects and at White Dam. This Au-rich mineralisation represents a distinct exploration target not previously associated with the Curnamona Province. Recent dating has indicated ages for Cu-Au mineralisation of ~1632-1612Ma (Re-Os; Skirrow et al., 2000) and ~1605 (U-Pb monazite; Teale & Fanning, 2000) suggesting an association with a possible pre-Olarian extensional and heating event. Research is being undertaken by the University of Adelaide on hydrothermal fluid processes including brecciation events and by Graham Teale and Paul Spry (University of Iowa) on the exploration significance of gahnite and garnet rich 'lode' rocks in the OD in comparison to Broken Hill.

Comparisons between the Curnamona Province and other Proterozoic provinces of the North Australian Craton (NAC) have been made based on geochronology (Raetz et al., 2002; Page et al., 2000), similarities in basin evolution and Mesoproterozoic Orogenesis (Betts and Giles, 2001) and similarities between the Willyama Inliers and the Eastern Fold Belt of the Mount Isa Inlier (Laing, 1996). In the NAC, the Mount Isa and McNamara Groups contain several of the largest shale-hosted Zn-Pb sulphide deposits known. The upper Willyama Supergroup (Strathearn and Paragon Groups) has many of the characteristics of the Mount Isa and McNamara Groups, in particular deposition during thermal subsidence of the lithosphere and



a reduced sedimentary environment. To the north of the outcropping Olary Domain large areas of Strathern Group, already known to host some Zn-Pb sulphides, may preserve a continuation of the network of Late Palaeoproterozoic basins rich in large shale-hosted Zn-Pb sulphide deposits.

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# ALKALIC MAGMATISM IN THE OLARY DOMAIN: GENESIS AND IMPLICATIONS FOR Cu-Au MINERALISATION

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## INTRODUCTION

Both silica-saturated and silica-undersaturated alkaline magmatism have been associated with mineralisation styles including porphyry Cu-Au, Fe-oxide Cu-Au and carbonatite-hosted Cu-Au-rare earth element (REE). Alkaline magmatism often occurs in broad-scale magmatic provinces, some of which are temporally associated with more intermediate compositions. Silica-undersaturated alkaline magmatism at Billeroo, north of Plumbago in the northwestern margin of the Olary Domain has affinities to other alkaline magmatic complexes that host Cu-Au mineralisation. This abstract will briefly address the petrogenetic evolution of the Billeroo magmatic complex. In view of these petrogenetic interpretations, the prospectivity of alkaline magmatism will be assessed with regard to its potential for Cu-Au mineralisation in the Curnamona Province, particularly in the Olary Domain.

## PETROGENESIS

The Billeroo alkaline magmatic complex is a highly heterogeneous intrusive body outcropping over <1km<sup>2</sup>. However geophysical data indicates that the complex has a two dimensional extent in excess of 5km<sup>2</sup>. The complex has ijolite, syenite, alkaline mafic dyke and breccia phases that are characterised by variable textural and petrological features. A primitive and depleted, mantle-derived source fractionated to first produce feldspathic-bearing ijolite phases. Typical ijolite mineralogy includes albite, phlogopite, garnet, Na-pyroxene, nepheline, cancrinite and accessory titanite, Fe-(Ti)-oxides, epidote, sodalite, analcime, K-feldspar, apatite and calcite. Continued fractionation of the primitive source produced porphyritic and equigranular alkali syenite phases. Syenites are composed of K-feldspar phenocrysts within a matrix of albite, muscovite, biotite, K-feldspar, sericite, titanite, Fe-oxides, sulphides and calcite. Syenite intrusion was contemporaneous with the intrusion of an orthomagmatic or diatreme breccia. The breccia contains clasts of metasediment and syenite annealed by syentic magma, massive carbonate and pulverised rock flour. The final products of fractionation produced alkaline mafic dykes that are composed of albite, epidote, Fe-oxide, phlogopite, biotite, muscovite, garnet, cancrinite and accessory fluorite, titanite and apatite. Late-stage carbonate veining was ubiquitous in all the phases.

Fractionation and hydrothermal alteration of a primitive source is supported by trends in major- and trace-elements with respect to SiO<sub>2</sub> and Zr. During the fractionation process CaO, MgO, Na<sub>2</sub>O and P<sub>2</sub>O<sub>5</sub> decreased as SiO<sub>2</sub> increased, as would be expected through crystallization of Na-Ca-pyroxenes, nepheline, cancrinite and apatite. A dramatic increase in F, Sr and Ba in the final stages of differentiation is interpreted due to a high volatile content during the final stages of fractionation. Chondrite-normalised REE patterns are LEE enriched and become progressively more enriched as would be expected during fractionation processes. Reducing magmatic conditions are supported through the mobility of sulphides in the system. The introduction of H<sub>2</sub>O during emplacement of the syenite resulted in changes in redox conditions such that Cu precipitated, leading to anomalous Cu-Au values. The fractionation of a mantle-derived, primitive source is reflected in the  $\epsilon$ Nd signature that

ranges between 0.3-3.5. These values are slightly more depleted than those obtained for the mantle-derived, rift-related 1700Ma A-type granitoids (Ashley et al., 1995).

A pervasive northeast trending fabric has developed in the ijolites, breccia and around the margins of the syenite. This produced a schistose to mylonitic texture to the complex, particularly the ijolitic phases, coincident with pervasive dynamic recrystallisation. The general trend of the fabric is similar in orientation to the Olarian D3 fabric of Berry et al. (1984). Thus based on current tectonic evolution models for the Olary Domain and field relations, magmatism is interpreted to have occurred after the initiation of the Olarian Orogeny (~1600 Ma), and before 1580 Ma.

## **MINERALISATION POTENTIAL**

Effects of Na-K-Fe-Ca hydrothermal alteration within the Billeroo alkaline intrusives have had a profound effect on the mineral assemblages. The hydrothermal alteration is interpreted to have occurred synmagmatically, although the majority of alteration is interpreted to have occurred during the final stages of crystallisation. Alkaline alteration is ubiquitous in all the different magmatic phases. However evaluating its full extent is difficult due to the primary feldspathic magmatic nature. Andradite, epidote, titanite, biotite, albite, Fe-oxides and calcite are characteristic minerals associated with Na-K-Fe-Ca alteration.

The hydrothermal assemblages at Billeroo are similar to those observed in world-wide alkaline porphyry Cu-Au systems and mesothermal Fe-oxide Cu-Au systems. Syenitic intrusions and such alteration assemblages are common in documented alkaline porphyry Cu-Au deposits such as Rayfield River, Galore Creek and Copper Canyon in the Canadian Cordillera, British Columbia (Lang et al., 1995). Anomalous Cu-Au values in the syenite may indicate a metal-bearing magmatic-hydrothermal system operated at Billeroo. At the current level of exposure, Cu-rich, Au-poor upper levels of such a system would have been eroded away. This has implications for supergene enrichment of Cu at the current level of exposure, and placer Au deposits in adjacent palaeo-drainage channels. Au-rich, Cu-poor mineralisation could still plausibly be at depth in the Billeroo system. Such a system would be of the high-grade, low-tonnage type. Skarn replacement-style mineralised systems may also be associated with the Billeroo intrusion if carbonate metasedimentary lithologies are nearby, similar to mineralisation in the Cadia system. The style of alteration observed in the Billeroo magmatic complex is also similar to those observed in Fe-oxide Cu-Au provinces. However this type of mineralisation is rarely associated within magmatic bodies. However large hydrothermal systems are known to have operated in the Olary Domain, making the Billeroo alkaline magmatism one of the potential reservoirs for Fe-oxide Cu-Au mineralisation in the Olary region.

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# PALAEOZOIC HISTORY OF THE BANCANNIA TROUGH & RESURRECTION OF THE MT WRIGHT VOLCANIC ARC

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It has long been known that the Bancannia Trough contains a sequence of Early to Middle Palaeozoic rocks that are fault bounded between the Curnamona Craton and the Koonenberry Belt (Figure 1). What remains poorly understood is the architecture of the basin. Outcrop is scarce and restricted to the more structurally deformed zones along its margins. Seismic, drill hole and wireline log data have enabled the recognition of three distinct stratigraphic packages separated by regionally important unconformities. It is widely accepted that the two uppermost packages are the Middle to Late Devonian Snake Cave Interval and the Late Devonian to Earliest Carboniferous Ravensdale Interval but the nature of the lower most package remains open to interpretation. This package could either comprise rocks of the Late Silurian to Early Devonian Winduck Interval or the Late Cambrian to Early Ordovician Mootwingee Group and equivalents. The nature of the basement to the trough and the timing of fault movements along the basin margins are poorly constrained.

The best exposed, most complete and relatively structurally uncomplicated sections of Early to Middle Palaeozoic strata along the eastern edge of the Bancannia Trough, are located within the Mutawinjtji region. A recent access agreement involving the Geological Survey of NSW, National Parks and the traditional aboriginal owners has enabled detailed mapping of this area in the hope that it may test existing basin models and provide some further palaeogeographic, structural and tectonic constraints for hydrocarbon and mineral exploration elsewhere within the Bancannia Trough and Koonenberry Belt.

## ARC BASEMENT TO THE BANCANNIA TROUGH?

Volcanics have long been recognised at the base of the Palaeozoic sequence outcropping on the eastern margin of the Bancannia Trough between the Mutawinjtji region and Mt Arrowsmith. These were proposed by Scheibner (1972) as remnants of an Early Cambrian arc edifice, which he named the Mt Wright Arc. Subsequent geochemical analyses by Crawford *et al.* (1997) divided these volcanics into a medium calc-alkaline suite (Cymbric Vale Formation and Mt Wright Volcanics) and an alkaline suite (Mt Arrowsmith Volcanics). As a result rocks with viable arc type chemistry were reduced to outcrops adjacent to the Mt Wright Fault in the Mutawinjtji region. Their limited extent and the lack of proximal arc-derived sedimentary rocks made the recognition of an Early Cambrian volcanic arc edifice difficult and thus Crawford *et al.* (1997) proposed a continental rift setting.

Recent mapping by the Geological Survey of NSW in the northern Mutawinjtji region between Bynguano Bore and Burkes Lookout, located numerous previously unrecognised outcrops of Cymbric Vale Formation (dacite, rhyolite and proximal volcanoclastics) re-supporting the presence of a more extensive volcanic edifice. How far these volcanics extend westward beneath the Bancannia Trough is presently unknown but volcanic-intrusive suites have been intersected in the Wahratta drill hole 50km east of Broken Hill (Platsearch NL & CRA Exploration 1997) and the Bancannia South No 1 drill hole 10km east of Fowlers Gap (Planet Exploration Co. Pty Ltd 1968). All yielded ages close to 520 Ma (Minfo 2001, M. Fanning unpublished data) which are identical to recalculated ages of zircons from the Cymbric Vale Formation in Mutawinjtji region (Jenkins *et al.* 2002). In addition Rb-Sr radiometric ages have been calculated at 532±23 Ma for acid – intermediate volcanics intersected in the Eaglehawk drill hole 50km southeast of Broken Hill. Strong deep magnetic signatures within the Bancannia Trough further support the presence of thick volcanic parcels at depth. It is therefore proposed here that the Early Cambrian Mt Wright Volcanic Arc forms the majority of the basement to the Bancannia Trough. In addition some workers (Gatehouse 1986, Scheibner & Basden 1998) propose the Gidgeapla Volcanic Arc of South Australia and Queensland may be a further extension of the Mt Wright Volcanic Arc. Where the arc is at shallow structural levels amenable to exploration such as on the eastern margin of the Bancannia Trough, the rocks should be considered prospective. Copper gold porphyry-style alteration has been recognised within arc rocks at the Wahratta prospect (Platsearch NL & CRA Exploration 1997).

### **MOOTWINGEE GROUP & EQUIVALENTS OR WINDUCK SHELF INTERVAL?**

Initial workers (e.g. Packham 1968) in the Bancannia Trough extended the Late Cambrian to Early Ordovician rocks outcropping along the eastern margin of the Bancannia Trough at Mt Arrowsmith, Scrope Range and Mutawinjti westward into the basin unconformably over the Gnalta Group. The unconformity was related to the Delamerian Orogeny which through large scale thrusting generated highlands to the south and west feeding a shelf, which Webby (1978) suggested was dominated by a large delta complex with alternating periods of shallow marine to non-marine deposition. This interpretation suggests Late Cambrian orogenic relaxation and extension, possibly due to the development of a new Ordovician subduction zone along the eastern margin of Gondwana, initiated the inception of the Bancannia Trough in a back arc setting. The margins of the basin at this time are hard to constrain but correlations of stratigraphic units within the Mootwingee Group either side of the Lawrence and Mt Wright Faults suggest they were not active during deposition.

More recent workers (e.g. Evans 1977, Bembrick 1997), using a sparse microspore flora obtained from near the base of Bancannia South Well No 1, interpreted the lowermost stratigraphic package as Late Silurian to Early Devonian Winduck Group equivalents. If true, the unconformity at the base of the Bancannia Trough can be correlated with Late Ordovician to Early Silurian Benambran Orogeny, triggered perhaps by a change in convergence direction along the eastern margin of Gondwana and subsequent plate rollback or development of a new subduction zone further east (New England), which resulted in a period of renewed extension (Scheibner 1987).

By the Late Silurian, fluvial type deposition had started on the western edge of the Koonenberry Belt, in the transtensional Mount Daubney and Churinga Basins (e.g. Neef and Bottrill 1991, Buckley this volume). Early Devonian extension also resulted in the accumulation of marine equivalents (Winduck Interval) in the Darling Basin further east.

Within the Mutawinjti region the Late Cambrian to Early Ordovician Mootwingee Group is unconformably overlain by the Middle to Late Devonian Snake Cave Interval rocks. There is no evidence for a Late Silurian to Early Devonian sequence. We therefore question the validity of inferring its presence throughout the Bancannia Trough and instead suggest a substantial period of non-deposition or minor erosion between the Middle Ordovician to Early Devonian. The Early Devonian Mt Daubney and Churinga Basins were localised intramontane depocentres, or perhaps part of a larger fluvial system feeding eastward into the Darling Basin. We suggest the Early Devonian Cobar Deformation (Scheibner 1998) that effected the Darling Basin was only a very minor event within the Bancannia Trough.

### **SNAKE CAVE INTERVAL**

The Middle to Late Devonian Snake Cave Interval makes up the middle stratigraphic package in the Bancannia Trough. Although considered predominantly fluvial in origin, rare intervals of vertical worm type burrows, within the Mutawinjti region, along the western margin in the Coco Range Sandstone (Neef *et al.* 1995), and at Copper Mine Range (Neef & Bottrill 1996) suggest brief marine incursions. Palaeocurrent data from the Snake Cave Interval in the Mutawinjti region (Carroll 1982) implies predominantly eastward flowing sandy to gravelly braided and alluvial fans sourced from the Adelaidean rocks to the west. Whereas palaeocurrent directions measured from the same interval in the Coco Ranges region suggest a complex interplay of northward, eastward and southward low-gradient alluvial fans or distal braid plains (Neef *et al.* 1995). The margins of the basins are difficult to constrain at this time but the absence of Snake Cave Interval between the Lawrence and Koonenberry Fault needs to be explained. Either, this part of the Koonenberry Belt was elevated prior to deposition of the Snake Cave Interval, preventing deposition, or later fault movement elevated the rocks after the deposition of the Snake Cave Interval and erosion removed them soon after. An uplifted highland of Neoproterozoic to Late Devonian rocks is challenged by the absence of westerly palaeocurrent directions immediately adjacent to the Lawrence Fault and the lack of diverse types of detritus within the quartzose Snake Cave Interval, except for locally derived material immediately above an unconformity. Furthermore predominantly southeast palaeocurrents directions, measured by Neef and Bottrill (1996) within Snake Cave Interval rocks east of the Koonenberry support an eastward flowing fluvial system across the Koonenberry Belt during this time.

The Snake Cave Interval is separated from the Ravendale Interval by an unconformity thought to relate to the Tabberabberan Orogeny, which initiated major thrusting and uplift along the present day basin margin, juxtaposing older rocks eastward and westward over the interior of the trough. The majority of this thrusting is thought to have occurred along northwest trending faults such as Lawrence Fault on the eastern margin of the trough and the Nundooka Creek Fault on the western margin of the trough. The Tabberabberan Orogeny was

related possibly to the rotation of crustal blocks along east Gondwana, not only at the active plate margin but also within it (Scheibner & Basden 1998).

### RAVENDALE INTERVAL

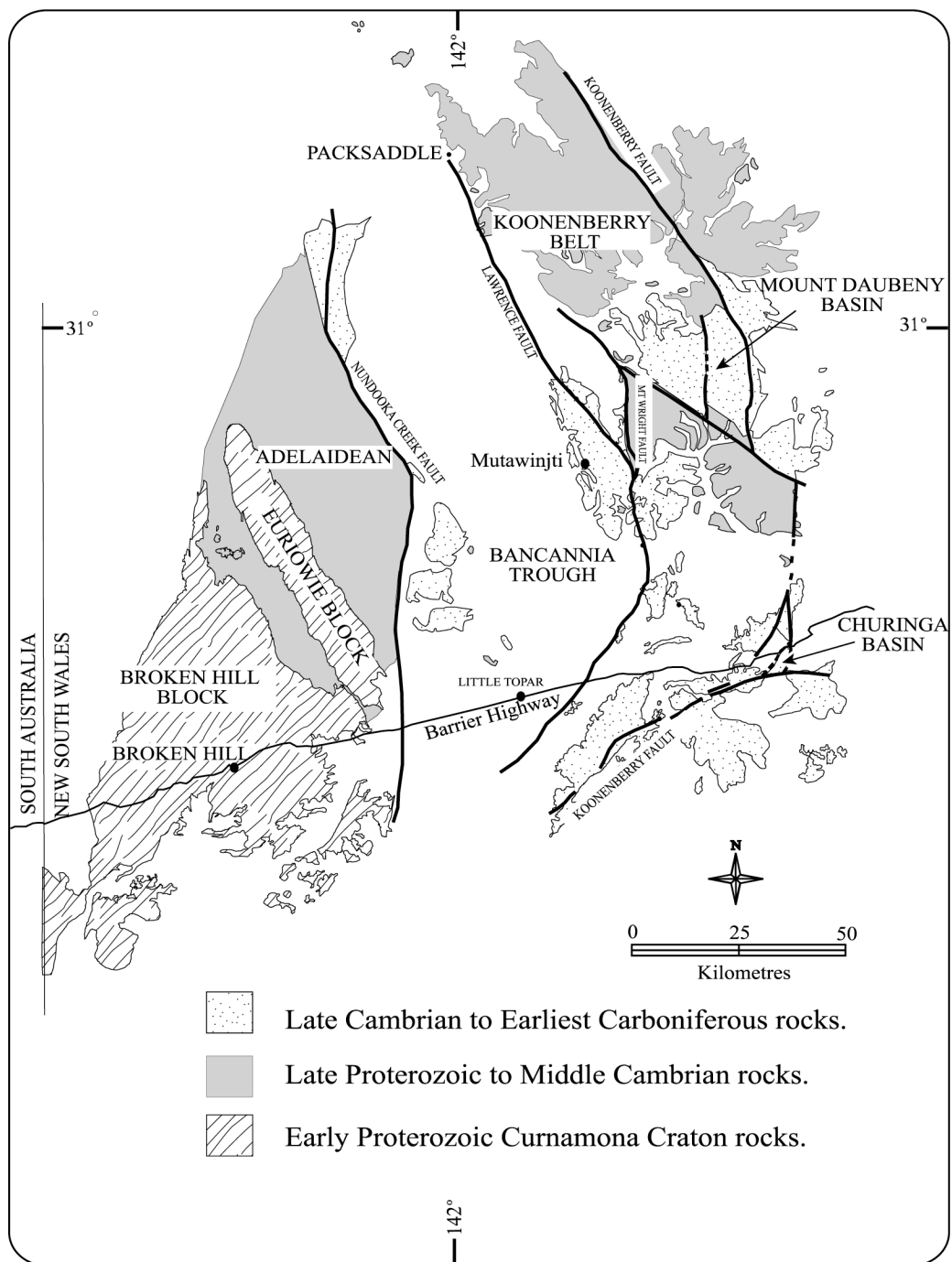
The Ravendale Interval rests unconformably on a variety of NeoProterozoic to Middle Devonian rocks throughout the Mutawinjti region. It has been derived predominantly from the west and deposited on alluvial fans growing in a general eastward direction (Neef *et al.* 1995, Neef & Bottrill 1996, Bembrick 1997). This entirely fluvial sequence removed much of the topography created by the Tabberabberan Orogeny. Although the detritus was still dominantly sourced from the Adelaidean, *Skolithos* bearing quartzite pebbles derived most likely from the Mootwingee Group make their first appearance at the base of the interval.

The final Palaeozoic structural activity recorded in the Bancannia Trough was the reactivation of older faults by the Carboniferous Kanimblan or Alice Springs Orogeny producing the present pattern of rocks in the Mutawinjti region.

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**Figure 1.** Simplified geological map of the Bancannia Trough showing its regional relationships.

# Fe-OXIDE Cu–Au DEPOSITS: POTENTIAL OF THE CURNAMONA PROVINCE IN AN AUSTRALIAN AND GLOBAL CONTEXT

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## FE-OXIDE CU–AU DEPOSIT CHARACTERISTICS

The Fe-oxide Cu–Au (IOCG) family of deposits encompasses a diverse range of magnetite- and hematite-associated mineralization, ranging in age from possibly Archaean through Proterozoic to the Mesozoic and Tertiary. Since its recognition as a deposit class (Hitzman et al., 1992), the boundaries in definition have been the subject of vigorous debate, as shown by the range of deposits described in two landmark volumes compiled by Porter (2000, 2002). The Olympic Dam Cu–U–Au–Ag deposit, Ernest Henry Cu–Au deposit in the Cloncurry district, and Tennant Creek Au–Cu–Bi district, are Australia's pre-eminent examples. Yet the Archaean/Proterozoic Carajás Mineral Province in Brazil (e.g., Salobo, Sossego, Alemão deposits) rivals Olympic Dam as the world's richest in terms of contained metal in an IOCG district with >1.8 billion tonnes of 1–2% Cu and 0.5–1.1 g/t Au (Haynes, 2000). The Chilean Iron Belt contains many Mesozoic examples, including the Candelaria deposit (384 Mt @1.1% Cu, 0.3 g/t Au).

Based on published descriptions and the author's observations (e.g., Skirrow, 1999), the unifying characteristics of IOCG deposits and districts are as follows.

### Composition

- Copper and gold are the principal economic commodities; Cu/Au ratios tend to be highly variable between deposits in a district and even between orebodies within a deposit.
- Ag, U, REE, Co, Bi are economic in some deposits, and Mo, F, Ba, P, Mn, Ni and carbonate are commonly elevated; Pb and Zn are generally in low concentrations.
- Epigenetic copper and iron sulfide and gold mineralization is spatially associated (at deposit- and orebody-scale) with abundant to minor magnetite, hematite, or both. The Fe-oxides pre-date or are coeval with sulfides and gold.
- Both hematite-rich and magnetite±pyrrhotite-bearing deposits may be present in an IOCG district, reflecting a range of oxidation states from oxidized to reduced deposits. This variation is also present within some deposits (e.g., Candelaria).
- Fe-sulfides (pyrite and much less commonly pyrrhotite) tend to be of sub-equal or lower abundance than the Cu±Fe-sulfides (chalcopyrite, bornite, chalcocite).
- Proximal alteration most closely associated with Cu–Fe sulfide and Au mineralization varies from assemblages of magnetite, biotite, K-feldspar and actinolite, to assemblages of hematite, white mica, chlorite; both end-member assemblages may contain carbonate, barite and fluorite.
- Quartz is not generally abundant in ore-stage assemblages.

### Style

- Deposit morphology and style, although variable, generally reflect strong structural controls by fault and shear zones where they intersect zones of differing rheology, permeability and/or chemical reactivity; styles include breccia-hosted disseminated mineralization, vein stockworks, and stratabound disseminated to semi-massive replacement orebodies.
- Deposits that formed at deeper crustal levels tend to be related to brittle-ductile shear zones (e.g., Ernest Henry, Salobo, Alemão), whereas those at shallower levels are dominated by breccias (e.g., Olympic Dam) and vein stockworks (e.g., Candelaria).

### Timing

- Relative timing of mineralization is broadly syn- to late-deformational, commonly within a multi-stage structural history.
- Where geochronology data are available, IOCG deposits appear to form during orogenesis (as yet poorly characterized), and commonly overlap in timing with felsic and mafic magmatism and low to medium grade regional metamorphism.



### Regional settings

- Host rocks are diverse, and include felsic and intermediate volcanic and intrusive rocks, and metasedimentary rocks of low to medium metamorphic grade; high grade metamorphic host rocks appear to be rare.
- Host sequences (particularly in footwalls) tend to contain little or no reduced carbon at exposed crustal levels (Haynes, 2000), whereas Fe is generally abundant as magnetite and hematite rather than as sulfides, resulting in regionally elevated magnetic responses (whether primary or secondary); basalts, evaporates, carbonates and their calcsilicate metamorphic equivalents are commonly but not universally known in IOCG districts.
- Most IOCG districts are characterized by regional-scale alteration zones containing albite, calcsilicates and magnetite; deposits of magnetite-apatite may form part of this suite.
- IOCG deposits show a broad spatial association with co-temporal felsic, intermediate and/or mafic intrusive rocks, but unlike porphyry copper deposits, local 'causative' intrusions have been observed only in some areas. The felsic intrusive rocks are generally magnetite-bearing I- or A-type. Mafic intrusives result in regional gravity highs.

### Fluids

- In the limited number of deposits for which there are data, two or more fluids are commonly recognised including: ~250–450°C hypersaline brines in equilibrium with magnetite; lower temperature less saline fluids in equilibrium with hematite; and CO<sub>2</sub>±CH<sub>4</sub>-rich fluids. The presence of some or all of these fluids is fundamental to the Fe-oxide rich character and metal and alteration signatures of IOCG deposits.
- Sulfur isotope ( $\delta^{34}\text{S}$ ) compositions of Cu–Fe sulfides are generally in the range –3 to +4‰ in magnetite-dominated deposits, and extend to more negative values in some hematite-dominated deposits.
- Oxygen isotope ( $\delta^{18}\text{O}$ ) compositions of ore fluids range from +4 to +11‰, overlapping with fluids in equilibrium with igneous or metamorphic rocks.

Although substantial descriptive and analytical data are now available for IOCG deposits, there remain many major areas of uncertainty in the interpretation of the data. For example, the role of igneous intrusions in IOCG genesis, and the tectonic/geodynamic settings and crustal architecture of IOCG districts are still poorly understood. The relationships between regional alteration, magnetite-apatite deposits, and IOCG deposits remain unclear, as do the relationships between IOCG, porphyry copper(-gold), lode gold and Broken Hill type Pb-Ag-Zn deposits, all of which may occur in nearby districts. Finally, a comprehensive understanding of ore fluid properties, which is fundamental to any unified model of ore genesis of the IOCG family of deposits, awaits further data acquisition the full range of deposits.

### **DOES THE CURNAMONA PROVINCE HAVE POTENTIAL FOR MAJOR CU-AU DEPOSITS?**

The Curnamona Province contains several significant Cu-Au prospects, including Portia, Kalkaroo, Waukaloo, and White Dam in the Olary Domain, and Copper Blow in the Broken Hill Domain. Many other Cu-Au occurrences are known; in conjunction with the major prospects they represent very widespread operation of Cu-Au mineralizing processes. However, none of these prospects has yielded sufficiently large tonnages of ore-grade mineralization to be economic. How does the Curnamona Province compare with well-mineralized IOCG districts in Australia and globally, and can we identify the 'ingredients' needed to form economic deposits? We assess each of the major groups of characteristics below, based on descriptions by Ashley et al. (1998), Skirrow et al. (2000), Teale and Fanning (2000), and Williams and Skirrow (2000).

**Composition:** Cu-Au mineralization is associated with anomalous Mo, Ag and Co at most of the prospects, and is spatially associated at deposit to hand specimen scale with variable amounts of magnetite and hematite. The metal association at Portia also includes anomalous LREE, Ba, F, Te, Bi, Hg, V, and B. The relative amounts of iron oxides are highly variable. For example, at Copper Blow the Cu-Au mineralization is hosted by massive magnetite-biotite ironstone within a shear zone, whereas at Kalkaroo lesser magnetite (up to 10 vol. %) is present as disseminations and veins in the footwall to the higher grade mineralization. The White Dam gold prospect may be an extreme case in which there is virtually no iron oxide associated with the gold and minor chalcopyrite-pyrite-molybdenite mineralization. Minor hematite is present in three forms: specular (e.g., Kalkaroo, Portia, in places pseudomorphed by magnetite); as dusting in feldspars; and as martite replacements of magnetite. Chalcopyrite co-precipitated with both magnetite and hematite in different stages of the parageneses. Iron sulfides are generally similar in abundance or subordinate to chalcopyrite, with pyrite (all prospects) by far dominant over pyrrhotite (Copper Blow, Lawsons, Dome Rock, Kalkaroo hangingwall). All prospects contain chalcopyrite, with only a few known hypogene bornite occurrences (e.g., Walparuta).

Alteration assemblages paragenetically associated with Cu-Au mineralization are typically potassic, as represented by biotite and K-feldspar (e.g., Kalkaroo, Portia, Copper Blow, Walparuta, Green & Gold).

Actinolite also is important in some mineralization (e.g., Kalkaroo and Portia footwalls, Waukaloo), and albite and carbonate are widespread phases. Some chalcopyrite co-precipitated with chlorite, which commonly replaced biotite and actinolite. Hydrothermal white mica is not prominent but has been noted as a post-sulfide phase at Mundi Mundi and Walparuta where  $^{40}\text{Ar}$ - $^{39}\text{Ar}$  dating yielded ages of ~1500 Ma (Skirrow et al., 1999) and ~480 Ma (Bierlein et al., 1996a).

Most of the compositional attributes described above are consistent with those of IOCG deposits that formed at moderate crustal depths, although the relative quantities of Fe-oxides are lower than in many of the major deposits.

Style and structure: Many of the Cu-Au prospects in the Curnamona Province are stratabound disseminated replacements and veinlet networks; massive ironstone-hosted mineralization is uncommon despite the existence in the Olary Domain and southern Broken Hill Domain of numerous small epigenetic ironstones. Brecciation is very limited in extent, and appears to be related to shearing (e.g., Walparuta). The lack of extensive zones of primary or secondary permeability, such as coarse clastic rocks, breccias, or fracture networks, is a major difference between prospects in the Curnamona Province and the larger IOCG deposits.

Timing: In all of the Curnamona Cu-Au prospects, mineralization was syn- to late-deformational and in some cases post-peak metamorphic (e.g., Copper Blow). However, mineralized assemblages at Kalkaroo, Portia, Waukaloo and White Dam are consistent with the peak or near-peak metamorphic assemblages in the upper greenschist to amphibolite facies host rocks. Re-Os dating of molybdenite in Cu-Au mineralized zones in these four prospects yielded one coherent age grouping of 1612–1616 Ma (six dates), and three older ages (1624–1632 Ma; Skirrow et al., 2000). These compare with the regional metamorphic peak (Olarian Orogeny) of ~1600 Ma, determined from U-Pb zircon dating (Page et al., 2000). Uncertainties of up to ~1% in the Re-Os ages (due to isotope spiking, decay constant errors, etc) mean that we cannot differentiate the younger six molybdenite ages from the Olarian Orogeny. These relationships to regional deformation and metamorphic events are in keeping with the timing of IOCG deposits elsewhere.

Setting: A number of the Cu-Au prospects in the Curnamona are hosted by high metamorphic grade quartzofeldspathic gneisses (Copper Blow, White Dam); the lower metamorphic grade sedimentary rocks of the Curnamona Group in the northern Olary Domain may be closer analogues to the host sequences of the major IOCG deposits. The generally Na-feldspathic Curnamona Group and Thackaringa Group equivalents in the Broken Hill Domain lack reduced carbon and contain widespread magnetite and local pyrite and hematite (e.g., in piemontite-bearing units). This relatively oxidized composition (whether primary or secondary) is evident in aeromagnetic data as elevated but variable responses. The overlying relatively reduced Strathearn Group (with local carbonaceous matter and pyrite-pyrrhotite) contrasts in its 'flat' magnetic response. Many of the Cu-Au prospects are situated close to the boundary between the oxidized and reduced rock packages. Such contrasts in oxidation state are present in some but not all of the major IOCG host sequences.

Regional albitic (-calcsilicate-magnetite) alteration in the Curnamona Province is analogous to that in many IOCG districts (see Porter, 2000, 2002). However, in the former, regional syntectonic Na-Ca alteration has been dated at ~1575 Ma (Kent et al., 2000) or ~1584–1588 Ma (Skirrow et al., 2000) and is apparently up to ~40 m.y. younger than Cu-Au-Mo mineralization at Portia, Kalkaroo, White Dam and Waukaloo. Fluid oxygen isotope compositions also indicate differences between regional alteration and Cu-Au ore fluids (see also below).

Although ~1580–1600 Ma granitoids are widespread particularly in the Olary Domain there is no close spatial or temporal association with known Cu-Au mineralization. Irrespective of whether magmas were sources of ore components in IOCG deposits or had less direct roles, the apparent lack of felsic and mafic igneous rocks coeval with Cu-Au is unlike most major IOCG districts. Further geochronology is needed to better constrain intrusive and hydrothermal events associated with the Olarian Orogeny.

Fluids: Relatively little is known of the fluids in Fe-oxide Cu-Au mineralization of the Curnamona Province. Bierlein et al. (1996b) reported a wide range of fluid types in epigenetic Cu and Pb-Zn mineralization in the Olary Domain: (1) hypersaline inclusions (homogenization temperatures ~240–330°C); (2) lower temperature more dilute fluids; and (3) CO<sub>2</sub>- and CH<sub>4</sub>-rich fluids. Reconnaissance fluid inclusion data from Kalkaroo indicate the presence of hypersaline brines (multi-phase inclusions with total homogenization at ~350–400°C) in quartz-magnetite-chalcopyrite assemblages (R. Skirrow, unpubl. data). In addition, moderately saline lower temperature fluids, and CO<sub>2</sub>±N<sub>2</sub> fluids, are present at Kalkaroo. Oxygen isotope compositions of fluids related to Cu-Au mineralization have  $\delta^{18}\text{O}$  values of +5.5 to +8.5‰, whereas regional Na-Ca alteration fluids yield

values of +8 to +13‰ (Skirrow et al., 2000). These fluid properties are very similar to those of the major IOCG deposits, and are perhaps one of the most favourable indicators of IOCG potential in the Curnamona Province.

## CONCLUSIONS

Iron oxide Cu-Au mineralizing systems were operating in the Curnamona Province broadly around the time of the ~1600 Ma Olarian Orogeny, a tectono-thermal event that is also recorded in the Gawler Craton at ~1590 Ma and during which Olympic Dam formed. The Mt Isa Inlier experienced metamorphism and hydrothermal activity (Osborne Cu-Au deposit) at ~1580-1600 Ma (Giles & Nutman, 2002; Gautier et al., 2001), but links involving the Curnamona Province, Mt Isa Inlier and Gawler Craton are yet to be reconstructed in detail.

Potential for large economic Cu-Au deposits in the Curnamona Province, in the author's view, is dependant on (a) recognition of chemical traps more efficient than those found to date, such as large ironstone bodies or preserved near-palaeosurface environments conducive to fluid mixing, and (b) identification of structural settings that provided large-scale secondary permeability, such as dilatant jogs in major fault/shear zones, or breccias of tectonic or volcanic/sedimentary origin.

## ACKNOWLEDGEMENTS

RGS publishes with permission of the Executive Director, Geoscience Australia. I would like to thank Paul Ashley, Colin Conor, George Gibson, Barney Stevens, Rod Page, Katz Suzuki and Neil McNaughton for their contributions to discussions on the Curnamona Province. Dave Huston and Subhash Jaireth are thanked for their reviews.

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# SPECULATIONS CONCERNING THE ORIGIN AND EXPLORATION SIGNIFICANCE OF LODGE ROCKS IN THE CURNAMONA PROVINCE

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## INTRODUCTION

In the Broken Hill Domain of the Curnamona Province, lode horizon rocks (garnet quartzite, garnetite, blue quartz-gahnite ( $\text{ZnAl}_2\text{O}_4$ ) lode, and lode pegmatite), which are spatially associated with over 400 minor Broken Hill-type (BHT) deposits including the main Broken Hill deposit, constitute a primary empirical exploration tool for BHT deposits. All four lode horizon rocks are spatially associated with the main Broken Hill deposit whereas blue quartz-gahnite lode is the most widely distributed of the lode horizons in the Broken Hill Domain (Barnes et al., 1983) followed, in order of abundance, by garnet quartzite and garnetite. Lode pegmatite is relatively uncommon outside of the main Broken Hill deposit. Despite the obvious spatial relationship of these rock types to base metal mineralization, their origin is steeped in controversy and the way these rock types can successfully be used as exploration guides to BHT deposits in the Curnamona Province deposits is yet to be determined. The present contribution discusses the origin and exploration potential of garnet- and gahnite-rich lode rocks in the Curnamona Province.

## ORIGIN OF GAHNITE-RICH ROCKS

At the main Broken Hill lode, blue quartz-gahnite lode is spatially associated with sulfides in C and B lodes and it also occurs along the margins of A lode as well as 2 and 3 lenses at the northern end of the deposit. Away from the Broken Hill deposit, blue quartz-gahnite rocks are generally medium- to coarse-grained, narrow (1-2 m wide) poorly laminated rocks, which occur intermittently for over 330 km (Barnes et al. 1983; Plimer 1984). In places, blue quartz-gahnite lodes grade into garnet quartzite, garnetite, sillimanite gneiss, and amphibolite. Most examples of blue quartz-gahnite lode are generally concordant to other rock types in which they are hosted (metasedimentary gneisses mainly) but it crosscuts, for example, metasedimentary gneisses at the Nine Mile deposit (e.g., Balkau, 1974), garnet quartz rocks at the Second to None mine, and garnet quartzite, in places, in the main Broken Hill lode. Although the structural and paragenetic relationship between blue quartz-gahnite lode and other rock types in the Mine Sequence, including sulfide mineralization and the garnet-rich lode, suggests that the precursors to gahnite-bearing rocks formed pre D1, it is also apparent that the spatial relationship of some gahnite-quartz rocks to D2 and D3 folds indicates that these rocks had a protracted history of development. In addition to occurring in quartz-gahnite rocks, gahnite has been reported in a variety of other lithologies in the Broken Hill Domain including banded iron formation, aluminous metasediments, Potosi gneiss, pegmatite, amphibolite, and quartz veins (Barnes et al., 1983). Most of the gahnite in the Broken Hill deposit formed by reactions in the system Zn-Fe-Al-Si-S-O (e.g., Spry and Scott, 1986; Jain, 1999), however, gahnite clearly formed by other mechanisms including: 1. Deposition from a metamorphic hydrothermal solution (e.g., Hillam, 1974) to explain the presence of gahnite in quartz veins, pegmatites, and shear zones; and 2. The involvement of a hydrothermal component (e.g., Zn and possibly Fe) with components (e.g., Al) from pelagic material. Such a sedimentary-metamorphic model accounts for gahnite in sillimanite gneisses (e.g., Plimer, 1984) and banded gahnite-garnet rocks at, for example, the Angus-Kintore deposit. Zincian spinel associated with massive sulfides in B and C lodes is enriched in the gahnite molecule relative to that in adjacent sillimanite gneisses, which contains a higher proportion of the hercynite molecule (Fig. 1). This is also the case for gahnite in similar rocks in and adjacent to minor BHT deposits. Preliminary data suggest that zincian spinel in and adjacent to the main Broken Hill lode contains between 5 and 15 mole % spinel *sensu stricto*, whereas that associated with rocks in and adjacent to minor BHT deposits exhibits a broader range of spinel *sensu stricto* compositions (0 to 20 mole %).

## ORIGIN OF GARNET QUARTZITE AND GARNETITE

Two main types of garnet-rich rock occur in the Broken Hill deposit: quartz-garnetite, locally referred to as "garnet quartzite," and garnetite. A variety of models have been proposed to explain the origin of garnet quartzite and garnetite in the main Broken Hill lode, including:

1. Metamorphism of mangiferous exhalites mixed with aluminous pelagic sediments (e.g., Plimer, 1984).

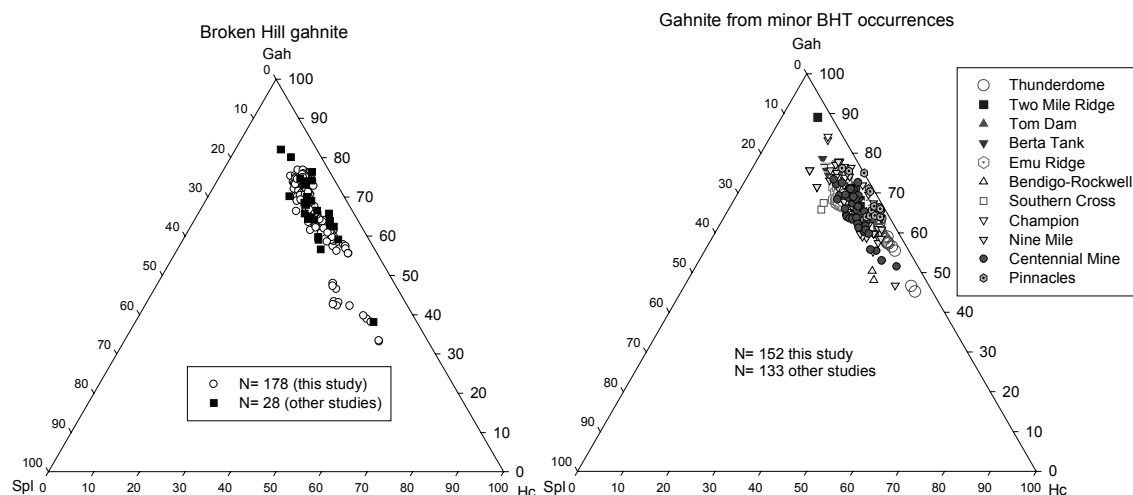


Figure 1. Ternary plot of gahnite compositions from the Broken Hill lode and minor BHT deposits. Data are from Balkau (1974), Hillam (1974), Spry and Scott (1986), Wiggins (1988), Jain (1999), and this study.

2. Metamorphism of an original detrital sediment.
3. Metasomatic interaction between the deposit and the wall rocks either pre-, syn- or post-peak metamorphism; and
4. A reaction between partially melted orebodies and the surrounding pelitic rocks (Mavrogenes et al., 2001).

Spry and Wonder (1989) recognized at least seven types of garnet quartzite and proposed that banded and fine-grained massive garnet quartzites, which are the most common types of garnet-rich rock in the Broken Hill deposit, are metamorphosed exhalites. However, Spry and Wonder (1989) also recognized a relatively minor, but distinct, coarse-grained remobilized variety of garnet quartzite in and adjacent to 2 and 3 lenses where it cross cuts banded garnet quartzite. The remobilized variety is different from a rock type known locally as "garnet rim." Remobilized garnet quartzite and "garnet rim" formed by metasomatic processes during D3.

Garnet-quartz rocks in the main Broken Hill deposit are very similar to quartz-garnet rocks throughout the Broken Hill Domain; however, there are some differences between the two groups of rocks. For example, whereas both groups of rocks contain the same major phases (mainly quartz and garnet with lesser amounts of feldspar, apatite, biotite, muscovite, gahnite, magnetite, grunerite, cummingtonite, pyrrhotite, secondary pyrite, galena, sphalerite, and chalcocopyrite), there appears to be a larger number of minerals associated with garnet quartzites and garnetite from the Broken Hill deposit. At the Pinnacles deposit, the second largest BHT deposit in the Curnamona Province, apatite occurs in garnet- and gahnite-rich rocks, and magnetite is present in garnet quartzite from the Melbourne Rockwell deposit and is also present along with grunerite and hornblende in the Thunderdome prospect. One mineral that is generally absent in garnet quartzites in the main lode is tourmaline. By contrast, it is relatively common in garnet quartzites in the Broken Hill Domain. A further difference is reflected in the composition of garnets in garnet-rich rocks. In the Pinnacles and Broken Hill deposits, garnet in garnet-rich rocks shows a range of Mn-Fe-Ca-Mg compositions that reflects the bulk composition of the associated orebody. However, most garnets in garnet-rich rocks in minor BHT deposits have compositions near the spessartine ( $\text{Mn}_3\text{Al}_2\text{Si}_3\text{O}_{12}$ )-almandine ( $\text{Fe}_3\text{Al}_2\text{Si}_3\text{O}_{12}$ ) join. Garnet is, in general, more depleted in the grossular ( $\text{Ca}_3\text{Al}_2\text{Si}_3\text{O}_{12}$ ) molecule compared to garnet in garnet-rich rocks in the Broken Hill and Pinnacles deposits (Fig. 2).

If the precursors to garnet in banded and fine-grained massive garnet quartzite in the Broken Hill deposit formed by exhalative or possibly inhalative processes, garnet in these rocks should exhibit ages equivalent to those of the Hores Gneiss ( $1693 \pm 5$  to  $1686 \pm 3$  Ma; Page et al. 2000). However, if garnet- and gahnite-rich rocks are products of peak metamorphic or post peak metamorphic mineralizing events involving metasomatism of a reactive Mn-Ca-Fe-rich sulfide orebodies or a syn-peak metamorphic reaction between country rocks and melting massive sulfides, then zircon should reflect the peak metamorphic event at  $1600 \pm 8$  Ma (i.e. D1) or some late event (D2:  $1597 \pm 3$  to  $1596 \pm 3$  Ma, or D3:  $1596 \pm 3$  to  $1591 \pm 5$  Ma; Page et al., 2000). U-Pb dates of zircon from garnetite by Ehlers et al. (1996) from the Pinnacles deposit and the South Operations mine of the Broken Hill deposit yielded ages of  $1587 \pm 4$  Ma and  $1589 \pm 5$  Ma, respectively. In addition, Ehlers et al. (1996) obtained a Sm/Nd whole rock age of  $1574 \pm 23$  Ma from garnetite in the Southern Leases. While these ages point to D2 or D3 ages, these are at odds with a Pb model age of 1675 Ma (Sun et al., 1996) of galena from the Broken Hill

deposit. Ehlers et al. (1996) interpreted their data to suggest that garnetite is a purely metamorphic/metasomatic product or that high-grade metamorphism erased all traces of older inherited zircons or garnets. They concluded that their data are inconsistent with a syn-sedimentary model for the Broken Hill deposit. However, the data of Ehlers et al. (1996) should be treated with caution since metasomatic overgrowths of garnet on euhedral cores are quite common (Spry and Wonder, 1989), especially near the edges of the lead-rich lodes where late D3 garnet envelope crosscuts garnetite. Furthermore, banded garnet quartzites and garnetites are notorious for being crosscut by late, white colored D3 stage quartz veins and associated metasomatic garnets.

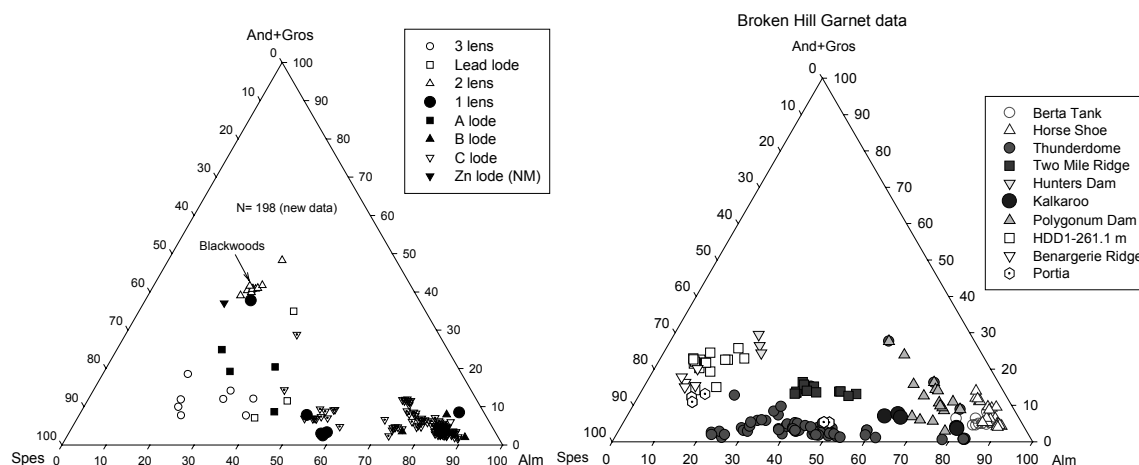


Figure 2. Ternary plot of garnet compositions in garnet quartzite and garnetite in the Broken Hill lode (data from Spry and Wonder (1989) and this study; and in garnet-rich rocks from minor BHT occurrences.

Frost et al. (2002) provided compelling arguments that some minerals in the systems Ag-Pb-S, Ag-Sb-As-S, Cu-Pb-Sb-S, Cu-As-S, Sb-As-S, Cu-Sb-S, and Fe-As-S may have melted since eutectic temperatures in these systems are below peak metamorphic conditions of 780°C and 5.2 kb that affected the Broken Hill deposit. However, minerals in these systems constitute <1 % of the orebodies. The most important ore system at Broken Hill is Zn-Pb-Mn-Fe-S. Mavrogenes et al. (2001) conducted experiments on the system Zn-Pb-Fe-Ag-S and argued that they supported the concept of widespread partial melting of the orebodies, the observed zonation of Zn-rich orebodies stratigraphically above Pb-rich orebodies, and the formation of the lode rocks. However, there are problems associated with the model that include: 1. Whether the experiments adequately mimic the ore system and metamorphic conditions at Broken Hill; 2. The absence of a mechanism to explain the ore zonation, which has not affected country rocks between individual orebodies; 3. How lode rocks form in minor BHT deposits in the Curnamona Province that were metamorphosed to P-T conditions well below that of the Zn-Pb-Fe-Ag-S sulfide eutectic; and 4. Why there are Zn-rich "restites" above and below the Pinnacles Pb lode orebody, if the density stratification of Zn and Pb sulfide concept of Mavrogenes et al. (2001) is correct.

### The Composition of Gahnite and Garnet in Lode Horizons as Potential Guides to Ore

Spry and Scott (1986) showed that the composition of gahnite in the assemblage gahnite-sphalerite-pyrrhotite±almadine±sillimanite, which is common in BHT deposits in the Curnamona Province, is fixed because the gahnite:hercynite ratio is buffered by the  $a_{FeS}$  in sphalerite coexisting with pyrrhotite. This is the main reason why zincian spinels in the Broken Hill deposit and minor BHT deposits have a fairly restricted composition. Therefore, the use of a major element signature involving Zn-Fe-Mg-Mn, which has been used in other metamorphic terranes as an exploration guides, will likely have less success in the Curnamona Province since all BHT deposits appear to have approximately the same composition. This lack of success in the Curnamona Province is compounded by the fact that gahnite compositions are also dependent upon: 1. Temperature (zincian spinels commonly contain more Zn at greenschist facies than at granulite facies). This effect should be evident when comparing gahnite compositions in BHT deposits from the Olary Domain (greenschist and amphibolite facies) with those from the Broken Hill Domain (amphibolite and granulite facies); 2. Bulk composition of gahnite-bearing host rocks; 3. Pressure; and 4. The fugacities of sulfur and oxygen.

The presence of grossular-rich garnets in some lodes in the Broken Hill and Pinnacles deposits suggests that the Ca content of garnet may serve as a potential guide to finding "larger" BHT deposits, since Ca-poor garnets are generally present in minor BHT deposits in the Curnamona Province. Garnet dominated by spessartine-almadine molecules is generally the norm for garnet in gahnite and garnet-rich lode rocks in the main Broken Hill lode and minor BHT deposits in the Curnamona Province. However, the use of garnet and gahnite compositions in distinguishing between potential large BHT deposits from minor BHT occurrences may lie with

trace element compositions (e.g., Walters, 2001). To date, the rare-earth element contents have received the most attention. For example, Lottermoser (1989) reported that garnet quartzites proximal to sulfide ore zones were enriched in  $\text{Eu}^{2+}$  whereas those from distal localities were depleted in  $\text{Eu}^{2+}$ . Although this suggests that the Eu anomaly could be used as a potential guide to ore, Wiggins (1988), for example, showed that garnet quartzites proximal to the Broken Hill deposit were enriched and depleted in  $\text{Eu}^{2+}$ . The positive and negative Eu anomalies in garnet quartzites while dependent on T, pH and oxygen fugacity also reflect variable contributions of detrital and hydrothermal components to the source material.

## CONCLUSIONS

Fine-grained massive and banded varieties of garnet quartzite, the most common garnet-rich rocks in the Curnamona Province, including the Broken Hill deposit, most of the blue quartz-gahnite lode horizon, and possibly garnetite, appear to be meta-exhalites. However, there is unequivocal evidence that some minor gahnite-rich rocks and other less common but distinct varieties of garnet quartzite, such as the so-called "remobilized" garnet quartzite of Spry and Wonder (1989), formed syn- or post-peak metamorphism as a result of metasomatism. While there does appear to be evidence for localized and very minor partial melting of the orebody rich in minor elements including Cu, As, and Sb, partial melting of the ore involving the major elements Zn-Pb-Fe-Ag-S to form the garnet- and gahnite-rich rocks remains in question. We recommend that the use of major and trace compositions of garnet and gahnite be further investigated to try and define a chemical fingerprint that can be used to distinguish between "large" BHT deposits and minor BHT occurrences.

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# UNDERSTANDING THE BROKEN HILL Pb-Zn FLUID SYSTEM

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This paper follows Huston et al. (1998) and Stevens (1999) in trying to developing a realistic, detailed model for the fluid system which formed the Broken Hill orebody and the other Broken Hill type deposits of the area. Hopefully it will stimulate research and maybe provide pointers for exploration. The model developed here is based on formation of the Broken Hill orebody at the same time as the enclosing rocks or shortly after, well before high grade metamorphism and accompanying deformation. This model has similarities to elements of previous models, but differs significantly and attempts to relate to observed geological features.

## CRITICAL FACTORS

The model was inspired by several critical observations:

1. There are a few hundred small Broken Hill type deposits spread over 3000 km<sup>2</sup> in the Broken Hill Block. Almost all lie in the Broken Hill Group, mostly in metasediments no different from those in the overlying Sundown Group or the underlying Cues Formation.
2. The volume of leached rock required to supply the metals for the Broken Hill orebody, is of the order of 8000 km<sup>3</sup>, assuming 10% leach efficiency (Huston et al. 1998), requiring a district scale, rather than local scale reservoir.
3. Lead isotope models (Carr and Sun 1996) permit the orebody to be as old as the Hores Gneiss host (1685 Ma), or as young as the middle Paragon Group (1650 Ma).
4. Zircon geochronology has shown that shallow intrusion of dolerite and granite sills approximately coincides with the time of deposition of Hores Gneiss.
5. Black smokers, a spectacular manifestation of seafloor mineralisation, are considered to be very inefficient, losing 90% of their sulphides to the water column. The important action takes place below the seafloor, where sulphide bodies grow like huge blisters, and fluids can flow sideways along porous beds to deposit "inhalative" mineralisation.

## A MODEL FOR BROKEN HILL TYPE MINERALISATION, WITH VARIATIONS

The model: the Broken Hill orebody formed from hot springs on the seafloor, or at shallow depth below it, or both. The banded iron formations (BIFs) stratigraphically below the orebody were seafloor exhalites formed from lower temperature springs preceding orebody deposition, while those above the orebody were formed later than the orebody, or were contemporaneous with subsurface orebody formation. Some small Broken Hill type deposits formed within the sedimentary pile; others may have formed on the seafloor. The quartz-gahnite "lode rocks" associated with the orebody are metamorphosed "inhalites", formed by lateral migration of fluids along permeable beds. Garnet quartzite "lode rocks" associated with Broken Hill type deposits are metamorphosed, sub-seafloor altered host rocks.

A further variation on the model, permitted by the Pb isotope models and some field data, is that the orebody formed in upper Sundown Group time, several hundred metres below the seafloor. Ore deposition at such depth could result from cooling of the ore fluid, possibly due to fluid mixing, or from boiling if the overlying water column was shallow. Depositional environments of the Willyama Supergroup are not yet well understood.

## THE FLUID RESERVOIR

If the configuration of the ~8000 km<sup>3</sup> fluid reservoir, needed to form the Broken Hill orebody, was similar to that illustrated by Davis and Fisher (1994) for the Middle Valley area (Juan de Fuca Ridge), its vertical dimension was probably no more than 1-8 km. The surface area was of the order of 1000-8000 km<sup>2</sup>. Small Broken Hill type deposits are spread over an area of ~3000 km<sup>2</sup>. Unfolding the rocks would increase the area to perhaps 12,000 km<sup>2</sup>, the order of magnitude required for the orebody reservoir. It is likely that the small Broken Hill type deposits mark the extent of the fluid reservoir that formed the Broken Hill orebody and they represent leakage from an underlying reservoir, situated in the Thackaringa Group or lower. A reservoir with area of 12,000 km<sup>2</sup>, vertical dimension of 1 km, and leach efficiency of 10% would produce sufficient Pb from normal crustal rocks, for 1.5 Broken Hill orebodies. With vertical dimension of 4 km and leach efficiency of 25%, there would be sufficient Pb for 15 Broken Hill orebodies, or 150 modest 30 mt orebodies.

## POSITION OF THE RESERVOIR IN THE STRATIGRAPHIC SEQUENCE

Some of the extensive albite rocks stratigraphically below the Broken Hill Group, especially in the Thackaringa Group, contain very low values of Pb and Zn, possibly the result of leaching. This makes the Thackaringa Group



a candidate for the reservoir, as implied by Huston et al. (1998). Albitisation and leaching of metals may have been part of the one process, as suggested by Brauhart et al. (2001) for the Panorama area in the Pilbara (W.A.).

There are oxidised (magnetite-bearing) zones in the Thackaringa Group and most of Thorndale Composite Gneiss (and Clevedale Migmatite) is magnetite-bearing. Magnetite in these rocks and the sulphur for the Broken Hill orebody could be products of inorganic thermochemical reduction of seawater sulphate (Ohmoto et al. 1983). The reaction:  $\text{SO}_4^{2-} + 2\text{H}^+ + 12\text{FeO}_{\text{rock}} = \text{H}_2\text{S} + 4\text{Fe}_3\text{O}_4$  requires a sulphide mineral such as pyrite to catalyse the reaction, and temperatures of 300-350°C. The presence of significant amounts of Au and other elements in the orebody indicates relatively high fluid temperatures and reduced conditions (Cooke et al. 2000). The abundant pyritic lodes in the Thackaringa Group could have either catalysed the reaction or formed as a result of that reaction.

### **IMPORTANCE OF A GOOD SEAL**

In order to create a large orebody on the seafloor, it is necessary to have a large reservoir with porous and permeable rocks. It is just as necessary to have a very efficient seal, to stop the fluids leaking out. The Broken Hill and Sundown Groups contain extensive sillimanite-rich pelites which were deposited as wet clay. Fluids can travel through rocks with primary porosity, such as sandstone, through lithified and fractured sedimentary rocks, and through rocks like dolerite which microfracture, but not through wet clay.

It is likely that the albite rocks in the Thackaringa Group were in part, porous sandstone, and that the more clay-rich Broken Hill Group formed an efficient seal. If the orebody formed during upper Sundown Group time, then the pelitic lower Sundown Group could have acted as an efficient seal.

### **THE FOCUS FOR THE BROKEN HILL OREBODY**

There was probably a huge, relatively horizontal reservoir, with an impermeable seal of wet clay. Somewhere an enormous leak developed, probably along a fault. Fluid flow modelling studies indicate that fluids travel up hot faults, and that the hottest faults are deep faults and faults with intrusions near them (Yang et al. 2001). The Rasp Ridge Gneiss was a granite sill emplaced stratigraphically below the Broken Hill orebody at  $1683 \pm 3$  Ma (Page et al. 2000), indistinguishable in age from the volcanoclastics of Hores Gneiss. The sill was emplaced no more than 1 km below the surface.

It is likely that ore fluids heated by the granite, travelled up a NE trending fault above the granite sill, and deposited either on the seafloor, or below it, where fluid mixing or boiling occurred. The heat from the granite could have lithified the overlying sediment, allowing fracture permeability to develop along a fault, and thereby breaching the seal.

If the orebody formed during upper Sundown Group time, the granite would have been cold, and maybe irrelevant. This alternative is less attractive.

### **DEVELOPMENT OF SMALL BROKEN HILL TYPE DEPOSITS**

Most small Broken Hill type deposits occur stratigraphically below Hores Gneiss, scattered through the Broken Hill Group, especially in or close to Parnell Formation. Preliminary Pb isotope data indicate that some of these deposits are the same age as the Broken Hill orebody (Parr and Carr 2002). So these deposits could not have formed on the seafloor. Other deposits are older than the Broken Hill orebody, and could have formed on the seafloor. Many small Broken Hill type deposits occur close to (some in) amphibolites of Parnell Formation, originally dolerite sills (Stevens 1998a) emplaced within unlithified sediments. The dolerites baked the enclosing sediments, lithifying them and allowing them to fracture. Metal-bearing fluids were able to leak into the metasediments and the microfractured dolerites, from the underlying reservoir.

### **“EXHALITES” AND “INHALITES”**

A range of unusual rock types at Broken Hill have been classed as “exhalites”. It is suggested here that only some types of iron formation were exhalites; the other “lode rocks” were “inhalites” and alteration products formed at shallow depth below the seafloor.

Quartz-gahnite rocks, associates of large and small Broken Hill type deposits, were “inhalites”. Just as the small Broken Hill type deposits of the same age as the Broken Hill orebody, could not have formed on the seafloor, neither could the associated quartz-gahnite rocks. The textures in quartz-gahnite rocks do not indicate precipitation on the seafloor: layering is poorly developed where developed at all, and is discontinuous. Quartz-

gahnite rocks are the result of leakage of metalliferous fluids along porous beds or along fractures, below the seafloor. Some have been remobilised during deformation.

The Mn garnet-magnetite-quartz-apatite BIFs of Broken Hill Group show features expected from seafloor chemical precipitates: fine-scale, very continuous lamination (Stanton 1976), and probable soft sediment slumping. They are very similar to BIFs found elsewhere associated with massive sulphides, and interpreted as exhalites (e.g. Peter in press)

### **MAGNETITE-BEARING METASEDIMENTS AS SIGNATURES OF BLACK SMOKERS**

In places BIFs are closely associated with disseminated magnetite in metasediments. The disseminated magnetite could be a dilute form of BIF. Examples are found near the Wilcannia road NE of North mine, and in drill hole DDH S2710, near the Western Mineralisation. It is hypothesised that some very extensive magnetite-bearing zones in metasediments might be signatures of black smokers, the exhaust from sulphide orebodies.

The inhalative Southern Cross Pb-Zn deposit (Purnamoota road) occurs just above Parnell Formation. Stratigraphically above the Southern Cross, Hores Gneiss is riddled with calc-silicate alteration, and towards the top of Hores Gneiss there are irregular, weak concentrations of magnetite. A few metres above, in basal Sundown Group metasediments, there is a strongly magnetic zone containing small patches of sillimanite-magnetite-tourmaline rock. All of these features could be linked, with the Southern Cross deposit forming beneath the seafloor, and spent fluids altering recently-deposited Hores Gneiss volcanoclastics, then exhaling to deposit the precursor of magnetite onto the seafloor sediments. The magnetite-bearing metasediments near Southern Cross are at the same stratigraphic level as the BIF above the Broken Hill orebody. In both cases the magnetite-rich rocks might represent the exhaust fluid from sulphide deposits forming at shallow depth below the seafloor.

Substantial magnetite bearing metasediment zones also occur in the upper part of the Sundown Group. These zones may indicate that hot springs were active at about 1670 Ma. The Sundown Group may be more prospective than previously thought.

### **CALC-SILICATE ELLIPSOIDS AS FLUID SAMPLERS AND EXPLORATION TOOLS**

Calc-silicate ellipsoids, originally diagenetic carbonate-bearing concretions (Stevens 1998b), occur in the Broken Hill and Sundown Groups and some contain sulphide mineralisation and/or scheelite. The original carbonates are likely to have reacted with, and sampled all fluids that passed through the rocks before metamorphism. They could provide clues to the fluid history of the rocks, and may be pointers to ore.

### **INTRAFORMATIONAL BRECCIAS**

Some modern seafloor deposits occur next to seafloor hills formed by uplift of sediment above shallow intrusions. It is common to find sedimentary breccias slumping off the hills. Small occurrences of probable sedimentary breccias are known from the Sundown Group.

David Huston reviewed this abstract and made valuable suggestions. Published with permission of the Director-General, NSW Department of Mineral Resources.

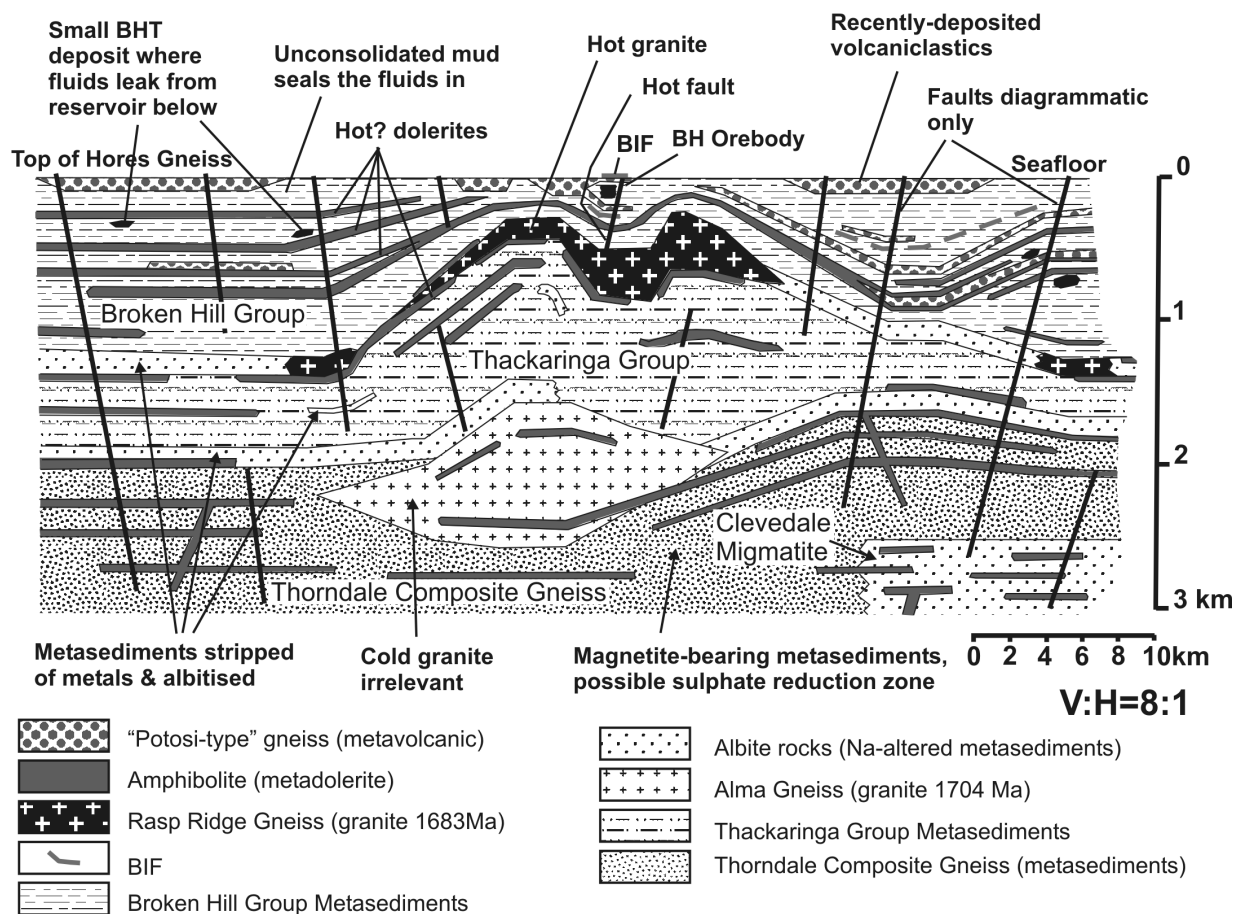
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### MODEL FOR THE BROKEN HILL OREBODY FLUID SYSTEM

(Attempted unfolding of geology to scale, but corrections for attenuation are very uncertain.  
Faults are diagrammatic, added because they are a factor in fluid flow.)



# COULD THERE BE A MT ISA TYPE OREBODY IN THE CURNAMONA PROVINCE?

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In the last few years a number of factors have pointed to the Paragon Group (New South Wales) or the equivalent Mt Howden Subgroup (South Australia) as a potential host for a Mt Isa type Pb-Zn deposit in the Curnamona Province:

1. Leyh (1998) recognised weak Zn mineralisation in Paragon Group drill core from CRA hole RD86PO16.
2. Page et al. (2000) found that part of the Paragon Group is the same age as the Urquhart Shale which hosts the Mt Isa Pb-Zn orebodies, and part is the same age as the host of the McArthur River orebody.
3. Barratt (2002) compiled stream sediment sampling data over the Paragon Group, and did some infill sampling. He found Pb-Zn anomalous zones in the Paragon Group.
4. Page et al (in prep.) found similarities in sedimentary characteristics of Paragon Group and Mt Isa Group.

## OBSERVED MINERALISATION IN PARAGON GROUP

Weak Zn mineralisation in CRAE drill hole RD86PO16 (Mundi Mundi Plains, N.S.W.) is concentrated in the upper Cartwrights Creek Metasediments, the King Gunnia Calc-Silicate Member, and the lower Bijerkerno Metasediments (Figure 1). Pyrite occurs as bedding-parallel lamellae and as concentrations in schistosity. Pyrite, sphalerite and trace galena occur in thin carbonate veins. Ovoid carbonate-sulphide spots may be zoned as follows: pyrite/pyrrhotite-trace galena-carbonate-sphalerite (Mason 1998). Lead isotope analysis implies a Delamerian age for the galena (G. Carr and J. Parr unpublished data) casting doubt on a Mt Isa age for the mineralisation. However, it is possible that the minute amounts of galena were deposited later than the other sulphides.

Teale (1985, 2000) described mineralisation similar to Mt Isa type Pb-Zn, in South Australia, from Marathon drillhole BD002 in the Benagerie Ridge, at the Lorenzo prospect and near Hunters Dam. All occur in graphitic phyllites and were described by Teale (2000) as “fine grained, bedding parallel layers....associated with an increase in fine grained, bedded pyrite”. Sphalerite also occurs in carbonate nodules. The host rocks resemble Mt Howden Subgroup rocks, but stratigraphic position is uncertain, and Teale (2000) considers the mineralisation to be ~1680-1700Ma in age, on the basis of Pb isotope data.

## STREAM SEDIMENT GEOCHEMICAL RESULTS

Stream sediment geochemistry was studied over outcropping Paragon Group in three areas: Bijerkerno, Cartwrights Well and Mundi Mundi Creek. All three showed anomalous results (Pb>60 ppm, Zn>100ppm). In the Bijerkerno area there is a clustering of anomalous Zn stream sediment samples, apparently sourced in the upper Cartwrights Creek Metasediments and lower Bijerkerno Metasediments. The Zn anomalous zone follows stratigraphy, suggesting a stratabound source. Anomalous Pb results are more patchy, but coincide with the Zn anomaly.

In the Mundi Mundi Creek area the Paragon Group displays all components of the Cartwrights Creek Metasediments, but the Bijerkerno Metasediments are not present. The structure is interpreted as a large refolded syncline. Anomalous Zn values are derived from the Cartwrights Creek Metasediments. Anomalous Pb values are coincident, but more restricted to the upper part of Cartwrights Creek Metasediments. Again the source appears to be stratabound.

## STRATIGRAPHIC AND CHRONOLOGICAL COMPARISON BETWEEN MT ISA AND CURNAMONA

Zircon dating reported by Page et al. (2000) and Southgate et al. (2000) shows that the following approximate correlations are possible between the Mt Isa and Curnamona Provinces:

- Big Supersequence with Thorndale Composite Gneiss -Thackaringa Group (NSW)-Curnamona Group (S.A.),
- Prize Supersequence with Broken Hill Group (NSW)-lower Saltbush Subgroup (S.A.),
- Gun, Loretta and River Supersequences with Paragon Group-Mt Howden Subgroup.

Between 1720 and 1640 Ma, the northern Australian sequence has been allocated to two superbasins, with the Calvert Superbasin overlapped by the Isa Superbasin. In the Mt Isa and Curnamona Provinces, mappable volcanic units are confined to the lower parts of the stratigraphy; in the Calvert Superbasin, and below the Sundown Group-Saltbush Subgroup. The Isa Superbasin sequence and the Paragon Group contain sediments with an airfall tuff component, but no mapped volcanic units. Between 1685 and 1671 Ma magmatic events occurred in both the Mt Isa and Curnamona Provinces. In the Mt Isa area the Sybella Granite and Carters Bore Rhyolite were emplaced between the Calvert and Isa sequences. In the Broken Hill area the Hores Gneiss volcanoclastic was deposited, and the granitic Rasp Ridge Gneiss and many or all of the doleritic sill and dyke precursors of the amphibolites, were emplaced. In the Olary Domain this event is recorded by differentiated sills of the Lady Louise Suite.

The youngest deposits in the Calvert Superbasin are equivalent in age to the middle Broken Hill Group. In the Mt Isa Eastern Succession the host rocks to the Cannington Ag-Pb-Zn orebody have a maximum depositional age of 1675-1670 Ma, the time of Sundown Group/Walparuta Schist deposition in the Curnamona Province.

### **HIATUS**

Between the sequences of the Calvert and Isa Superbasins there is a gap in deposition of about 15 m.y. In parts of the Olary Block (S.A.) there is no Sundown Group equivalent and the upper Broken Hill Group is generally missing, leaving a 20-40 Ma gap in deposition below the Mt Howden Subgroup (Paragon Group equivalent). In the Broken Hill Block the boundary between Sundown and Paragon Groups is abrupt, permitting a period of non-deposition. But in the Euriowie Block the Sundown Group appears to grade upwards into the Paragon Group.

### **GEOCHRONOLOGY OF THE PARAGON GROUP, MT HOWDEN SUBGROUP AND MT ISA GROUP**

The maximum age for the base of the Paragon Group is constrained by the  $1672 \pm 7$  Ma age of the youngest detrital zircons in the underlying Sundown Group. These are the same age as the Sybella Granite which predates the Mt Isa Group. The basal deposits of the Isa Superbasin are dated at about 1668 Ma.

The ages of the basal Bijerkerno Metasediments and equivalent Mooleulooloo Psammopelite (S.A.) are very similar to that of the Urquhart Shale (Figure 1), the host to the Mt Isa Pb-Zn orebodies. A psammitic unit in the upper part of Dalnit Bore Metasediments is very similar in age to that of the Barney Creek Formation, the host to the McArthur River orebody.

### **LITHOLOGICAL COMPARISONS: PARAGON GROUP-MT HOWDEN SUBGROUP AND MT ISA GROUP**

The Paragon Group has similar ages to the Mt Isa Group and contains anomalous Pb and Zn at a similar stratigraphic level. How similar are the rock sequences? Questions to be eventually answered include: did Curnamona and Mt Isa provinces experience similar events; were the Curnamona and Mt Isa Provinces once joined, and were the Paragon and Mt Isa Groups deposited in a single, huge basin?

The Paragon Group contrasts markedly with the rest of the Broken Hill sequence (Willyama Supergroup). Sediments were finer grained, dominated by shale, siltstone and very fine sandstone; they were organic-rich, and the sandstones feldspathic. Very minor dolomitic carbonate is represented by the King Gunnia Calc-Silicate Member. The Isa Superbasin sequence is characterised by rhythmically laminated fine grained siliciclastic sediments, with minor detrital carbonate in the Mt Isa area, and carbonate sediments on the Lawn Hill Platform to the northwest. There are similarities between the Paragon and Mt Isa Groups, but matching the sequences in detail is difficult. Approximate matches can be made as follows.

Interbedded chialtolite-rich and chialtolite-poor schists in the lower Cartwrights Creek Metasediments (Figure 1) might be counterparts of the siltstone-mudstone rhythmites of the Moondarra Siltstone.

The King Gunnia Calc-Silicate Member represents the only carbonate sedimentation in the Paragon Group, and could be a very thin equivalent of the carbonate siltstone-mudstone rhythmites in the Native Bee Siltstone. The King Gunnia Calc-Silicate Member is planar bedded, and apparently deposited in very quiet conditions below storm wave-base.

Just below and above the King Gunnia Calc-Silicate Member, the Cartwrights Creek Metasediments are characterised by thick units of planar-laminated (with rare low angle crossbeds) very fine sandstone/siltstone

These are interbedded with units of graphitic micaceous schist/phyllite. Below the Calc-Silicate, they could correlate with the siliciclastic mudstones of the Breakaway Shale; above the Calc-Silicate, they may correlate with the Urquhart Shale, the host to the Mt Isa Pb-Zn deposits. The Urquhart Shale is described as mixed carbonate-siliciclastic siltstone-mudstone rhythmites. The small apparent difference in age between the Urquhart Shale and the upper Cartwrights Creek Metasediments may be accounted for in the analytical uncertainties of the zircon dating, or may indicate a time-transgressive sequence boundary.

The Bijerkerno Metasediments (Paragon Group), represents an influx of fine sand, some of it tuffaceous. The metasandstones are rich in albite, and high-angle crossbeds are common. The Spear Siltstone (Mt Isa Group) is fine grained, albitic and also exhibits high angle crossbeds.

## CONCLUSIONS

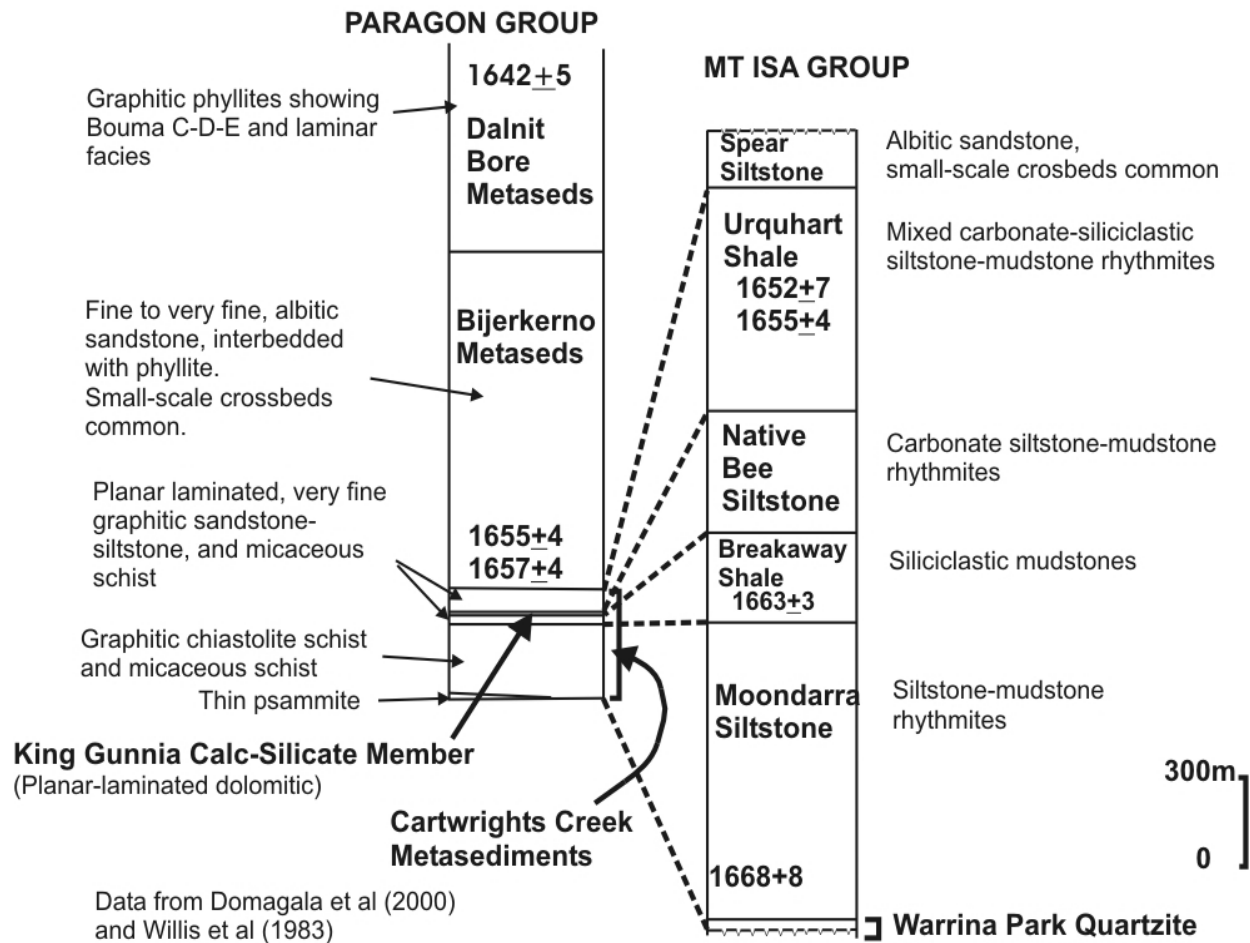
The lower Paragon Group was deposited contemporaneously with the Mt Isa Group and shows Pb-Zn anomalism at about the same time interval in which the Mt Isa Pb-Zn orebodies were deposited. A tenuous correlation of lithological facies is made between the lower Paragon Group-Mt Howden Subgroup and the Mt Isa Group. The stratigraphic correlations suggested here should be tested by a purpose-designed comparative study.

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# ATTEMPTED CORRELATION OF PARAGON GROUP AND MT ISA GROUP BASED ON LITHOLOGY AND GEOCHRONOLOGY



# EVIDENCE FOR HIGH-PRESSURE METAMORPHISM IN THE GRANULITES OF THE BROKEN HILL AREA

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Previous studies of regional metamorphism have established that the Broken Hill area has been subjected to a high-grade regional metamorphism at ca. 1600 MA (M1) that increases in grade from andalusite-muscovite grade in the north to granulite grade in the immediate Broken Hill area. This area has been subjected to a later deformation at perhaps 500 Ma that produced broad cross-cutting schist zones that record a second, generally lower grade metamorphism (M2) (e.g., Phillips, 1980, Phillips and Wall, 1981, Hobbs et al, 1984). In the hope of further constraining P-T conditions near the ore body, we collected a suite of mafic granulite, garnet amphibolite, and pelitic gneiss for detailed themobarometry. Sample localities include Black Bluff (south of the Broken Hill airport, mafic gneisses), "Airport" (1 km east of northern extent of the Broken Hill airport, pelitic gneiss), and Round Hill (east of the city of Broken Hill, pelitic gneiss and garnet amphibolites).

Although retrogression and hydration of granulite facies assemblages is extensive and widespread in the Broken Hill area, two-pyroxene mafic granulites from Black Bluff show almost no retrogression. Two-pyroxene thermometry for two samples from Black Bluff yields temperatures of  $827 \pm 37^\circ\text{C}$  and  $840 \pm 17^\circ\text{C}$ . Feldspar-rich leucosomes with randomly oriented orthopyroxene crystals at Black Bluff are most probably small partial melts that formed due to dehydration melting of hornblende in quartz-bearing mafic granulites during peak metamorphic conditions. The two-pyroxene thermometry is consistent with estimates for first melting temperatures of quartz-bearing amphibolites (Beard and Lofgren, 1991, Patino-Douce & Beard, 1995). Based on these data, we conclude that peak metamorphic temperatures at Black Bluff reached or exceeded  $850^\circ\text{C}$ .

Unlike the mafic granulites at Black Bluff, the mafic granulites at Round Hill have been extensively retrograded to amphibolites. Two-pyroxene granulites from Round Hill yield a peak temperature of  $764 \pm 27^\circ\text{C}$ , almost  $100^\circ\text{C}$  lower than Black Bluff. This result suggests either a very steep gradient in temperature between Black Bluff and Round Hill or, more probably, that the mafic granulites have been significantly reset to lower temperatures as a consequence of the extensive retrogression at this locality.

Two texturally distinct occurrences of garnet amphibolite were observed at Round Hill: comparatively coarse-grained garnets with inclusions of oriented, large hornblende grains, and fine-grained garnet intergrown with randomly oriented fine-grained actinolitic hornblende. We interpreted the coarse-grained garnet amphibolites to be products of M1 metamorphism and the finer-grained enclaves to be products of M2 metamorphism. Garnet, hornblende, and plagioclase compositions for the M1 intergrowths yield pressures of 5.5 kbar and temperature of approximately  $615^\circ\text{C}$  for these rocks.

Pelitic gneisses from Round Hill and the Airport locality contain the same assemblage: Kspar-quartz-garnet-cordierite-sillimanite-biotite. Cordierite mantles garnets in these samples. At the airport this assemblage last equilibrated at 6.5 kbar and  $750^\circ\text{C}$  whereas the same assemblage from Round Hill last equilibrated at 5.5 kbar and  $750^\circ\text{C}$ . Rutile occurs as inclusions within garnets where it is invariably separated from the host garnet by ilmenite.



The GRAIL assemblage (garnet-rutile-aluminosilicate-ilmenite) dictates pressures above 9 kbars at Round Hill (assuming 775°C temperature records peak T), whereas this same assemblage records pressures in excess of 8 kbars at the Airport locality. These pressures are significantly higher than previously recognized and suggest that M1 occurred at significantly deeper crustal levels than previously believed.

Both the GRAIL textures and the cordierite mantles on garnets from Round Hill and the Airport locality indicate high temperature decompression following peak metamorphic conditions. Further cooling and decompression accompanied by retrograde metamorphism produced the garnet amphibolites at Round Hill. These observations require that the M1 metamorphic event reached high pressure and temperatures, followed by high temperature decompression, or an overall clockwise P-T path.

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# **FULL UTILISATION OF THE HYMAP DATA AVALANCHE**

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## **INTRODUCTION**

HyMap is an imaging spectrometer (or hyperspectral imager) that acquires image data at a spatial resolution of up to 2.5 m for 126 bands covering the wavelength range 450 nm to 2500 nm. In 2002 the Department of Mineral Resources contracted HyVista Corporation to fly an area of 4000 km<sup>2</sup> centred on the Broken Hill line of lode. The pixel resolution of this survey was 3 m. This equated to 55 north-south flight lines, producing data swaths each 512 pixels, or approximately 1.6 km, wide with approximately 20% overlap between swaths. The total data volume acquired was over 400 GB. At the time of its collection the survey was the largest of its kind ever collected. Previous imaging spectrometer surveys have tended to focus on small areas of particular geological or environmental interest and so this was the first survey where questions such as across-track and across-survey area map continuity would be of major interest. The raw data was converted to apparent reflectance using proprietary software and real-time geo-location information used to create data files that can be used in commercially available software to geo-reference and subsequently mosaic image products.

## **PROCESSING THE BROKEN HILL HYMAP DATA**

HyMap swaths are flown with alternating flight line directions. This results in different illumination parameters and shadowing effects in adjacent swaths and these differences being at a maximum at the swath edges where the images must be mosaicked. This can result in blatant illumination discontinuities in enhanced images and in severe endmember abundance discontinuities between-swaths. The writer has developed processing strategies which reduce these effects to inconsequential levels. Commercially available software is used throughout and no special programming skills are required. Geological information is concentrated within the visible (VISNIR) part of the spectrum, where the transition elements generate spectral features in minerals such as goethite, hematite and certain garnets, and in the shortwave infrared (SWIR) part of the spectrum where hydroxyl ions cause minerals such as the micas, amphiboles and chlorites to be spectrally distinctive. The VISNIR and SWIR parts of the data were therefore processed separately and the resultant component abundance maps combined later for classification and interpretation.

Well established processing techniques were used to compress subsets of the VISNIR and SWIR data into smaller numbers of spectrally significant bands and to isolate extreme pixels. The latter were assessed for the probability that they represented spectral endmembers and, if so, these were used in subsequent mapping operations.

## **INTERPRETATION OF IMAGING SPECTROMETER DATA**

Imaging spectrometry acquires a high resolution spectrum for each pixel of reflected light across the visible, near- and shortwave infrared. The high spectral resolution means that sufficient data redundancy exists for scene statistics to be used to estimate the relative contribution of multiple components to the spectral response of each pixel. This, in-turn, leads to a capability to generate maps of within-pixel end-member abundance. Endmembers may be regarded as spectrally unique terrain components of such consistency that their abundance

can be separately mapped. Techniques for processing imaging spectrometer data are well established and available in software packages such as ENVI. There are no agreed strategies for interpreting the data acquired in surveys such as undertaken at Broken Hill.

The writer received a subset of the Broken Hill HyMap data soon after acquisition in order to undertake a demonstration study on behalf of the Department of Mineral Resources. Major objectives of this study were to determine the extent of geological information content with the imagery, to establish techniques for interpretation of multi-swath scenes and to demonstrate the range of potential geological applications of the data. It quickly became apparent that the information content of the imagery is so large that few investigations are likely to ever make full use of all the information content and that interpretation techniques are likely to be application-dependant. From a mineral exploration perspective the possible applications that the Broken Hill HyMap data may be put to can be summarised as follows:

- regional lithology mapping
- regional stratigraphic mapping
- regional and prospect scale mineral abundance mapping
- prospect scale key lithology/mineralogy mapping

Study areas around the Rockwell, Little Broken Hill and Rupee localities were chosen. Each study area was chosen so as to involve multiple image swaths. The results described here are preliminary, with further in-depth investigations being carried out by the writer and several research students at various levels. Examples from the Rockwell and Rupee study areas are described below. Full illustration of the results achieved is provided in the oral presentation.

## **REGIONAL LITHOLOGY MAPPING**

The number of spectrally distinctive terrains recognised and separately mapped in the Rupee study area was 15 and in the Rockwell area was 21. Dominant minerals in the spectral signatures of these terrains were muscovite, illite, halloysite, riebeckite, clinozosite, antigorite, actinolite, vermiculite, goethite, hematite and almandine garnet. Several terrains containing muscovite and illite as the dominant minerals could be separately mapped because of variations in terrain albedo, mica abundance and species.

In terrains such as occurring at Broken Hill rock outcrops are composite features consisting of actual fresh and partly weathered outcrop, partly weathered loose float and intervening soil patches. Outcrops that might be some tens of meters apart and are separated by float and soil are likely to be shown by conventional mapping as a single mappable unit. The Broken Hill HyMap survey is at sufficient resolution for these terrain components to show as separate mappable endmembers. It was no surprise, therefore, to discover that units mapped as discrete lithologies by the previous conventional mapping were frequently delineated by HyMap by the occurrence of two or more endmembers in an intimately associated pattern. This feature suggests to the writer that automated methods of mapping of lithologies will find it difficult to recognise rock units, although they may be successful at mapping individual mineral abundances.

The Rockwell region lies approximately 20 km southeast of Broken Hill and is approximately 20 km<sup>2</sup> in size. The previously mapped stratigraphy of this area is shown in figure 1 (a). The distribution of 18 distinctive lithologies is shown in figure 1 (b). These are based on unique patterns and associations displayed by the 21 recognised endmembers.

## **REGIONAL STRATIGRAPHIC MAPPING**

Source and metamorphic history leave an imprint on the mica and garnet compositions of high grade metamorphic rocks. HyMap discriminates rocks on the basis of their mineral compositions. It has been found in this study that metasediments, gneisses, basic amphibolites and pegmatites having differing stratigraphic associations are spectrally distinctive. Figure 1 (c) shows the HyMap-derived stratigraphy for the Rockwell region. This interpretation has allowed the first recognition of previously un-mapped major outcrops of the Parnell formation and a subdivision into Parnell Formation, Freyers Metasediments and Hores Gneiss of units previously mapped collectively as Purnamoota Subgroup. Regolith units are also reliably mapped using HyMap with kaolinitic soils dominating creek courses, illitic soils predominating on the alluvial flats and kaolinite/smectite and muscovite dominated soils occurring adjacent to particular rock outcrops.

## **REGIONAL/PROSPECT SCALE MINERAL AND SPECIES MAPPING**

The investigation to date has shown that attempts to map mineral abundances using spectra derived from overseas-sourced spectral libraries have only limited success. This is believed to be because the spectrally significant minerals occurring at Broken Hill (micas, clays, garnets, chlorites and epidotes) all show extensive solid solution compositional variation. There is therefore a great need to assemble a library of local mineral spectra and the writer is attempting to do this. The distribution of mica-dominated endmembers at both Rockwell and Rupee show that it is possible to map the separate occurrence of Na-rich white mica (paragonitic), potassic mica (phengitic) and illite. The Na-rich micas are strongly associated with retrograde schist zones and possibly associated with areas of mineralisation. In the Rupee region considerable discrimination of basic granulites has been possible because of the ability to map separately actinolite, riebeckite, antigorite clinozoisite and vermiculite.

## **PROSPECT-SCALE KEY LITHOLOGY/MINERALOGY MAPPING**

Garnet quartzite outcrops have been mapped at both Rockwell and Rupee by the occurrence of distinctive endmembers dominated by garnet and weathering products such as goethite and montmorillonite. Work is in progress to characterise the spectral features of the garnet quartzites, Banded Iron Formations and quartz gahnite rocks and the minerals that comprise them. Particular attention is being paid to the spectral properties of manganese containing minerals.

## **CONCLUSIONS**











Imaging spectrometry provides mineralogical information that allows for the discrimination and mapping of rock outcrops and regolith. Mica, and to a lesser extent garnet, compositions are related to both lithology and stratigraphy, thus providing an additional tool to aid geological mapping and mineral exploration.

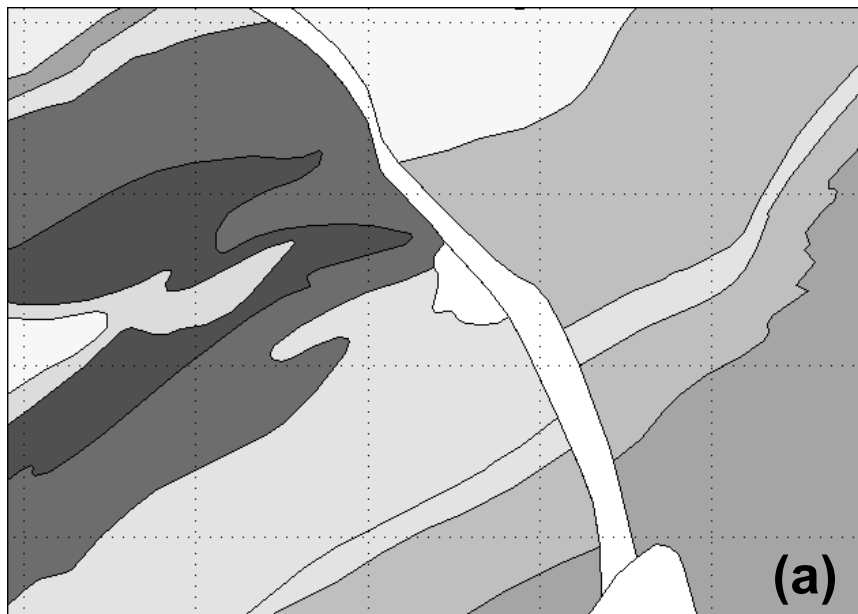
## **ACKNOWLEDGEMENTS**

The writer would like to acknowledge the logistic and financial support of the Department of Mineral Resources, Geological Survey of New South Wales and of HyVista Corporation. Particular thanks are due to Terry Cocks, Peter Cocks, Dave Robson, Lindsay Gilligan, Barney Stevens and Richard Barratt.

### Previously mapped stratigraphy

#### Legend

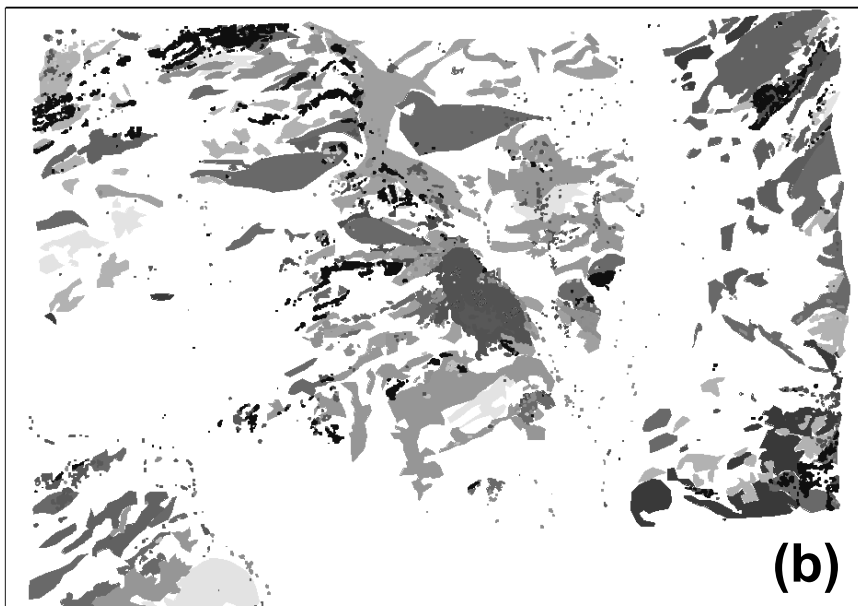
-  Sundown Group
-  Hores Gneiss
-  Freyers Metaseds
-  Parnell Formation
-  Allendale Metaseds
-  Rasp Ridge Gneiss
-  Purnamoota Group
-  Himalaya Form.
-  Retrograde schist
-  Red Hill Serpentine



### HyMap-derived Lithologies

#### Legend

-  retrograde schist
-  composite gneiss
-  composite\_gneiss2
-  iron\_oxides&illite
-  Leuco\_pegmatite
-  pegmatite
-  psammite&psammopelite
-  Psammopelite&pelite
-  psammopelite
-  psammopelite2
-  psammopelite3
-  biotite\_gneiss
-  clinozoisite
-  antigorite
-  vermiculite
-  actinolite
-  glaucophane
-  reibeckite



### Interpreted Stratigraphy

#### Legend

-  Rockwell schist
-  Parnell Formation
-  Himalya Formation
-  Purnamoota Group
-  Rasp Ridge Gneiss
-  Parnell Formation Mafic Gneisses
-  Parnell Formation Felsic Gneiss
-  Freyers Metasediments
-  Hores Gneiss
-  Sundown Group
-  Red Hill Serpentine
-  Allendale Metasediments
-  Faults

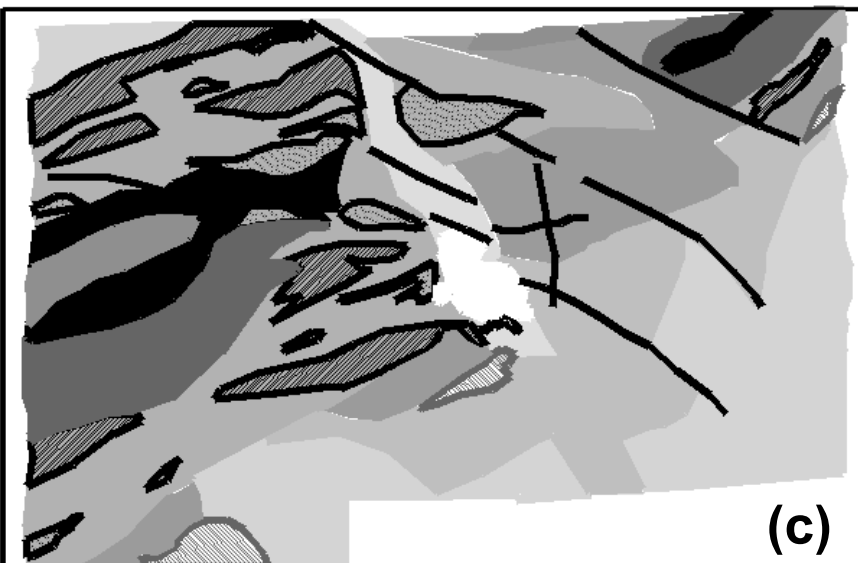


Figure 1

# IRON OXIDE, COPPER-GOLD MINERALISATION STYLES FROM THE CURNAMONA PROVINCE.

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## INTRODUCTION

The Curnamona Province covers an area of approximately 100,000km<sup>2</sup>, most of which is under cover. Exploration for iron oxide, copper-gold (IOCG) mineralisation in the Province is, in reality, in its infancy. The more highly prospective areas are generally under moderate to deep cover and many of the more significant gravity/magnetic features have had only rudimentary testing. Much of the drill testing has occurred in the last decade, although earlier exploration and stratigraphic drilling (e.g. CSR, Marathon Petroleum, SADME) provided the framework for later and current exploration. Outcropping deposits and prospects have been partially to adequately tested (e.g. Waukaloo, Gunsight, Parabarana) and provide some information on host rocks, structure and mineralisation styles.

IOCG mineralisation, or its equivalent, in the Province is either 1580Ma-1610Ma or approximately 450Ma. Classic hematitic breccias ( $\pm U \pm F \pm Mo \pm Cu \pm REE \pm Ba$ ) are known from the Mt. Painter area (~450Ma) and there are minor hematitic breccia occurrences at some of the other prospects/deposits (e.g. North Portia; 1605Ma). Mineralised hematitic breccias may be discovered along the northern flank of the Province and adjacent to major, long lived fault structures (e.g. the Paralana Fault Zone; the western bounding fault of the Benagerie Ridge). These structures controlled volcanism and sedimentation in the Mesoproterozoic and certainly some of the Neoproterozoic and Cambrian sedimentation

IOCG mineralisation and variants occur across the Province from the south-east (e.g. Copper Blow) to the north-west (e.g. Parabarana). Some of the better prospects/deposits are White Dam, Kalkaroo, Waukaloo, Portia-North Portia, South Koolka, Parabarana, Gunsight, Yudnamutana and Mt. Gee-East Painter. The latter two are Palaeozoic in age. Emerging domains containing anomalous copper within hematite/magnetite-bearing brecciation have also been delineated (e.g. Platsearch-BHP, DDH-Call-1; Platsearch-Inco-Allender Group, Dolores Prospect) and will require further exploration.

## SIGNIFICANT IOCG PROSPECTS/DEPOSITS; CHARACTERISTICS AND SUBDIVISION

The better prospects/deposits will be discussed and summarised within groups that have major similarities with regard to stratigraphic/structural position, age, alteration, ore mineralogy, etc.

### Palaeozoic

(a) *Lower Adelaidean-Stratabound*: Cu-Au-Mo-REE mineralisation is associated with magnetite replacement zones in carbonates and calc-silicates. Early high T veining (e.g. chalcopyrite-magnetite-pyrite-actinolite  $\pm$  grossular andradite garnet  $\pm$  allanite) and upgrading of mineralisation by lower T retrogression (e.g. tremolite replacement of clinopyroxene; development of magnesio-riebeckite) has occurred. Allanite is the dominant REE-bearing phase. Better intersections include 12.10m @ 1.84% Cu and 0.66ppm Au (including 6m @ 0.08% Mo) in DDH YD01 and 56m @ 0.42% Cu in drillhole YX015. It should be noted that most drillholes in this area were not analysed for Au or Mo.

(b) *Hematitic breccias associated with thrust faulting*: The hematite breccias of the Mt. Gee-East Painter area are copper and gold poor (up to 0.08% Cu) and tend to be enriched in U, Mo, REE, Co, F and lesser Ba. They develop in the basement rocks of the Mt. Painter Block. The mineralogy can be complex with primary minerals dominated by hematite-quartz-monazite  $\pm$  magnetite  $\pm$  uraninite  $\pm$  churchite  $\pm$  samarskite  $\pm$  cattierite  $\pm$  chalcopyrite  $\pm$  Co-pyrite  $\pm$  pyrite  $\pm$  fergusonite  $\pm$  xenotime  $\pm$  molybdenite. Intense weathering and oxidation has created a vast array of secondary U + REE minerals with hematite replaced by goethite and chalcopyrite replaced by chalcocite-covellite. Better intersections include 34.70m @ 725ppm  $U_3O_8$  and 60.70m @ 0.14%  $U_3O_8$  in drillhole 91GE33 (CRAE) and 150m @ 740ppm  $U_3O_8$  (and abundant LREE, Mo and lesser Cu) in drillhole GE003 (Goldstream Mining N.L.). The age of the mineralisation is approximately 450 Ma (Fanning and Teale; in prep.).

### **Mesoproterozoic**

(a) *North Portia-Kalkaroo Type*: Cu-Au-Mo (-F-Ba-LREE  $\pm$  Co  $\pm$  U) mineralisation at North-Portia, Kalkaroo and Parabarana areas all share a similar stratigraphic and structural position. In all areas albitisation (and intense K-feldspar alteration) is superimposed on carbonaceous meta-pelites, calc-pelites and carbonates. This alteration is grossly crosscutting with mineralisation often enveloped in carbonaceous metasediments that "surround" the albitised and mineralised rock-types. Replacement and fracture-fill mineralisation is present with carbonate beds often replaced by sulphides. An early "calcic" alteration type occurs in the structurally lower sections of the mineralisation (actinolite-magnetite  $\pm$  allanite  $\pm$  calcite  $\pm$  chalcopyrite  $\pm$  sphene) and is replaced and/or cut by later veins that become more biotite  $\pm$  K-feldspar-rich. Biotite selvages on veins are common (North Portia). Numerous other vein types and parageneses are present (c.f. Teale and Fanning, 2000; Skirrow et. al., 2000) with a late, lower temperature "upgrading" of Cu-Au mineralisation observed. This is associated with, for example, chlorite development (Kalkaroo, North Portia and Parabarana), fluorite-telluride  $\pm$  chalcopyrite vein introduction (North Portia), adularia-chlorite replacement of biotite (Parabarana) and talc-carbonate alteration (North Portia).

The mineralisation is dominated by chalcopyrite, pyrite, molybdenite, pyrrhotite, and cobaltian pyrite and (depending on the deposit) lesser to rare tellurides, gold, bornite, selenides, sulphosalts and arsenopyrite. Significant supergene upgrading occurs at Kalkaroo (e.g. 20m @ 3.1% Cu and 0.7ppm Au, DDH-KA6) and at North Portia (e.g. 11m @ 6.1% Cu, BEN395). Anhydrite occurs as inclusions in gold and/or chalcopyrite at North Portia and Parabarana. Rare earth-bearing phases are dominated by allanite and sphene in the early, structurally lower veins (North Portia, Kalkaroo and Parabarana) and by monazite, uraninite and REE fluocarbonates (bastnasite, synchisite, cordylite) at higher structural levels (North Portia, Parabarana).

Better intersections include 36m @ 1.1% Cu (DDH-PD03), 56.40m @ 0.79% Cu (NFP13), 75m @ 0.49% Cu and 24.40m @ 0.83% Cu (including 15.20m @ 0.22% Mo; NFP2) at Parabarana; 76m @ 1.06%Cu, 1.21ppm Au and 235ppm Mo (DDH-BEN592), 72m @ 0.72% Cu, 0.56ppm Au and 838ppm Mo (DDH-BEN596) and 53m @ 0.8% Cu and 0.6ppm Au (DDH-BEN600) at North Portia; 317.40m @ 0.26% Cu and 0.07ppm Au (KMD001) and 40m @ 1.2% Cu and 0.91ppm Au (KND003) at Kalkaroo.

The hangingwall to this type of mineralisation invariably contains base metal sulphides (Pb-Zn-Ag) that are significantly older (~1680Ma-1700Ma) than the Cu-Au mineralisation. The latter was introduced at ~1605Ma (North Portia Cu-Au; c.f. Teale and Fanning, 2000) to

~1625Ma (Mo mineralisation, Kalkaroo; c.f. Skirrow, et. al., 2000). The host sequence has been deformed prior to the introduction of mineralisation. Footwall albitites are generally magnetite-rich.

(b) *Waukaloo Type*: This mineralisation is developed entirely in monotonous, magnetite-bearing albitites, some of which were originally felsic tuffs. It is a large, low grade (uneconomic) occurrence developed over a distance of greater than 1500m. Mineralisation tends to be confined to veins, crackle breccias and fractures with lesser disseminated sulphide. It appears to be zoned with bornite-chalcopyrite (-magnetite) → chalcopyrite (-magnetite-hematite) → chalcopyrite-pyrite (-magnetite-hematite) → pyrite (-magnetite-hematite) → pyrite (-hematite). The alteration may also be zoned laterally and vertically in the hydrothermal system and is superimposed on the albitites. There is an early biotite-magnetite development, either as veins or segregations and the biotite can contain allanite ± sphene ± monazite. Allanite is also present as inclusions within chalcopyrite in some bornite-magnetite-biotite-chalcopyrite veins. Elsewhere, less oxidised clinopyroxene-sphene ± actinolite veining, segregations and replacement domains are present. These two (early) alteration types are spatially distinct and the clinopyroxene-bearing style utilises the pre-existing carbonate developed during the albitisation process.

The introduction of additional Cu-Au occurs during the late destruction of biotite and the conversion of magnetite to hematite. Late, crosscutting Au and Mo rich breccia veins are also present.

Better intersections at Waukaloo are 10m @ 0.74% Cu, 118ppm Mo and 2.1ppm Au (DD91WA8), 14m @ 0.42% Cu and 0.14ppm Au (DD91WA6) and 7.50m @ 0.69% Cu and 0.16ppm Au (DD91WA3).

(c) *Gunsight Type*: Mineralisation at this prospect, sited to the SW of the Parabarana deposit in the Mt. Painter area is dominated by Cu-LREE-U-Co-F. Gold and molybdenum are absent. The mineralisation is hosted by extremely deformed replacement iron formations, calc-silicates, meta-volcanics, micaceous schists and feldspathic gneisses. Major sulphide, oxide and REE phases are pyrite, chalcopyrite, magnetite, cobaltian pyrite, allanite, monazite, cobaltian arsenopyrite and uraninite. Minor to rare glaucodot, scheelite, bastnasite, seigenite, allosclerite, bornite and pyrrhotite are also present.

Cobalt-bearing sulphides are restricted to layer parallel quartz veins that develop within the mica-rich schists. Cobaltian pyrite can be found in these schists and is often enclosed in cobaltian chlorite (up to 3.2% CoO). A significant proportion of the copper mineralisation crosscuts the strong shear fabric and is associated with fluorite-epidote, scapolite-tremolite ± pyrite, siderite ± chlorite, hematite-chlorite and adularia ± chlorite ± pyrite veins. Better intersections from this prospect are 6m @ 1.96% Cu, 0.14% Co and 0.18% U<sub>3</sub>O<sub>8</sub> (DDH8) and 16.76m @ 0.42% Cu (DDH1).

(d) *The South Koolka Skarn Type*: This style of mineralisation is magnetite dominated and contains Cu-Au-Mo-LREE-F-Co-P. It is possible that the mineralisation sits in approximately the same stratigraphic position as Kalkaroo and North Portia. The coarse grained skarn is enclosed within a potassic calc-silicate "envelope" and magnetite, hedenbergite, garnet and ferrohastingsite dominated skarns contain the mineralisation. Sub-vertical garnet skarns are host to the better mineralisation. Higher grade copper mineralisation can be associated with a



variety of unusual rock-types (e.g. chalcopyrite-apatite-allanite) and a late alteration of hedenbergite and ferrohastingsite to Mn-actinolite causes an upgrading of copper values.

These skarn types are superimposed on "calcic skarn" (diopside-plagioclase  $\pm$  sphene  $\pm$  tremolite  $\pm$  scheelite) which has replaced earlier developed albitites. This prospect has been discussed by Teale and Brewer (this volume).

## CONCLUDING REMARKS

Significant exploration dollars have been spent on prospects/deposits such as Yudnamutana, Portia-North Portia and Kalkaroo with early drilling intersections holding great promise. As yet however no economic IOCG deposit has been delineated in the Curnamona Province. A variety of mineralisation styles are present and two ages (~1580Ma-1610Ma and ~450Ma) are noted. The Palaeozoic mineralisation appears to occur only on the Province margins (e.g. Mt. Painter Region; Anabama area, southern Olary domain). Hematitic breccias that can exhibit milled textures, breccia clasts within breccia, clast-rich and clast-poor variants and high concentrations of U, F and LREE (as well as anomalous Mo, Cu, and Ba) are Palaeozoic in age.

Mesoproterozoic mineralisation contains Cu-Au-Mo as well as significant U and Co. The only exception to this is the Gunsight Prospect that is Au and Mo absent. Most contain high F values (up to 4% F at South Koolka) and moderate to very high LREE concentrations. The LREE can be contained in early allanite and sphene or late monazite and REE fluocarbonates. North Portia, Kalkaroo and Parabarana probably occur at a similar stratigraphic and structural level. Mineralisation is underlain by magnetic albitites and stratigraphically overlain by carbonaceous (or graphitic) meta-pelites. The mineralisation develops in non-magnetic albitites, carbonates, meta-calc-pelites and "K-feldspar rocks". Evidence suggests a shallow water, possibly evaporitic origin for these meta-sediments.

All of the larger prospects/deposits exhibit lateral and vertical zonation with regard to both mineralisation and alteration. Numerous parageneses of veining and replacement can be present culminating in a late, lower T upgrading of mineralisation. Potential for significant Cu-Au mineralisation exists along the northern Province margin and adjacent to major structures that traverse the province.

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# **THE SOUTH KOOLKA Fe-Cu-Au SKARN, KALABITY AREA, CURNAMONA PROVINCE**

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## **INTRODUCTION**

The South Koolka Fe-Cu-Au Prospect lies approximately 50 km NNW of Olary, 60km SSW of the Portia-North Portia Prospects, 20km west of Kalabity Station and 7km WNW of Mt. Howden. It is overlain by 6m to 20m of Tertiary and Recent cover and base of oxidation ranges from 40m to 60m. The general area exhibits complex magnetics with disrupted linear magnetic trends and discrete magnetic highs. An earlier weak copper intersection by CRAE was known. In the immediate environs of the prospect the meta-sediments dip moderately to the north. Abundant graphitic meta-pelites are present to the north of the prospect and sodic rock-types are common to the south. The best intersection to date is from DDH-KY1362 which intersected 19.5m @ 1.16% Cu and 0.17ppm Au.

## **REGIONAL GEOLOGY**

The regional geology and/or structure of the Olary Region have been discussed by Berry et. al., (1978) and Clarke et. al., (1986). Regional stratigraphy and nomenclature have been discussed by Conor (2000) and a formal stratigraphic scheme proposed. The latter presents numerous problems if, for example, one accepts that at least some of the rock-types and units present are the result of regional alteration and are transgressive. In the South Koolka area the mineralisation sits on the upward facing limb of a D<sub>2</sub> antiformal structure that is overturned to the south. A major fault structure dips moderately to shallowly to the north and cuts this structure. An aircore traverse, approximately 10km in length (north-south) and with holes spaced approximately 100m apart shows that graphitic meta-pelites overlying aluminous meta-pelites to the north of South Koolka are repeated to the south where the aluminous meta-pelites may structurally overly the graphitic meta-pelites.

## **GEOLOGY OF THE SOUTH KOOLKA AREA**

Approximately 500m of “stratigraphy” has been encountered during drilling in the area. In a loose sense this stratigraphy can be summarised as footwall phyllites, overlain by calc-silicates and marbles which are in turn overlain by aluminous and then graphitic meta-pelitic schists. The so-called Bimba Formation (Conor, 2000) is probably present at South Koolka. The presence of a thin sulphidic horizon (e.g. 6m @ 0.94% Zn and 0.16% Pb in DDH-KY1366) overlain by an intercalated marble and potassic calc-silicate unit, similar to that observed, for example at Mt. Howden mine, supports this view.

The Bimba Formation and its associated sequence has been dated at 1690Ma to ~1710Ma (Page et. al., 2000; Teale and Fanning, 2000) and there is now a reasonable correlation of both the Thackaringa and Broken Hill Groups with formations in the Olary Domain (c.f. Page et. al., 2000). The South Koolka “stratigraphy” and “pseudostratigraphy” presented here will be described using a simple subdivision that has been arrived at by detailed logging and thin section study. No attempt will be made to “squeeze” the various “units” into Olary Domain stratigraphy.

The hangingwall units are dominated by aluminous schists that exhibit a strong crenulation cleavage ( $S_2$ ). The lower (non-graphitic) aluminous schists are approximately 100m thick and contain abundant porphyroblastic sillimanite-bearing rocks which are intercalated with quartz-rich meta-sediments, biotite-muscovite schist and rare garnet-plagioclase-biotite schist. Quartz absent schist contains corundum. The graphitic meta-pelites are more aluminous and can contain unusual graphite-sillimanite ( $\pm$  biotite  $\pm$  tourmaline) rocks. Ilmenite and rutile are the dominant Fe-Ti oxide phases and magnetite is generally absent.

The footwall units at South Koolka can be divided into an interbedded marble-K-rich calc-silicate unit that overlies a fine grained meta-calc-pelite to meta-pelite. The former is remarkably similar to zinc-rich rock-types found on the Benagerie Ridge (c.f. Teale, 2000). The marbles contain abundant clinopyroxene, scapolite, epidote, grossular garnet, tremolite and Pb-Zn sulphides. Associated K-feldspar-rich bands contain abundant biotite, clinopyroxene and tremolite. The fine grained meta-calc-pelites/pelites, underlying the marble and K-rich calc-silicate unit, commences with numerous, layer parallel calc-silicate zones that are occasionally transgressive. These meta-calc-pelites/pelites are composed of quartz-K-feldspar-biotite-muscovite-garnet-plagioclase-magnetite  $\pm$  epidote  $\pm$  pyrite. Garnet compositions are spessartine-rich ( $\sim 20\%$  MnO) with significant CaO.

Albitites and “calc-silicates” develop adjacent to the mineralised and non-mineralised skarns and associated breccias. Albitites occur only in the hangingwall and develop via the total albitisation of pre-existing rock-types. They contain from 7% to 10%  $\text{Na}_2\text{O}$ , are exceptionally fine grained (20-60 micron) and contain minor apatite, sphene, rutile, Mg-biotite and sometimes tremolite-actinolite and pyrrhotite. The skarns and skarn breccias are enclosed by a K-rich calc-silicate alteration zone that may have developed in calcic or carbonate-rich rock-types originally. This alteration zone is not similar to the footwall intercalated marble-K-rich calc-silicate unit discussed earlier.

### **SKARN DEVELOPMENT AND MINERALISATION**

The potassium-rich calc-silicate alteration domains enclose skarn, skarn breccia and non-mineralised potassic breccias. The latter form a central domain in the hydrothermal system and can have a skarn matrix or can be totally replaced by skarn assemblages. The unaltered clasts are predominantly a quartz-K-feldspar-amphibole-plagioclase-magnetite-sphene  $\pm$  biotite  $\pm$  garnet  $\pm$  epidote rock-type or a two-feldspar-quartz-biotite rock-type. The latter could represent clasts from a high level granite or sub-volcanic felsic intrusive.

There are five skarn types represented with these being (early through to late) calcic skarn (Ca), magnetite skarn (Fe), hedenbergite skarn (rare; Ca-Fe-Mn), garnet skarn (Ca-Fe  $\pm$  Mn) and ferrohastingsite skarn (Ca-Fe). The calcic skarn develops as veining and replacement along crackle brecciated albitites and culminates in total replacement of the pre-existing rock-type. It is dominated by coarse grained diopsidic clinopyroxene, sphene, tremolite and rare sulphides and scheelite. In addition, an integral component of this skarn type is the development of a “new” coarse grained plagioclase that can be either albitic or calcic. The calcic skarn is sited structurally above the main Ca-Fe skarn.

The magnetite skarns are composed of essentially magnetite with lesser pyrrhotite, pyrite, plagioclase, ferrohastingsite, apatite, allanite and late, introduced chalcopyrite. They can be fluidised and “flow banded” or can be massive “pod-like” replacement domains. Large angular clasts of calc-silicate, now altered to ferrohastingsite skarn, occur in the “flow

banded” variants and magnetite breccias are present. Unusual variants contain, in addition to magnetite, abundant pyrrhotite (up to 30%), apatite (up to 20%), allanite (up to 9%) and fluorite (up to 30%). The magnetite skarns can be flanked by hedenbergite skarn, ferrohastingsite skarn or they can be replaced by garnet skarn.

The garnet skarns are composed of Mn-andradite, andradite, grossular andradite, hedenbergite, chalcopyrite, fluorite, apatite, magnetite, uraninite, allanite and ferrohastingsite. They appear to develop late and are sub-vertical and usually copper-rich (up to ~4% Cu over 1m). Sphalerite and molybdenite are trace components and epidote and quartz are minor. The dominant garnet is a yellow mangan-andradite that is veined and replaced by grossular (-andradite) garnet and more rarely by fluorite + siderite (high  $f_{HF}$ ). The garnet skarns are rimmed or selvaged by ferrohastingsite skarn or biotite  $\pm$  K-feldspar alteration.

The ferrohastingsite skarn type is spectacular and contains potassic ferrohastingsite grains up to 5cm in size. The grains exhibit a random orientation and no fabric is present. Biotite can be a common inclusion phase and ubiquitous and abundant apatite and allanite are present as well as minor chalcopyrite, andradite and fluorite. This skarn type flanks the garnet skarn and invariably there is a juxtaposition of this skarn with unusual Fe-P-F-LREE-rich rock-types. Chalcopyrite-allanite-apatite rock, pyrrhotite-apatite-allanite rock, magnetite-apatite rock and apatite K-feldspar rock can be associated.

The sulphide mineralogy is reasonably simple with the dominant minerals being pyrite, chalcopyrite, pyrrhotite, and “secondary pyrite”, all in association with magnetite. Molybdenite, uraninite, coffinite, tellurides and sphalerite are minor phases. Chalcopyrite occurs as coarse grained aggregates within the garnet skarns as well as in late veins (e.g. with fluorite  $\pm$  quartz), early veins (e.g. grossular-ferrohastingsite-chalcopyrite) and as extremely fine grains within ferroactinolite replacing either hedenbergite or ferrohastingsite. In magnetite-rich skarns chalcopyrite occurs as extensional vein fills, as crosscutting veins with siderite or other minerals, along magnetite-magnetite grain boundaries or as discrete grains interspersed with the magnetite. Lower temperature retrogression of the skarns has been fundamental to the upgrading of copper (and gold) values. Mn-ferroactinolite, ferroactinolite, grossular garnet and epidote can be associated with increased but localised, chalcopyrite development.

Probable primary bornite and chalcocite have been noted and rare cobaltite grains may be present. Analysed pyrite contains no cobalt or arsenic suggesting that separate phases are host to these elements (mineralisation contains up to 700ppm Co and 100ppm As). Molybdenite is generally coarse grained (~ 0.2mm) and occurs in a number of different skarn types. It can contain inclusions of pyrrhotite and occurs as inclusions in magnetite, apatite, clinopyroxene and pyrite. Sphalerite, when present, can have an intimate relationship with gold, often occurring with gold as an annealing phase in shattered pyrite. Gold is rare and can be up to 330 micron in size. It is silver-rich (20%-25%Ag) and close to electrum in composition but does not contain any Hg, Te or Cu. It can contain hessite ( $Ag_2Te$ ) inclusions.

## **CONCLUDING REMARKS**

In summary, the following can be stated:

a) A stratigraphy, or pseudostratigraphy, for the South Koolka area has been presented. It recognises that many of the rock-types now present represent the end product of intense metasomatic activity; this activity can be summarised as follows:

- intense albitisation and minor K-feldspar alteration of pre-existing schistose to phyllitic assemblages
  - minor sulphide veining, including molybdenite-bearing veins
  - brecciation of albitic lithologies and replacement by calcic skarns (diopside-sphene  $\pm$  tremolite)
  - generation of a potassic calc-silicate envelope (abundant K-feldspar + diopside + tremolite + scapolite + sphene); “fringing” calc-silicates
  - creation of magnetite, hedenbergite, garnet and ferrohastingsite skarns and introduction of Cu-Au.
  - retrogression of the above and introduction of additional Cu and Au
  - zeolite activity; minor movement of copper
- b) The garnet skarns (and probably the hedenbergite and ferrohastingsite skarns) are subvertical within a shallowly north dipping sequence.
- c) The garnet skarns host the better copper mineralisation with lesser mineralisation surrounding these zones.
- d) Free gold and tellurides are located within magnetite, pyrite and pyrrhotite and there is an association of gold-pyrrhotite-sphalerite which anneals shattered pyrite.
- e) There is a high  $\text{Fe}^{3+}$  content in some of the mineralised skarns; e.g. andradite garnet, presence of allanite, abundance of magnetite, etc. Changing oxidation ratios from skarn type to skarn-type may facilitate precipitation of Cu-Au. Hematite is not present.
- f) Garnet and pyroxene chemistry is similar to other Cu-(Au) skarns, including the Palaeoproterozoic (-Mesoproterozoic) Mt. Elliot deposit, near Cloncurry; and
- g) The only deposit/prospect similar to South Koolka is the Gunsight Prospect in the Mt. Painter area, NW Curnamona Province. Mineralisation here is of a replacement nature and is enriched in Fe-Cu-Co-LREE-F-P (similar to South Koolka). The South Koolka skarn can be classified as a variant of the Proterozoic Fe oxide, Cu-Au mineralisation type.

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# Pb-Pb DATING OF GARNET, STAUROLITE AND TOURMALINE BY A STEPWISE DISSOLUTION TECHNIQUE

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## INTRODUCTION

The overall evolution of a metamorphic terrane can be constrained by the reconstruction of a  $P$ - $T$ - $t$  path defined by carefully selected samples. In its most rigorous expression, this is possible only with a combined approach involving metamorphic petrology and geochronology. A typical problem encountered in such studies, however, is that petrological data often cannot be easily linked to conventional geochronological data. For example, the temperatures experienced by rocks in areas of medium to high-grade metamorphism commonly exceed 600°C. This restricts the number of applicable geochronometers when attempting to unravel multiple episodes of deformation and metamorphism as the timing of earlier events may be completely lost by resetting. Perhaps even more problematic is the fact that metamorphic minerals also tend to be *variably* reset, which hinders the direct measurement of metamorphic ages by conventional techniques.

As a consequence of these complexities, indirect dating approaches have often provided the only means of constraining ages in many cases. U-Pb zircon and monazite dating within structural markers (commonly pre-, syn- and post-metamorphic intrusions) are the most commonly applied tools in amphibolite-granulite chronometry (e.g. Nutman and Ehlers, 1998, Page et al., 2000). This approach, however, relies heavily on the validity of field interpretations which may in turn be based on ambiguous data. Furthermore, direct dating of accessory minerals with high U/Pb ratios, such as zircon, monazite and xenotime, commonly are difficult to associate uniquely with well-defined  $P$ - $T$  conditions and quite often they exhibit partial protolith inheritance (Nutman and Ehlers, 1998). In contrast, the significance of ages obtained from micas and amphiboles, which are structurally and texturally well-constrained phases that generally can be related to distinct  $P$ - $T$  conditions in high-grade metamorphic terranes, are often interpreted as cooling ages (Harrison, 1981).

These problems could be overcome if (1) direct ages could be obtained on phases which are the product of well-constrained metamorphic reactions and (2) closure temperatures ( $T_c$ ) were higher than the temperature at which these reactions took place.

In this study, the feasibility of Pb-Pb step leaching (PbSL) as a new and reliable silicate digestion technique for geochronological studies of metamorphic minerals with low  $^{238}\text{U}/^{204}\text{Pb}$  such as garnet, staurolite and tourmaline is explored. Through the integration of PbSL applied to metamorphic minerals from a known structural/metamorphic setting, and an understanding of the controls on Pb closure temperature, an approach for directly dating deformational events has been developed.

## BACKGROUND

Increasing use is being made of Pb step leaching (henceforth PbSL) techniques in several branches of geochronology. In the metamorphic realm, the method circumvents most if not all of the potential problems which plague other chronological techniques noted above. Although

the principle is not new, the development of more efficient analytical equipment has increased the scope of the process in recent years.

PbSL can thus be defined as a new silicate digestion technique based on sequential acid treatment which allows the selective recovery of radiogenic and common Pb components from a mineral, making single-phase Pb-Pb dating possible. Although the products of the leaching process are strictly mixtures (or 'unmixtures') of components in the mineral lattice, the fact that they derive from a single mineral results in mixing lines which have true age significance (i.e., they are also isochrons). The potential of the step leaching technique to enhance the spread in  $^{206}\text{Pb}/^{204}\text{Pb}$  and  $^{207}\text{Pb}/^{204}\text{Pb}$  ratios, allows age determinations to be undertaken on a wide range of minerals, particularly those in which bulk U/Pb ratios are generally unfavourable for conventional dating. For example, in the experiments conducted in this study an extremely large spread in isotopic ratios has been obtained during the step leaching of garnets.

One additional advantage of the PbSL approach is an ability to clearly delineate the possible influence of sub-microscopic inclusions (e.g. monazite or zircon) in a given mineral, and to determine whether or not these are in isotopic equilibrium with their host. This is achieved by comparing leaching spectra in the uranogenic ( $^{206}\text{Pb}/^{204}\text{Pb}$ ,  $^{207}\text{Pb}/^{204}\text{Pb}$ ) vs thorogenic ( $^{206}\text{Pb}/^{204}\text{Pb}$ ,  $^{208}\text{Pb}/^{204}\text{Pb}$ , ) isotope diagrams, which provide a monitor of time-integrated variations in U/Th ratio. A linear arrangement of PbSL data points in both diagrams might be expected if the mineral under investigation was compositionally homogeneous and unaffected by later disturbance. Alternatively, multiple arrays in the thorogenic diagram may result from bulk mixing of Pb from different phases, with different U/Th ratios. If this is the case, this information not only helps to identify and exclude isotopic information which is influenced by the inclusions, but also potentially to extract age information from the inclusions themselves.

In summary, the step leaching procedure uses only information from different leachates and residues from a given mineral and, thus, completely avoids problems associated with unknown initial Pb isotopic compositions. Step leaching potentially yields highly reliable (and for old rocks commonly also precise) Pb-Pb ages provided the dated mineral is isotopically homogeneous, there were no inclusions, or inclusions are coeval, behaved inertly during leaching, or released their isotopic signature during one or two single leaching steps. A disadvantage of the step leaching procedure is the poor precision in Pb-Pb ages for young samples (restricted by the rate of recent generation of  $^{207}\text{Pb}$  as most  $^{235}\text{U}$  decayed early during Earth's history).

In this study the technique is applied to a suite of samples from the Southern Cross area of the Broken Hill Block, Australia. This area has been the location of the University of Melbourne third year Structural and Metamorphic field camp for many years and consequently has been thoroughly documented in terms of the lithologies present, and their structural and metamorphic history. The many years of observation and research were recently documented by Wilson and Powell (2001). Consequently, the Southern Cross area provides an ideal natural laboratory in which to test the potential application of the PbSL geochronometer since metamorphic phases can be chosen within a clear structural/metamorphic context. Furthermore, geochronological studies in and around this area have also been conducted, using techniques such as SHRIMP U-Pb analyses (Nutman and Ehlers, 1998; Page and Laing,

1992; Page et al., 2000), and provide important constraints in assessing the results of this study.

## RELATIVE AGES AND THEIR SIGNIFICANCE

The most important apparent ages resulting from this study may be summarised as follows:

- A  $1599 \pm 1$  Ma Pb-Pb age from garnet (GD1) associated with the D<sub>1</sub> deformational event
- A  $1592 \pm 16$  Ma Pb-Pb age from garnet (GR) associated with D<sub>1</sub> or a later event
- A  $1594 \pm 7$  Ma Pb-Pb age from garnet (GMT15)
- A  $1556 \pm 10$  Ma Pb-Pb age from garnet (GMT12) associated with a post D<sub>1</sub> event (probably D<sub>3</sub>)
- A  $1568 \pm 3$  Ma Pb-Pb age from tourmaline (MT) hosted in pegmatite ('late' pegmatite, possibly late D<sub>2</sub>)<sup>1</sup>.
- A  $1498 \pm 28$  Ma Pb-Pb age from garnet (garnet amphibolite) in a calc-silicate leucosome (unconstrained event)
- A  $1553 \pm 18$  Ma Pb-Pb age from retrograde staurolite (sample MT13, D<sub>3</sub> event)
- A two age component  $1330 \pm 33$  Ma (inclusions) and  $876 \pm 71$  Ma (host) from retrograde staurolite (sample MT4, D<sub>3</sub> or younger)

The  $1599 \pm 1$  Ma Pb-Pb age for the garnet GD1 is identical with that of  $\sim 1600$  Ma constrained on the basis of U-Pb SHRIMP zircon data (Page et al., 2000). These ages are thus considered to represent the time of the first upper amphibolite facies metamorphic event that occurred synchronously with the first ductile deformational event D<sub>1</sub>.

The age of the garnet GMT15 of  $1594 \pm 7$  Ma is identical with these as well as the age  $1595 \pm 7$  Ma for monazite and sphene from the mine sequence rocks (Gulson, 1984) and the  $1595 \pm 7$  Ma for zircon formed during high-grade metamorphism in an area adjacent to the Southern Cross area of this study (the Allendale mine). The age  $1498 \pm 28$  Ma obtained from the garnet amphibolite is also similar to the  $1483 \pm 20$  Ma K-Ar age obtained from a muscovite sample from the northern end of the Broken Hill Block, measured by Harrison and McDougall (1981). The ages obtained from garnet GMT12 of  $1556 \pm 10$  Ma and from the tourmaline of  $1568 \pm 3$  Ma are similar to Pidgeon's (1967) youngest isochron age (garnet-sillimanite gneiss) of  $1571 \pm 35$  Ma. These younger ages also agree with the  $^{40}\text{Ar}/^{39}\text{Ar}$  ages for hornblendes ( $1573 \pm 5$  Ma) measured by Harrison and McDougall (1981), which were interpreted as cooling ages. Binns and Miller (1963) determined a K-Ar age on the Mundi Mundi granite of  $1307 \pm 56$  Ma, which is similar to  $1330 \pm 33$  Ma obtained from inclusions within staurolite sample MT4. Thus, despite large uncertainties on some of these results, it appears that the majority of the new PbSL age estimates are substantiated by earlier studies.

## CONCLUSIONS AND DIRECTIONS FOR FURTHER RESEARCH

The geological history of the Willyama Group of the Southern Cross area is characterised by repeated events involving high-grade metamorphism associated with deformation and magmatism. The results of the PbSL investigation document events at about 1600 Ma, 1550 Ma and 1500 Ma. In addition, two enigmatic and younger events are recorded in staurolite porphyroblasts from one locality; a possible inclusion age of 1330 Ma and that of the staurolite host at about 870 Ma.

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<sup>1</sup> Note: this is a only a preliminary result based on a 4 point isochron.



In addition to supporting the occurrence of at least three distinct metamorphic events, the PbSL data from this study also imply a larger temporal-frame than previously proposed, spanning from 1600 Ma to 1330 Ma. Another important distinction between the results of this work and previous studies is that D<sub>1</sub> and D<sub>2</sub> events appear to be separated by a significant time interval. Consequently, this new technique invites a revaluation of the existing geochronological data which form the basis of the geological history of the Broken Hill Block.

Finally, in light of the results presented in this study, several issues emerge which are worthy of future investigation:

- How does the composition of the metamorphic phase/host rock control the success of the PbSL method? For example, garnets extracted from metapelitic samples generate a wider range in Pb isotope values compared with those from the garnet amphibolite leucosome (e.g.,  $^{206}\text{Pb}/^{204}\text{Pb}$  values range from ~20 to >~400 in the former, compared with only ~20-70 in the latter). This has important consequences for deriving high-quality isochrons, and thus for the utility of PbSL, as applied to garnet in different geological contexts.
- Does the timing of metamorphism and deformation in the Broken Hill inlier require re-evaluation? This may best be approached via additional PbSL studies in key locations for which the structural and metamorphic context is well established.
- How might the step-leaching protocols be optimised for different mineral phases? This study has revealed the highly variable, and in some cases less than optimal, U and Pb release profiles for different phases.
- Can a PbSL approach be successfully developed for ore-stage minerals such as sulfides (e.g. pyrrhotite/chalcopyrite) in order to directly date the age of mineralisation?

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# MINERALISATION STYLES IN THE OLARY DOMAIN, SOUTH AUSTRALIA

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The Willyama Supergroup (1720-1640Ma) in the Olary Domain has been divided into two groups and four subgroups (Conor, 2000) and contains thick siliciclastics with minor carbonates that in the Portia and Kalkaroo areas (eg. Bimba formation) host Cu-Au deposits. The Willyama sediments were deformed by the Olarian Orogeny and major mineral occurrences in the region are controlled by those Olarian structures.

The metasediments in the Domain host varieties of mineral deposits. Three types of mineralisation are recognised in this study. The first is layered Zn-rich deposits in the reduced black pelites of the Strathearn Group such as those intersected in the Portia and Hunters Dam drillholes. The mineralised pelite is generally laminated. The lamination has a depositional origin although been subjected to later alteration. These deposits are more or less similar to Mt Isa-style Zn-Pb deposits and in the Olary Domain they are distributed in the Benagerie Ridge and northeastern region. Their potential in the Domain is poorly known and could be huge.

The second type is fault-breccia hosted Cu-Au deposits and represented by the deposits at Mount Howden and Billeroo. The deposits are fault-controlled or elongated, generally lens-shaped and en echelon-arranged. The mineralised lodes or lenses cut across the  $S_1$  layering. The alteration is dated at 1632-1612 Ma (Re-Os on molybdenite, Skirrow and Ashley, 2000) or 1630-1605 Ma (SHRIMP on mozonite, Teale and Fanning, 2000) in the region.

The third is the Portia and Kalkaroo-style Cu-Au deposits that are commonly accumulated in the  $F_3$  fold axis or  $D_3$  fault zones. Primary mineralisation in the Portia area is mainly deposited in fracture zones and hydrothermal fluids are suggested to be remobilised from intrusion of ~1590 Ma granite. A SHRIMP U-Pb date, ~1588-1583 Ma, on titanite (Skirrow and Ashley, 2000) may provide approximate age for this heating event. Other mineralisation dates in the region, however, point to a major alteration age interval of 1605-1632 Ma (Teale and Fanning, 2000; Williams and Skirrow, 2000). The evidence suggests the mineralisation is associated with the multiple-phased alteration systems.

A mineralisation model, the stratigraphic trapping for secondary Cu-Au mineralisation in the Olary Domain, is proposed based on character of the Portia and Kalkaroo deposits (Fig. 1). Regionally, the Willyama Supergroup sediments were pervasively metamorphosed during the Olarian Orogeny and most porosity in the sediments had been filled by albitisation, calc-silicification and occasionally argillic alteration. Carbonates of the Bimba formation overlie the albitite of the Peryhumuck Formation and, in turn, are overlain by pelitic Strathearn Group. Both pelitic and albitic metasediments are impermeable. The carbonates, particularly those with evaporitic deposits, would be likely mobilised during hydrothermal events, transported and trapped minerals to structures. Associated faults were also important mineralisation zones for hydro-fluids, but their alteration was restricted to timing of tectonics when faults were still active. The stratigraphic traps could last through entire hydrothermal periods and had the best chance for mineral concentration.

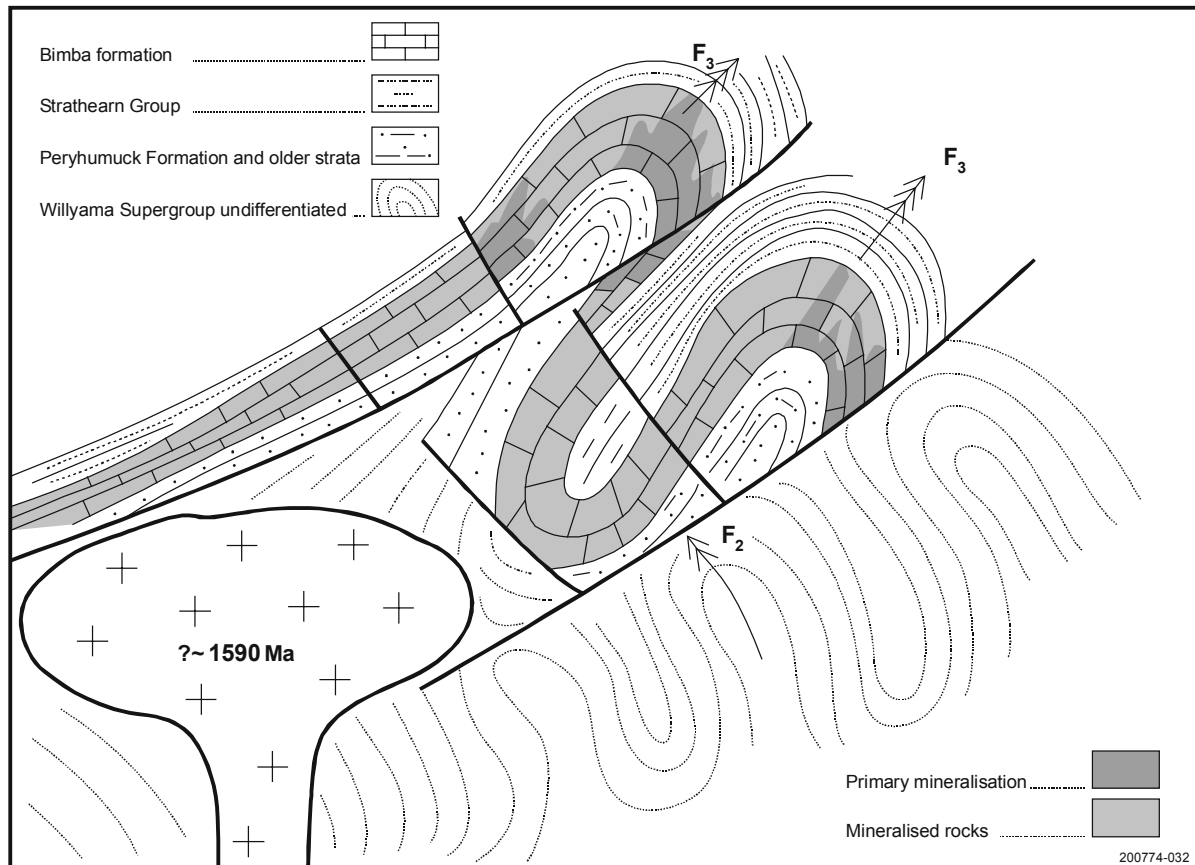


Figure 1. Preliminary interpretation of the Portia mineralisation.

**Acknowledgements.** The author thanks C. Conor, S. Robertson and M. Schwarz for support and valuable discussions.

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