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Broken Hill Exploration Initiative:

Abstracts for the September 2006 Conference

Compiled by *R.J. Korsch & R.G. Barnes*

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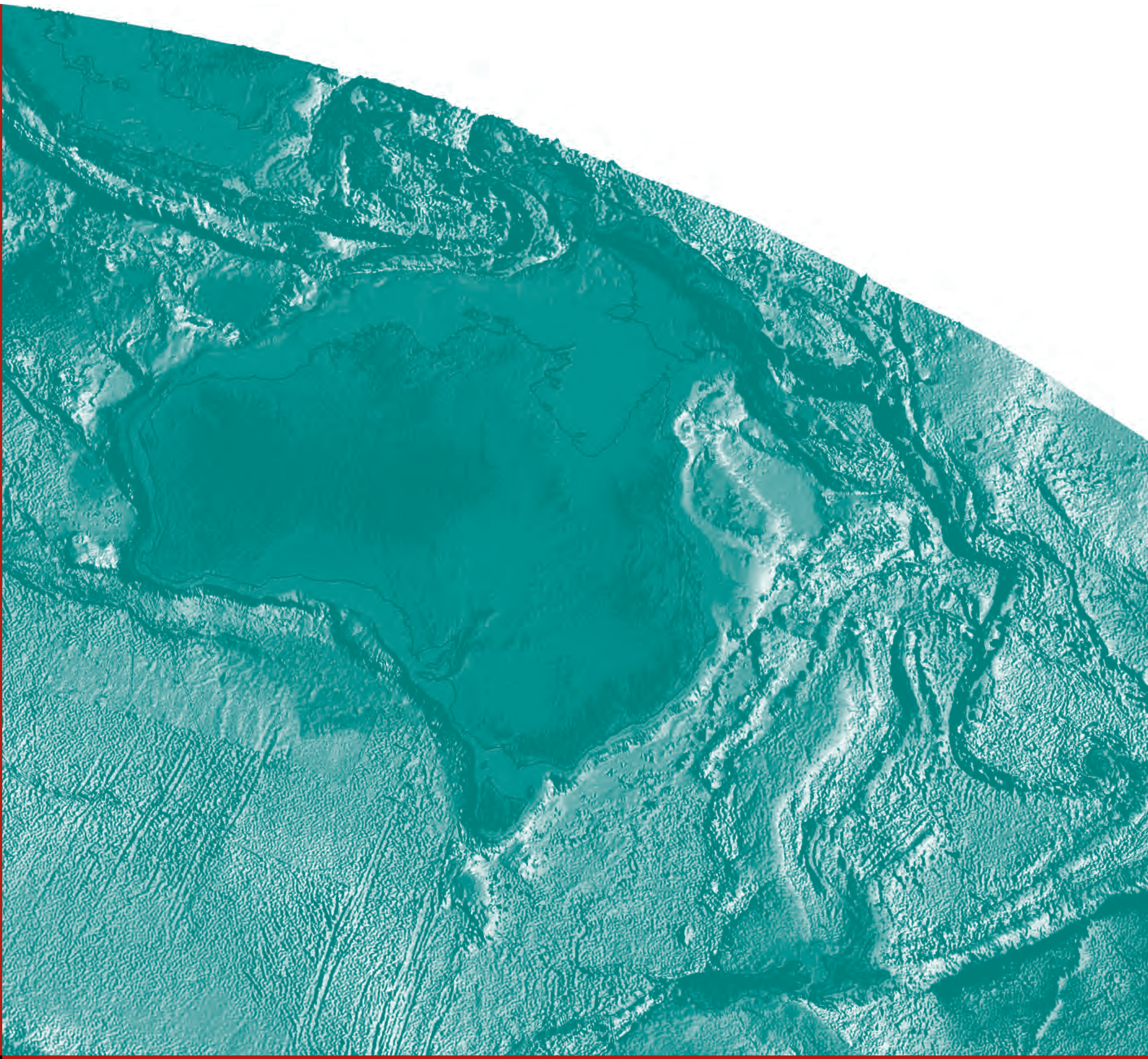

SPATIAL INFORMATION FOR THE NATION

BROKEN HILL EXPLORATION INITIATIVE: ABSTRACTS FOR THE SEPTEMBER 2006 CONFERENCE

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Abstracts were solicited by the Organising Committee of the 2006 Broken Hill Exploration Initiative Conference and were reviewed by the home institutions of the authors. They were not formally reviewed for this volume, however, and thus any analyses or scientific opinions expressed in this volume are the sole responsibility of the authors.

CONTENTS

The BHEI Falcon Gravity Survey and Goldfinger BHT Project - exploration geophysics, geochemistry and geology integrated in 3D

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Falcon Gravity Gradiometry and Inversion

Initial drill based evaluation of the PMD-CRC – NSW DPI Falcon® airborne gravity gradiometry data for the Broken Hill region returned a number of promising geochemical "leads", with the best result from the first order "Goldfinger" GDD anomaly, north of known BHT style mineralisation at Galena Hill and 18km south of Broken Hill.

Goldfinger integrated model – gravity, geochemistry, structural geology

Following limited RC and RAB drilling coverage of the Goldfinger gravity trend DDH02 was drilled to 436m TD, testing the easternmost closure in the GDD data (Figure 1). This hole intersected a thick sequence of garnetiferous "lodey" metasediments and amphibolite, consistent with a BHT setting. Intervals of moderate level base metal mineralisation were analysed for BHPB's proprietary alteration index guide for proximity to economic BHT ore, and returned "compelling" indices. Re-processing and inversion of the gravity data, and deep penetrating IP surveys indicated potential for density and sulphide accumulations respectively, at depth some 600 -700m west of DDH02. Drill tests of these, and a local magnetic feature immediately south of the gravity target have all returned significant alteration zones and strong base metal geochemistry.

Structural logging and interpretation of diamond drill core indicates potential sub-horizontal D2 fold closures as favourable targets for local ore-grade development within the Goldfinger BHT zone. The major folding that controls the distribution of lithology, lode rocks and the gravity response are inclined F2 folds with sub-horizontal axis tending roughly east west (Figure 2). Steep north dipping shears parallel to the regional Thackaringa – Pinnacles shear zone add complexity.

The core of the GDD anomaly where drilled to date in DDH03 corresponds both to increased garnet alteration, a lode zone and thick amphibolite. The lack of correlation between holes DDH02 and DDH03 suggest the presence of at least three separate lodey horizons in the system.

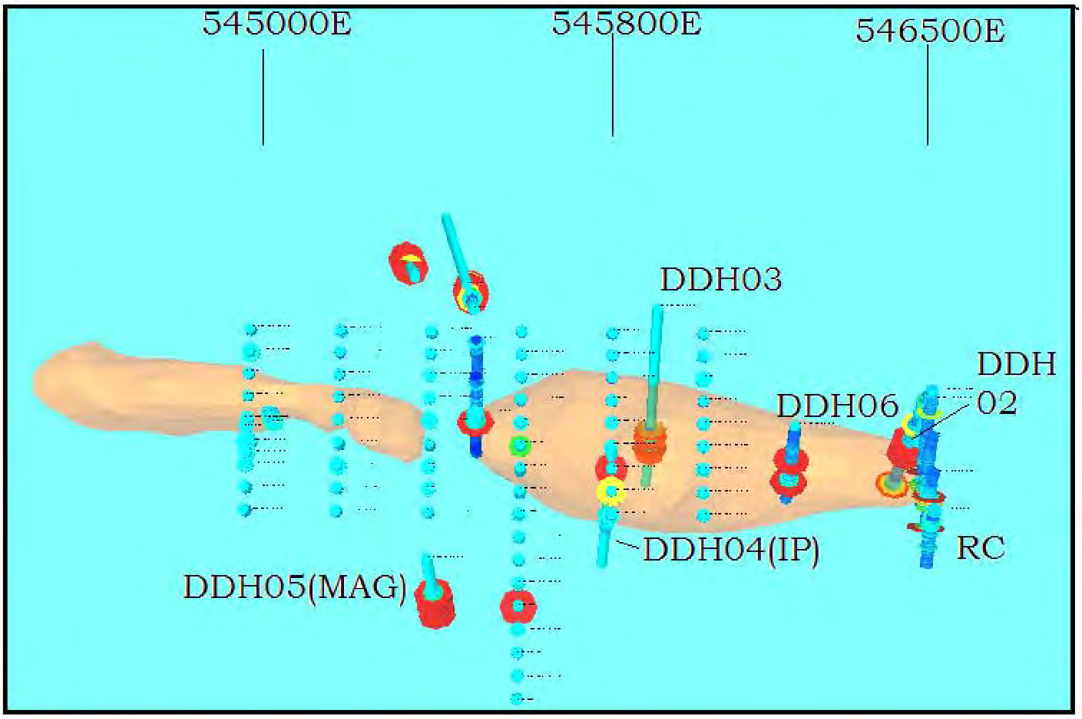

Figure 1. Goldfinger Gravity Inversion Model and Drill Hole Zinc Intercepts

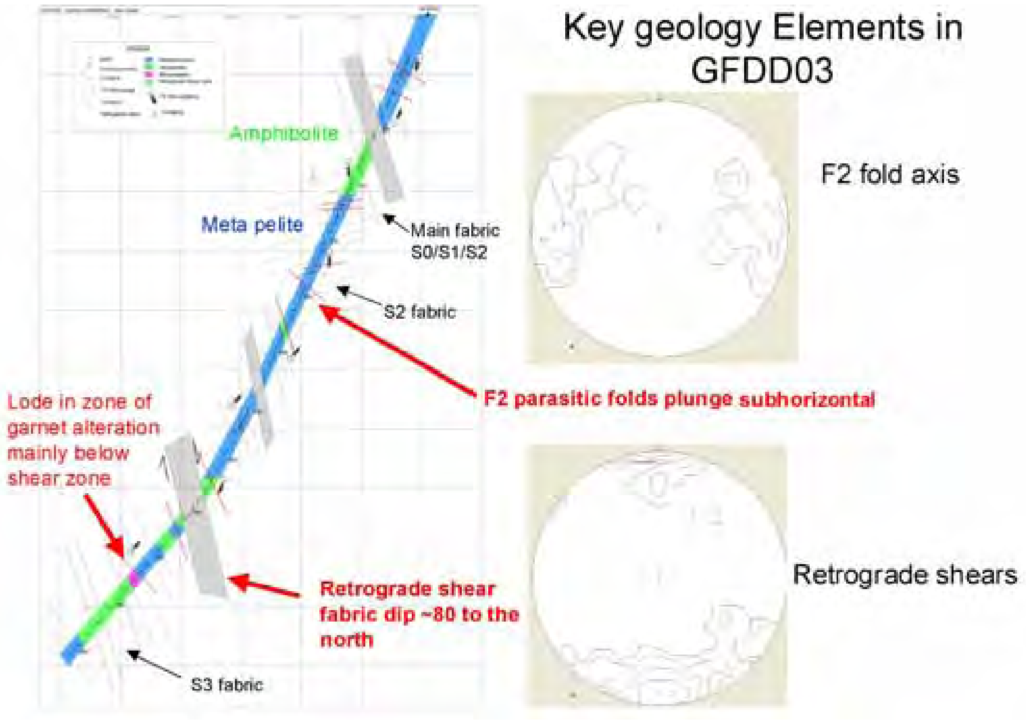

Figure 2. Goldfinger important structural elements

Integration of geophysical, geological, geochemical and structural interpretations into a comprehensive 3D view is progressively providing an insight into prospectivity of the project. Further drilling targets have been outlined and planned for testing as rig availability allows.

Acknowledgements

Stellar Resources wishes to thank officers of the NSW DPI and the PMD CRC who made the Broken Hill Falcon ® survey a reality, and the companies which collaborated in the survey Joint Ventures. In particular we wish to thank BHPBilliton for their continuing interesting, and technical support for the Goldfinger evaluation, and the co-operation of our JV partners in the project, Triako Resources Ltd. and AngloGold Ashanti Australia Ltd.

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Geochemistry and geophysics in the Curnamona Province: Can this marriage be saved?

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Summary

Ca 1580 Ma volcanic rocks of the Benagerie Ridge in the northwestern part of the Curnamona Province are sampling underlying crust different from the rest of the province, and are more similar to equivalent age granites of the Crockers Well Suite in the western-most Curnamona Province and Hiltaba age granitoids and volcanics in the eastern Gawler Craton. Deep seismic reflection data and an anomalous gravity signature in the Curnamona region support a possible crustal scale boundary in the western Curnamona Province. Geochemical signatures suggest juxtaposition of meta-igneous crust with pre-Willyama metasedimentary rocks. Such a suture zone could also have acted as a pathway for fluid movement from the deep crust/mantle. This interpretation enhances the mineral exploration potential of the western Curnamona Province for IOCG-type deposits.

Background

The geochemistry, geochronology and Sm-Nd isotope composition of granites can help to constrain deep seismic reflection data interpretations of crustal scale structures in ancient orogenic belts. Tectonic plate-scale accretionary activity may juxtapose terranes of different age and/or composition. Such crustal block differences may be detected through: U-Pb zircon dating and identification of inherited crust; Sm-Nd isotopic mapping of lower crustal blocks of differing age; and geochemical variations that arise from differences in crustal source composition.

Recently published interpretation of the 2003-2004 PIRSA-GA deep crustal seismic survey across the southern part of the SA Curnamona Province suggests that the western-most edge of the line features a series of narrow zones interpreted east-dipping faults. These features are crustal scale, and divide the block into two regions with distinct seismic properties (Korsch et al., 2006). These workers suggest the faults may represent terrane amalgamation, in this case the Gawler Craton to the west and the Curnamona Province to the east.

This paper illustrates the application of granite geochemistry and Nd isotope variation to the interpretation of crustal architecture derived from geophysical data. Ca 1580 Ma granitic activity occurred from west to east across the Gawler-Curnamona boundary, from the eastern Gawler Craton (Hiltaba event and Gawler Range Volcanics) to the western Curnamona Province (Benagerie Ridge Volcanics and Crockers Well Suite) and the central Curnamona region (the Bimbowrie Suite). A number of workers have previously noted the similarities of the Benagerie Ridge Volcanics to the Gawler Range Volcanics, highlighting their IOCG potential (e.g., Giles and Teale, 1979; Teale, 2000).

Results and Discussion

The Benagerie Ridge Volcanics were sampled from the Culberta 1 drillhole. The unit is a massive quartz-feldspar porphyritic rhyolite with hematite alteration zones. A SHRIMP age of ca 1581 Ma from the proximal Mudguard 1 drillhole (Fanning, 1998) confirms their temporal coincidence with the abundant ca 1580 Ma Bimbowrie Suite to the south and west. Seven samples analysed for whole-rock Sm-Nd isotope composition yield a restricted range of initial □$_{Nd}$ values (-4.3 to –3.3). These values indicate dominant intracrustal derivation, with little or no mantle input. These values are also indistinguishable from the range of data for Olympic Dam and Moonta Hiltaba Suite Granites, and also from ca 1580 Ma Curnamona granite data across the Curnamona. If the deep seismic reflection zone highlighted by Korsch et al. (2006) is documenting juxtaposition of crustal blocks, the age contrast of those blocks may be insufficient to detect with the Nd isotope signature the granites inherited from the crustal columns they passed through.

The geochemical signature of the BRV samples reflects mild to strong enrichments in Zr, Nb and REE and anomalous Ga/Al ratios characteristic of ‘A-type’ granites. Their geochemistry is similar to Hiltaba Suite granites and Gawler Range Volcanics. Patterns are also similar to those of the Crockers Well Suite of the southwestern Curnamona Province, but in marked contrast to the Bimbowrie Suite granites of the Curnamona Province.

The Benagerie Ridge and Crockers Well region correlates with a strong negative gravity anomaly. While the source of the gravity anomaly has been interpreted as a large felsic pluton at shallow regions by Williams and Betts (2004), Milligan et al. (2000) have highlighted that the density contrast is detectable at considerable depths.

If the deep seismic data and the gravity contrast are marking juxtaposition of two differing crustal blocks, their age contrast is not great enough to be detected through Nd isotope variations. But, the great contrast in the geochemical signature of ca 1580 Ma granites across the proposed suture, from the eastern Gawler Craton to the central Curnamona Province, support these geophysical interpretations. Such a possibility links emplacement of the Olympic Province granitoids with the Curnamona Province Benagerie Ridge and Crockers Well magmas into the same crustal block, enhancing the IOCG potential of the western Curnamona region.

Acknowledgements

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Pb-Pb step-leaching chronology of chalcopyrite and magnetite from Copper Blow

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Pb-Pb step-leaching (PbSL) is a geochronological tool aimed at unmixing the common and radiogenic Pb components present in low-U minerals, using sequential leaching with a range of acids (HBr, HCl, HNO_3, HF). Frei and Kamber (1995) showed that this approach can produce highly correlated Pb isotope unmixing arrays with age significance for a number of low-U silicate minerals, and thus provide a new single mineral dating tool for assemblages normally unfavourable for U-Pb dating.

Here we present the results of a PbSL study of chalcopyrite and magnetite and an *in situ* laser ablation Pb isotope investigation of magnetite from Copper Blow, with the aim of documenting the distribution of radiogenic versus common Pb in this mineral. Laser ablation is an ideal tool to examine if Pb isotopes are distributed uniformly (suggesting uniform distribution of U in the mineral lattice) or in “hot spots” of localized U enrichment, such as in inclusions or cracks.

PbSL and *in situ* laser-ablation Pb isotope data for chalcopyrite and magnetite from Copper Blow reveal:
^{206}Pb-rich spikes and domains related to U-rich inclusions and/or impurities along grain surfaces and cracks;
Copper Blow magnetite contains clear evidence for U-rich (low-Th/U) micro-inclusions c 1200 Ma old;
Strongly scattered PbSL ‘isochrons’ with anomalously young apparent ages for these minerals might be the result of mixing of common Pb with a heterogeneous radiogenic Pb component related to late addition of U.

Acknowledgements

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The Western Mineralisation – Rasp Mine

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Geology of CML7

CML7 contains up to 40 m of waste rock and tailings covering outcrops. Weathering is to a depth of 30-50 m, the Zinc Lodes are weathered to a depth of 30 m and the Lead Lodes are selectively weathered to a depth of 120 m. Exposure is restricted to a few remnant outcrops in the Kintore, BHP, Block 14 and Blackwood Open Pits and the CML7 geological map has been compiled from an 1887 topographic map, the map of Andrews (1922), mapping of outcrop before CML7 was covered with waste rock, remnant outcrops and open pits.

Measurement of lithological packages, graded bedding and bedding-schistosity relationships in oriented diamond drill holes and mapping in the Kintore and Block 14 Open Pits shows that the Zinc Lodes on CML7 are on the western limb on an inverted F_1 nappe and that the Lead Lodes are on the limb of an inverted F_1 nappe and in the hinge of a south- and north-plunging F_2 Antiform (Broken Hill Antiform). Coplanar with the axis of the F_2 antiform are S_2 and S_3 axial plane sulphide projections and the Main Lode Shear, a high metamorphic grade shear zone formed in $D_{2/3}$ and within which the No 2 Lens and No 3 Lens have been transposed. F_3 folds plunge both north and south and the Main Lode Shear have been deformed by easterly- and westerly-plunging open small F_4 folds. The dominant structure on CML7 is F_2. The Main Lode Shear is transgressed by high-grade shear zones (e.g. Thompson Shear, van den Heyden and Edgecombe, 1990) and, in Block 14 Open Cut, is transgressed by retrograde shear zones of unknown age. In proximity to the Lead Lodes, the Main Lode Shear bifurcates into retrograde shear zones of unknown age and is pseudomorphed by retrograde assemblages of unknown age along strike in Kintore Open Pit.

The gross structure of CML7 is in accord with that published by Laing *et al.* (1978). However, the structure within 20 m of the Lead Lodes is unrelated to the regional structure and probably reflects the extreme competency differences between galena-rich and the enclosing silicate rocks. Until 2005, the geology of the area immediately to the east of the Broken Hill orebody was known from the Andrews (1922) map, a few diamond drill holes and remnant outcrop. Eastward diamond drilling in 2005 has shown an upward-facing repetition of the stratigraphy from the top of the Broken Hill Group to the top of the Thackaringa Group thereby confirming the Laing *et al.* (1978) position of the Broken Hill Antiform.

On CML7, Unit 3.10 was rarely intersected in drilling and comprised foliated felsic gneiss equivalent to the Rasp Ridge Gneiss. Unit 3.10 crops out west and east of CML7. In places, the foliated felsic gneiss contains swathes and schlieren of sillimanite. The contact between Unit 3.10 and Unit 4.1/4.3 is sheared and the structural style and metamorphic grade are unchanged across the lithological boundary. Units 4.1 and 4.3 comprise well-bedded psammopelitic and psammitic metasediment sequences and Unit 4.4 is a distinctive sequence comprising psammopelitic metasediments and amphibolite veined by garnet which grades into garnet amphibolite which in turn grades into a foliated feldspar-quartz-garnet-biotite rock, locally known as “Potosi Gneiss” (Main *et al*., 1983). The amphibolite is of tholeiitic basaltic composition and commonly has a sharp garnetised upper and lower contact and associated with the amphibolite are grains, stringers, veins and pods of pyrrhotite, pyrrhotite-chalcopyrite, sphalerite and galena. Minor layer-parallel horizons of coarse grained garnet-biotite are associated with amphibolite and are probably altered mafic tuffs. Unit 4.5 is dominantly a psammitic unit with minor psammopelite and pelite layers, common bedding and graded bedding and, towards the top of the Unit, minor lode horizons comprising blue quartz ± ferroan gahnite ± manganoan almandine ± pyrrhotite ± chalcopyrite ± sphalerite ± galena. In places, the lode horizon is concordant with S_0/S_1, whereas in other places it is discordant and replaces metasediments.

A massive pelite (Unit 4.6) with rare bedding and interbedded psammopelite and psammite is used as a stratigraphic marker horizon in drilling on CML7. However, Unit 4.6 is not present in the southern segment of CML7 (although possibly occurs at depth) and is replaced by a thinner facies equivalent comprising a faintly bedded sillimanite-feldspar-biotite pelite. In places, on the south of CML7, Unit 4.6 is replaced by a spotted garnet psammopelite. The thinnest segments of Unit 4.6 are associated with the thickest development of sulphide rocks. Unit 4.6 is black (rarely dominantly white) and comprises crenulated elongate bundles of S_1 sillimanite, crenulated S_1 biotite, K feldspar and rotated disarticulated almandine porphyroblasts up to 4 cm in size about which S_2 sillimanite and biotite are wrapped. In places, Unit 4.6 is cut by Potosi Gneiss (foliated garnet-plagioclase gneiss) and usually drill intersections of Unit 4.6 intersected one to three 5-20 cm thick garnet horizons towards its stratigraphic base. The domination of psammite and common occurrence of graded bedding in Units 4.5 and 4.7, which envelops Unit 4.6, suggests that Unit 4.6 was originally shale formed during a low energy sedimentation phase between periods of high rates of clastic sedimentation.

Unit 4.7 dominantly comprises poorly bedded psammopelitic and psammitic metasediments with rare S_1 foliated garnet-plagioclase gneiss at the base of Unit 4.7, a spotted psammopelite and quartz-gahnite and quartz-garnet rocks. In places, S_1 is crenulated by S_2. The metasediment sequence in Unit 4.7 is thickening upwards with the Broken Hill orebodies present in the highest energy part of the metasediment sequence. Within Unit 4.7 is a pelite of similar appearance to Unit 4.6 although it contains more K feldspar and less sillimanite than the Unit 4.6 pelite. The stratigraphic relationships of this pelite with the dominant psammites and psammopelites of Unit 4.7 are unclear. Although amphibolite is present in Unit 4.7 elsewhere at Broken Hill (Haydon and McConachy, 1987), it has not been observed in Unit 4.7 on CML7 and Unit 4.4 amphibolite deep on the western part of CML7 is correlated with magnetic amphibolite on the eastern part of CML7. However, cm thick horizons of garnet-biotite in Unit 4.7 may have been altered mafic tuff. The lode horizon rocks comprise blue quartz ± gahnite ± spessartine ± pyrrhotite ± galena (blue quartz lode and quartz-gahnite rock), plumbian orthoclase pegmatite –quartz ± galena ± pyrrhotite (green feldspar pegmatite), quartz-spessartine rocks ± pyrrhotite ± galena ± chalcopyrite (quartz-bearing garnetite), garnet ± quartz ± chalcopyrite ± galena ± löllingite ± tetrahedrite (garnetite) and sulphide rocks. Lode horizon rocks occur in proximity to massive sulphide rocks.

The foliated garnet-plagioclase gneiss contains minor pegmatites and ptygmatic veins of pegmatite composition suggesting formation of axial plane F_1 pegmatites. Both the F_1 pegmatites and S_1 have been folded by F_2 and a weak S_2 is defined by biotite crenulation and axial plane S_2 pegmatites. Equidimensional garnets, 2-4 mm in size in both the foliated garnet-plagioclase gneiss and the pegmatites are rimmed by biotite. The Potosi Gneiss occurs in both Units 4.4 and 4.7 and, in Unit 4.7, is a local name for a foliated garnet-plagioclase-K feldspar-biotite-quartz gneiss with abundant small garnet porphyroblasts both in the matrix and pegmatitic segregations. At the stratigraphic upper contact of the Potosi Gneiss is foliated augen feldspar gneiss which may represent early (D1?) shearing along the competency boundary between Potosi Gneiss and metasediments. The K-feldspar: plagioclase ratio of the Potosi Gneiss is variable, as is the garnet content. On CML7, the foliated garnet-plagioclase gneiss is a minor part of Unit 4.7 and occupies at least three distinct stratigraphic positions stratigraphically above the Lead Lodes. It crops out on CML7 as lensoidal masses and has been intersected to the east of the Broken Hill orebodies in the latest program of diamond core drilling. At the termination of lensoidal masses of the foliated garnet-plagioclase gneiss are quartz-rich rocks and spotted garnet-bearing psammopelites. In the immediate area of the Broken Hill mines, the thinnest horizons of foliated garnet-plagioclase gneiss occur associated with the maximum sulphide rock development and the geochemistry of the foliated garnet-plagioclase gneiss is used as an indicator of proximity to sulphide rocks.

Stevens and Barron (2002) showed that the foliated garnet-plagioclase gneiss of the Hores Gneiss to the north and west of the Broken Hill orebody contains inclusions which they interpret as imperfectly-consolidated sediment rip-up clasts, mass flow cobbles, amygdules or lithophysae, eutaxitic textures, euhedral feldspar phenocrysts, bipyramidal embayed quartz phenocrysts after β-quartz and calc-silicate ellipsoids. They suggest that the garnet-plagioclase rocks of the Hores Gneiss were submarine lavas, shallow intrusions and/or volcaniclastic deposits. The SHRIMP zircon date of 1686 ± 3 Ma (Page et al., 2000) dates the supracrustral rocks at the top of the Broken Hill Group which is the stratigraphic position of the Broken Hill orebody, thereby constraining the age of the Broken Hill orebody. The thin foliated garnet-plagioclase gneiss of Stevens and Barron (2002) occurs between Units 4.6 and 4.8, is interpreted as Unit 4.7 and this volcaniclastic mass to the north and west of Broken Hill is the strike equivalent of the thick metasediment-dominated Unit 4.7 in the Broken Hill mines area.

In many places on CML7, the foliated garnet-plagioclase gneiss grades transverse to S_1/S_0 into feldspathic psammitic and psammopelitic metasediments. In Unit 4.7, there was no gradation into amphibolite as is present in Unit 4.4. Feldspathic psammite and psammopelite also contain equidimensional garnet porphyroblasts, 2-4 mm in size, and rimmed by biotite. There is nomenclature confusion in the literature as to what constitutes Potosi Gneiss and most commonly it has been used to describe a spotted foliated to weakly foliated felsic rock with spots defined by 2-4 mm sized equidimensional garnets rimmed by biotite. However on CML7, such spotted rocks are transgressive to stratigraphy and hence the occurrence of garnet-bearing feldspathic psammite and psammopelite and garnet-plagioclase gneiss may represent a pre-metamorphic overprint on reactive feldspathic rocks. On CML7, the Potosi Gneiss is mapped as a quartz-plagioclase-K feldspar-garnet-biotite gneiss with biotite-rimmed garnet porphyroblasts. Hence elsewhere in the Broken Hill field, what is termed in the literature as Potosi Gneiss proximal to the Broken Hill mines may be an alteration type rather than a lithological horizon coplanar with other strata in Unit 4.7 (i.e. Hores Gneiss). There is a gradation from the garnet-bearing feldspathic psammite and the garnet-plagioclase gneiss into a blue quartz-garnet ± biotite ± pyrrhotite ± chalcopyrite rock suggesting replacement of high metamorphic grade garnet-bearing rocks by blue quartz.

On CML7, the complete section of the Zinc Lodes (C Lode, B Lode, A Lode and 1 Lens) and the Lead Lodes (2 Lens and 3 Lens) sulphide rocks has been intersected in recent diamond core drilling. Each sulphide rock mass at Broken Hill is spatially separated by metasediments and has a characteristic chemistry and hence a characteristic mineralogy. Most of the sulphide rocks on CML7 display a cataclastic texture and contain angular to rounded clasts of wall rocks including bleached pelite and psammite, quartz, plumbian orthoclase, garnetite, garnet quartzite, quartz-gahnite rocks and other sulphide rocks.

The stratigraphically lowest sulphide mass (C Lode) comprises quartz-gahnite-sphalerite-galena-pyrrhotite-garnet. C Lode comprises transgressive masses, layer parallel masses, S_2 axial plane masses and cataclastic ore along S_0/S_1, S_2 and S_3. Minor quartz-bearing garnetites are associated with C Lode and there is a halo of spotted garnet-bearing psammopelite associated with C Lode. B Lode comprises quartz-sphalerite-galena-garnet-gahnite-pyrrhotite-chalcopyrite associated with quartz-bearing garnetite. Most of B Lode is on the westerly-dipping limb of an F_2 antiform and, in the hinge of the antiform, B Lode is a cataclastic high metal content ore with bleached clasts of angular wall rocks. The edge of B Lode is characterised by sheared retrogressed pelites partially replaced by cataclastic pyrrhotite-chalcopyrite. The up-dip extensions of A Lode have been intersected in diamond core drilling on CML7 and these comprise quartz-bearing garnetite with minor pyrrhotite, galena and gahnite and blue quartz-gahnite-garnet-pyrrhotite rocks. Garnet rocks equivalent to A Lode are replaced by blue quartz-gahnite rocks. The down dip extensions of A Lode occur within the Western Mineralisation as quartz-sphalerite-galena-hedenbergite-garnet ± rhodonite rocks. The Eastern Mineralisation comprises quartz-orange garnet-hedenbergite with associated cataclastic massive sulphide ore and quartz-galena ± chalcopyrite-sphalerite veins. The No 1 Lens has not been intersected on CML7 and stratigraphic equivalents of No 1 Lens are characterised by blue quartz-gahnite-garnet rocks.

On CML7 there has been extensive mining of No 2 Lens. Exposures in the Kintore and Block 14 Open Pits remain and drill intersections comprise galena-sphalerite-calcite-fluorite-fluorapatite±garnet. The stratigraphically highest sulphide rock, No 3 Lens, is exposed in Block 14 Open Pit and comprises a quartz-galena-sphalerite-rhodonite ± garnet rock. In Block 14 Open Pit, the Lead Lodes occur in a downward-facing F_1 limb that has been folded into a S-plunging F_2 antiform and N- and S-plunging F_3 antiforms. The Main Lode Shear is coplanar with $S_{2/3}$ and No 3 Lens on the eastern limb of the Broken Hill Antiform has been dragged up into the Main Lode Shear. Axial plane to $F_{2/3}$ are fans of droppers of cataclastic galena-rich ore derived from No 3 Lens. The F_2 and F_3 folds and the Main Lode Shear have been folded by D_4 to produce E- and W-plunging folds and a cataclastic mass of No 3 Lens has been injected along S_4 and transgresses the No 2 Lens in Block 14 Open Pit.

On CML7, stratigraphically above the sulphide rocks are psammite and psammopelitic metasediments, foliated garnet-plagioclase gneiss and a massive pelite horizon (Unit 4.8). It appears that Unit 4.8 is discontinuous; it has not been intersected by CBH in drilling on CML7 but appears in the drill core from CRA drilling in the 1980s. It is similar in appearance to Unit 4.6 although it contains less sillimanite and more K feldspar than Unit 4.6. Unit 4.8 comprises abundant crenulated biotite, disarticulated rotated almandine garnet porphyroblasts, crenulated sillimanite and K-feldspar and contains minor magnetite and laminated garnet-quartz ± magnetite horizons.

Drilling of the Western Mineralisation has shown that Unit 4.7 (including the sulphide rocks) has been transgressed by N- and NW-trending epidotised tholeiitic dolerite dykes. The dykes show marginal alteration to biotite schist and contain pelitic enclaves altered to biotite.

The Western Mineralisation

The Western Mineralisation has been correlated with A Lode (Haydon and McConachy, 1987), B Lode (Gentle, 1968) and A, B & C lodes (Leyh, 2000). Drilling by CBH suggests that whilst a stratigraphic relationship exists between the Western Mineralisation and the ore lenses associated with the main lode system, the Western Mineralisation is spatially, and probably, chemically separated from the Zinc and Lead Lodes of the main line of lode system. The system is terminated at depth by the Globe Vauxhall Shear Zone where it is repeated as the Centenary Mineralisation. The Centenary Mineralisation however, is located both within the Hores Gneiss (Unit 4.7) and the Freyers Metasediments (Unit 4.5).

Earliest drill records indicate that the Western Mineralisation was identified prior to World War I but, despite a number of drilling campaigns, the zinc-dominant Western Mineralisation was not economically attractive until recent times. Data from previous operators who have drilled and sampled the Western Mineralisation has enabled CBH to calculate a robust global resource of 10mt @ 4.9% Zn, 3.5% Pb and 43g/t Ag over a strike length of some 1.7km. The system remains open along strike and down dip for much of CML7. In particular the main target for extensions to the resource is the northern reverse plunge which mirrors the geometry of the main line of lode.

The dominant host mineral assemblage is blue quartz – gahnite with an increasing garnet content where sulphide content increases. Where the Western Mineralisation is characterised by garnet quartzite, sulphide content is commonly low and dominated by pyrrhotite. Pyrite content is very low with rare chalcopryite occurring as late stage fracture infill.

Mineralisation style is not dissimilar to that of the main line of lode, where sulphide mineralisation is controlled by stratigraphy with grade controlled by structure. Grade is enhanced at the intersections of fold hinges and associated with transgressive shear zones.

The depletion in chondrite-normalised REE in the Western Mineralisation compared to the main line of lode sulphide rocks suggests a more distal setting for sulphide formation. The system is relatively poor in iron and silver compared with the main line of lode. The lower silver content could reflect depletion during retrograde metamorphism or the general low lead tenor of the Western Mineralisation, the lower iron content more likely reflects the change in composition of an evolving ore fluid.

There is limited mapping of the ore system through four main development drives put in by Broken Hill South during the 1950s and 1960s. This mapping shows marked variability in the orientation of high grade zones, both along strike and between levels. This variable geometry is expected to reflect complex structures that will require close spaced drilling and underground mapping that can then be used to predict the location of similar structures and locate these high grade zones. Safe underground access is currently unavailable and CBH is planning an exploration decline to the existing main underground levels for further geological studies.

The Eastern Mineralisation

Minor historical drilling and limited surface mapping has indicated the presence of mineralisation and lode horizons east of the main lode. The paucity of data and exploration has resulted in difficulty in deriving a realistic geological model that can place this mineralisation into perspective.

More recent drilling by CBH and Normandy and subsequent geological interpretation indicates that mineralisation falls into three separate settings. These include distinct stratigraphic positions, an updip extension of the 3 Lens synform and shear structures associated with transposition of sulphides from the main orebody.

There is sufficient drilling to enable compilation of complete cross sections through the Broken Hill Group rocks on CML7 in few places and unequivocal correlation between the stratigraphic successions either side of the main lode shear remains elusive. Some of the major differences between these sequences that make correlation difficult are the presence of magnetic amphibolite, Potosi Gneiss and metasediments and the absence of the stratigraphic marker Unit 4.6 and its associated banded iron formation that is readily observable in drill core in the west of the lease area. This Eastern Mineralisation and associated package of magnetic rocks has been traced for the entire 3.8km strike extent of CML7 west of the Western Mineralisation.

The cultural aspects of Broken Hill mean that the geology of the Eastern Mineralisation will only be resolved through deep drilling programs as much of the geology has since been obscured by mining waste, dwellings, concrete and tar.

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The tectogenetic explanation of the uranium potential of the Paralana Mineral System in the Mt Painter Inlier, northwest margin of the Curnamona Craton, South Australia

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Introduction

The U-rich Paralana Mineral System (PMS) is located in the area historically known as Mt Gee or Mt Painter, which is covered by the exploration tenement EL 3258 held by Marathon Resources Ltd. The area appears in the SW part of northeasterly trending Mt Painter Inlier. It represents basement rocks of the NE margin of the Curnamona Craton.

The area has been intensively explored and an extensive geological and drilling database was produced by government and a number of exploration companies. Historical exploration work and interpretation provided a critical base for the understanding of geology and U mineralisation. However, the source and distribution of the mineralisation, geological factors and mechanisms for its development and, more importantly, the exploration and resource potential of the area have never been satisfactorily explained.

A method of tectogenetic analysis of the mineral system has been used in this study (Bogacz, 2001, 2002). Application of the tectogenetic analysis of the PMS was aimed at providing an understanding for, and explanation of:

- geological nature of the mineral system and its relationship to the host rock,
- criteria governing the distribution of mineralised zones,
- controls on uranium mineralisation and grade distribution,
- mineral composition and ore genesis of the mineral system,
- exploration and resource potential of the PMS, and
- regional exploration potential in the NW part of the Curnamona Craton.

Tectonic genesis and relating internal complexity implies structural controls on mineralisation with predominantly tectonic factors contributing to the formation of the PMS. The main stage(s) of mineralisation is associated with a specific extensional tectonic deformation event(s), which provided the required space for mineralisation placement. Uraninite (uranium oxide), and its modification pitchblende, is a dominant uranium carrying mineral (Kucha et al., 2006). In some areas, it is accompanied by coffinite (uranium silicate). Monazite appears to be U-free and uranium mineralisation belongs to a different stage, confirming that the PMS is predominantly epigenetic, hydrothermal of origin. Uranium carrying torbernite observed in the area is seen as resulting from later epigenetic processes.

Based on the results of tectogenetic analysis and associated investigations, tectogenetic criteria were developed and applied in Marathon's exploration strategy and resource assessment. These allowed a conceptual exploration and geometric model for the PMS to develop which, in particular, has led to re-identification and re-definition of the Mt Gee deposit. Based on these criteria, further strong potential at shallow levels and with depth of the PMS has been identified.

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Geology and mineralisation of the Cambrian to Devonian inliers in the Tibooburra area

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Introduction

Mapping of four 1:100 000 map sheets (Olive Downs, Tibooburra, Milparinka, Yantara) covering the Koonenberry Belt in northwest NSW was completed in late 2005. Detailed mapping of the Cambrian to Devonian basement inliers and onlapping Cretaceous Eromanga Basin sedimentary rocks was accompanied by reconnaissance-style mapping of the remainder. The four map sheets form part of the Koonenberry project, which includes a total of eleven 1:100 000 map sheets. The project integrates geological mapping with regolith mapping, SHRIMP geochronology, petrography, geochemistry, assaying of potentially mineralised samples, zircon provenance studies and palaeontology. Products to be released include a GIS data set, 1:100 000 scale geology and regolith maps, detailed 1:25 000 scale geology map sheets of the inliers, a 1:250 000 scale solid geology map and one volume of explanatory notes.

Regional Setting

Several inliers of Cambrian to Devonian age have been recognised in the Tibooburra and Milparinka districts. These include the Tibooburra, Warratta, Mt Poole, Mt Browne and Gorge inliers. The inliers occur within the Koonenberry Belt and have been formerly included in the Delamerian Orogen (Greenfield and Reid, 2006), Kanmantoo Fold Belt (Scheibner, 1972), the Thomson Fold Belt (Thalhammer et al., 1998) and the Lachlan Fold Belt (Scheibner and Basden, 1996). These inliers are exposed through Cretaceous sedimentary rocks of the Eromanga Basin, Tertiary sediments of the Eyre Formation and widespread silcretes and Quaternary fluvial and aeolian sediments.

The inliers comprise Middle to Late Cambrian, deep to possibly shallow water marine metasediments with local thin rhyolitic volcaniclastic units. Some inliers have been intruded by pre-D_1 mafic dykes and sills and by pre- to syn-D_1 Silurian felsic to intermediate sills and dykes. The Tibooburra Inlier has been intruded by at least three large earliest Devonian (410-412 Ma), syn- to post-D_1 granodioritic plutons (S. Shaw, in Cooper and Grindley, 1982). Major faults separate, and in places truncate, the inliers (Figure 1).

Structure

Two major deformational events have been recognised in this study. The first event, D_1, corresponds to the regional D_2 deformation and has produced concertina-styl folding accompanied by well developed slaty cleavage, steep reverse faulting and significant axial plane dislocation. Fold axes strike NNW and generally plunge shallowly to the south in the

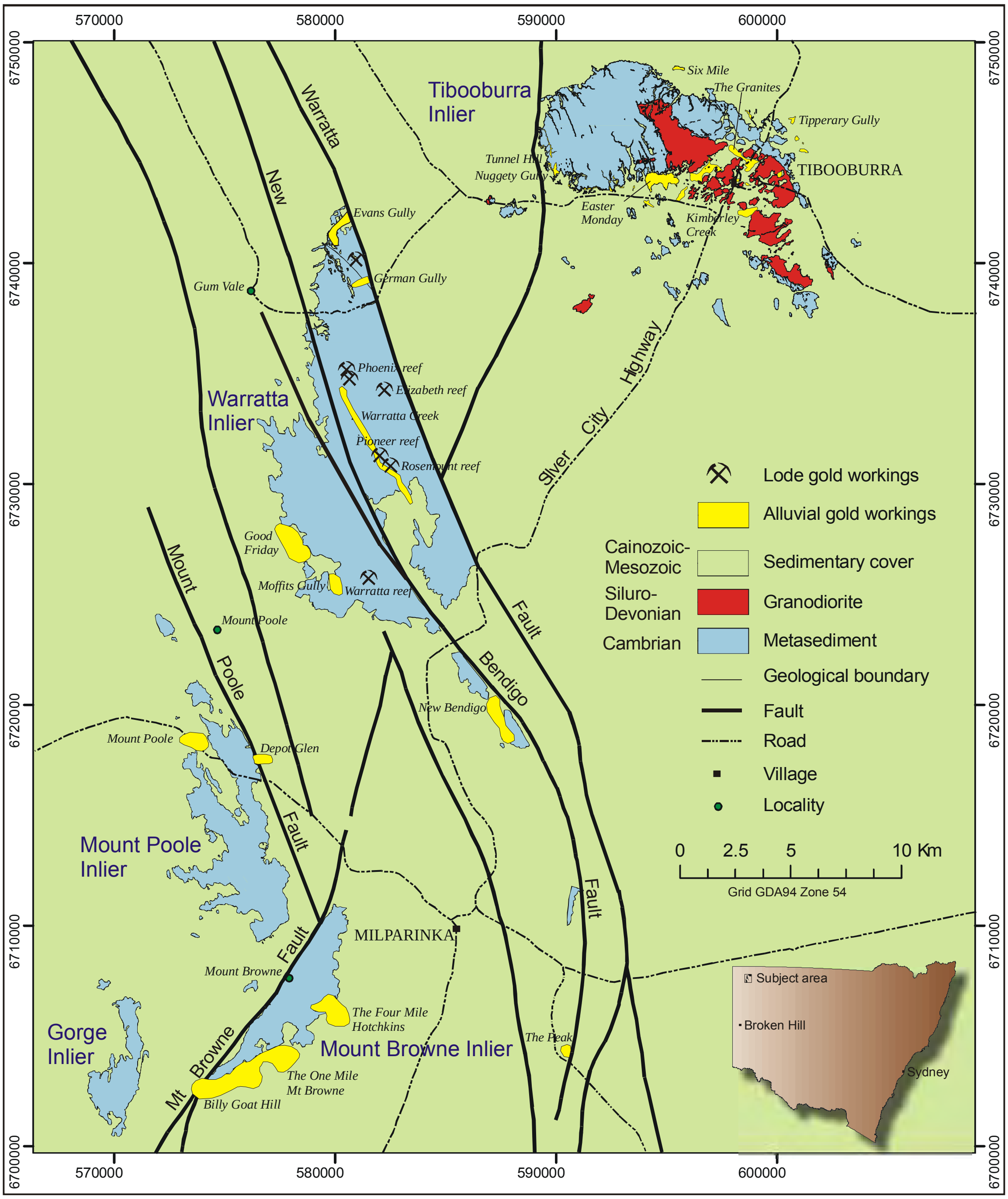

Figure 1. Location, general geology and mineral occurrences of the Tibooburra-Milparinka area.

Tibooburra Inlier, and generally to the north in the other inliers. Fold wavelengths are commonly 100-200m with some folds up to 2 km. Enveloping surfaces are flat with major fold amplitudes varying from about 80m in the Tibooburra Inlier, 500m in the Mt Poole Inlier and 2500m in the Warratta Inlier. Thalhammer (1992) estimated up to 40% crustal shortening during D_1 in the Mt Poole and Warratta inliers.

The second deformation event, D_2 (regionally D_3) produced NE striking kink banding and mesoscopic folds. Gentle refolding of F_1 and domains of chevron folding in the Warratta Inlier are recognised. Local deformation events D_1 and D_2 are referred to in this paper.

Tibooburra Inlier

Late Cambrian sediments of the Easter Monday beds comprise deep water marine turbidites of quartz-rich psammitic to pelitic composition with minor reworked rhyolitic volcaniclastics, rare diamictite rich in felsic volcanic clasts, and pre-D_1 mafic dykes and sills. A volcaniclastic unit in the western portion of the Tibooburra Inlier provided a depositional age of 496.2±2.6 Ma from a population of magmatic grains (Black, 2006). These were intruded by three earliest Devonian syn- to post-D_1 I-type granodiorite plutons (including the Tibooburra Granodiorite), a diorite body, and numerous dacitic quartz-feldspar porphyry, aplite and pegmatite dykes. The Easter Monday beds are regionally metamorphosed to low-mid greenschist facies, with thermal overprinting to pyroxene hornfels facies proximal to the plutons. Major faulting has removed most of the western extent of the thermal aureole.

Quartz veins are relatively minor within the Tibooburra inlier and comprise two apparent generations. The first generation is pre-D_1 and comprises blue quartz, that are narrow (less than 20cm wide) and discontinuous (less than 5m long). The second generation is syn- to post D_1 (parallel to cleavage and fractured by D_2) and comprises massive to fractured white quartz. The youngest quartz veins are up to 1m wide and persistent for up to 100m. None of the veins analysed were found to be anomalous in gold.

Siliceous and calcareous breccias up to 20cm wide are associated with D_2 kink bands. Breccias are commonly ferruginous with rarely preserved pyrite and no anomalous gold. “Gossanous” pods associated with metabasaltic intrusives in the central and western parts of the inlier contain anomalous arsenic and zinc, but no gold. Alteration zones are minor and relatively small, up to 4m wide, and comprise sericite-pyrite-carbonate and associated ferruginous, barren quartz veins.

Warratta Inlier

The Warratta Inlier comprises deep marine turbidites of the Jeffreys Flat beds. These sediments consist predominantly of pelites (slates) with minor lithic and feldspathic sandstones. Rare limestone lenses are probably allochthonous as associated chert pebbles are inconsistent with a formational derivation. A large diamictite lens comprises clasts of quartzite, felsic tuff, sandstone and leucogranite. A felsic tuff clast has been dated at 510.4±3.0 Ma (Black, 2006), suggesting a temporal association with felsic tuffs in the Ponto Group to the south. The Jeffreys Flat beds are intruded by post D_1 porphyritic monzodioritic to rhyolitic sills and dykes dated at 423-421 Ma (Black, 2006). Regional metamorphism attained lower greenschist facies conditions.

Quartz veins are abundant in the Warratta Inlier occurring as single veins or vein networks. The major vein networks are parallel to S_1.

Thalhammer (1992) identified three generations of quartz veining within the Warratta and Mt Poole inliers. These veins include:

1. Pre-D_1 narrow (mm thick), discontinous, recrystallised quartz only;
2. Syn-D_1 structurally controlled auriferous vein networks generally 5-10 m wide and 100-200m long. Individual veins are massive to laminated and generally less than 40cm wide and 1m long. The veins comprise subordinate albite, host rock, pyrite, white mica, carbonate, chlorite, arsenopyrite and gold. Thalhammer (1992) and Greenfield and Reid (2006) reported crack seal textures indicative of long lived vein development along active fluid pathways; and
3. Syn-post-D_2 crosscutting the entire folded and cleaved fabric, indicating origin during the final stage of deformation.

Two types of alteration zones accompany vein networks in the Warratta Inlier: narrow phengite-chlorite-pyrite-carbonate-haematite haloes less than 3m wide; and large, bleached carbonate-sericite alteration zones extending for kilometres along strike of major quartz vein networks. The largest bleached zone accompanies the Pioneer-Phoenix reef, striking for over 5km long and extending up to 300m wide. Thalhammer (1992) interpreted an age of 440 Ma for the formation of auriferous quartz veins based on K-Ar dating of white mica in hydrothermally altered slates.

Mt Poole Inlier

The Mt Poole Inlier comprises sediments of the Depot Glen beds dominated by psammites with subordinate pelitic phyllites and minor interbedded rhyolitic volcaniclastic rocks. A fine grained rhyolitic volcaniclastic has been dated by Black (2006) and provides an age of sedimentation of 504.5 ± 2.6 Ma. The sequence has been intruded by dolerite mafic to intermediate dykes and sills. These intrusives include pre-D_1 basaltic andesite and dolerite, and syn- to post-D_1 monzonite and monzodiorite. The Depot Glen beds have been regionally metamorphosed to mid-upper greenschist facies. Quartz vein morphology is similar to the Warratta Inlier, apart from shallow dipping veins that intrude monzonitic sills. However significant gold mineralisation is not apparent.

Mt Browne Inlier

The Depot Glen beds in the Mt Browne Inlier comprise similar facies to those in the Mt Poole Inlier, dominantly pelitic phyllites with subordinate coarse psammite, some of which are locally pyritic. Very minor reworked felsic tuff and rare interbedded metabasalt occur within the sequence. Rare mafic dykes intrude the sequence. The Depot Glen beds in the Mt Browne Inlier have been regionally metamorphosed to lower greenschist facies. Quartz veining is abundant with no associated gold mineralisation apparent.

Gorge Inlier

The Gorge inlier comprises interbedded pelitic phyllites with subordinate quartz-rich metasandstone and metawacke and large volumes of reworked felsic volcaniclastic rocks. The latter have been dated by Black (2006), providing a depositional age of 508.3±2.2 Ma. Mafic intrusives are rare. Sediments have been affected by regional metamorphism to lower greenschist facies conditions. Stubby Quartz veins are relatively common and associated with wide bleached zones of carbonate-sericite alteration. There has been no prospecting of basement rocks recorded in this inlier.

Primary Gold Mineralisation

The first discovery of gold in the district was reportedly made by a shepherd in 1867 at Evelyn Creek; however payable gold was first reported by the Wilcannia Mining Warden in 1880 at Depot Glen, near Mt Poole Station (Mine Inspectors, 1960). The extreme heat, lack of water and an opal boom at White Cliffs saw the demise of fulltime production by 1898 (Mine Inspectors, 1960).

The Jeffreys Flat beds of the Warratta and New Bendigo inliers are the only basement rocks to have produced primary gold. Total production from quartz reef mining since 1883 is 217.5 kg at an average grade of 20.5 g/tonne representing 10% of the total gold production from the Tibooburra-Milparinka district of approximately 1870 kg (Kenny, 1934; Barnes, 1974). During the 1880s more than 200 shafts and pits were sunk into large quartz vein networks in the Warratta Inlier. The Pioneer-Phoenix reef system is the largest and is in part associated with a broad alteration zone. This system is associated with a 15-20km long and 500-1000m wide magnetic low interpreted as a magnetite destruction zone. Alteration and presumably auriferous vein emplacement took place at 440 Ma (Thalhammer, 1992) probably in response to the onset of the Benambran Orogeny and preceding the emplacement of felsic dykes and sills within the inlier approximately 20 Ma later. The relatively simple vein chemistry and mineralogy and syn- to post-kinematic quartz vein-alteration development suggest an orogenic gold model for the mineralisation (e.g. Groves et al., 1998). The presence of bedding-cleavage concordant crack-seal veins, the vein mineralogy and carbonate-sericite alteration are typical of turbidite-hosted/slate belt gold deposits worldwide.

The Warratta gold deposits are similar to those in the Victorian goldfields (Greenfield and Reid, 2006). Deposits are similarly situated close to the eastern margin of the Gondwana margin, are of early Silurian age, possess similar Pb and S isotopic signatures and are developed in similar structural settings.

Secondary Gold Mineralisation

Alluvial gold has been found on the margins of all inliers. Almost all historical production was mined from alluvial gold in basal conglomerates of the Cretaceous Eromanga Basin and reworked Quaternary channel sediments. Gold production from the Tibooburra and Mt Browne inliers accounts for nearly 90% of total production from the Tibooburra-Milparinka district, including primary mineralisation.

Deposits hosted within gently dipping basal conglomerates of the Eromanga Basin include Tunnel Hill, Nuggetty Hill, Easter Monday diggings, Six Mile diggings, Kimberley Creek diggings, Gladstone Reef, Chilliville diggings, Two Mile diggings, Tipperary Gully, The Granites diggings and Saddlers Gully. Gold is found on all sides of the inlier (Figure 1) within rounded quartz pebble conglomerate at the base of the Cretaceous sequence. Mineralisation at the Granites diggings however, represents an area where the Cretaceous sediments have been eroded away, leaving gold-rich alluvium on top of the exposed Tibooburra Granodiorite. Gold is coarse and nuggetty and is prospected successfully with metal detectors. The source of gold remains enigmatic, particularly as primary mineralisation in the Tibooburra Inlier has not been identified. Many nuggets show significant rounding and flattening indicative of prolonged alluvial working and transportation. However, a significant number of nuggets retain partial crystal faces indicating close proximity to source. The closest known occurrence of primary gold, the Warratta Inlier, is disfavoured as a source for the alluvial gold due to the partial crystallinity of gold grains and the uniform distribution of gold around the Tibooburra Inlier.

Alluvial gold deposits associated with the Mt Browne Inlier represent a significant proportion of historic gold production in the Tibooburra-Milparinka district. Gold is similarly located in basal quartz pebble conglomerates of the Eromanga Basin where they onlap onto the eastern margin of the Mt Browne Inlier. Deposits include Billygoat Hill, The One Mile, Stringers Gully, The Four Mile and Hotchkins. Gold is found near surface as at Tibooburra and has been worked to a depth of 60m following the conglomerate down dip away from the inlier. Most extensive workings are shallow where conglomerate crops out near the boundary with the Depot Glen beds. Shafts were sunk at three localities with no successful discoveries, due to ground water inundation and the patchy, disseminated character of the gold within shallowly dipping sediments. Shallow alluvial leads of Cainozoic age were worked along the SE margin of the Mt Browne Inlier to an average depth of two metres.

Alluvial gold workings in and around the Warratta Inlier are of Cretaceous and Quaternary age. Alluvial deposits associated with the Eromanga Basin occur along the northern (Evans Gully) and eastern (German Gully) margins associated with quartz pebble-rich conglomerates. Quaternary aged deposits include the Good Friday diggings along the western margin of the inlier and sediments within the inlier along the Warratta Creek and in the New Bendigo area. Small alluvial gold fields have been worked on the eastern and western margins of the Mt Poole Inlier. In places, alluvial deposits are located less than 100m away from the hard rock source.

Prospectivity

The Warratta Inlier provides the most prospective location for a hard rock gold deposit of all the inliers in the Tibooburra-Milparinka district. Extensive alteration zones coupled with abundant auriferous veins provide excellent potential for an economic resource. Further structural analysis, geochemistry and reconnaissance drilling should provide further control on likely gold targets in an area where no bedrock drilling has been undertaken.

All inliers provide numerous targets for alluvial gold exploration. In particular, the Tibooburra and Mt Browne inliers have produced significant alluvial gold resources. Gold prospecting around these inliers continues to be a profitable venture with the continual discovery of gold nuggets at surface. Identification of palaeochannels from the inliers into cover sequences where historic gold production has been recorded provides excellent targets. These areas include the shallowly buried southern margin of the Tibooburra Inlier and the southeast margin of the Mt Browne Inlier. Similar targets around the Warratta and Mt Poole inliers are also highly prospective. Recent mapping has confirmed the shallow dip of cover sequences dipping away from the inlier along non-faulted contacts, therefore providing shallow areally extensive targets around most of the inliers.

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Lithostratigraphy-related mineralisation of the Olary and Mulyungarie domains

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Introduction

Much of the metallic mineralisation of the southern Curnamona Province, both syngenetic and epigenetic, shows a strong relationship to lithostratigraphy of the Willyama Supergroup. This is true of both the Olary and Mulyungarie Domains, as it is for the Broken Hill Domain (see Preiss, this volume for approximate domain boundaries).

A feature of major importance in the region is manifest by an intense region-wide magnetic gradient that is due to a change from a magnetite-bearing oxidised rock mass in the lower part of the succession to chemically reduced, less magnetic rock that overlies. While at regional scale the magnetic gradient appears to separate the lower from the upper Willyama Supergroup, in detail the boundary does not adhere to any particular stratigraphic position. As a generality it would appear that Cu-Au mineralisation dominates the oxidised part of the succession while zinc and lead mineralisation is preferentially developed in the upper part. The change from apparently oxidised to reduced rocks has been discussed in terms of a regional redox front (Leyh & Conor, 2000), the geophysical manifestation of which has allowed effective targeting during exploration.

Wiperaminga Subgroup

Lead-Zinc

No major Pb-Zn deposits are known in the lowest part of the Willyama Supergroup in the Olary and Mulyungarie Domains. However gahnite is recorded from two localities: the Tommie Wattie Formation near Tommie Wattie Bore (C.F.P. Clark, pers. comm. 2005), and the East Doughboy Mine (Zdziarsky, 1997) in the George Mine Formation. Although shallow shafts and pits were developed on copper mineralisation at the later locality, its geometry is very similar to that of the Broken Hill Pb-Zn-Ag deposit (result from a sample from the workings: 11.35% Cu, 0.62% Zn, 245 ppb Au). The mineralisation is associated with manganiferous quartz-garnet-magnetite chemical sediment bodies, which are within a 50 m thick psammopelite lens contained within a 330m thick succession of A-type Basso Suite felsic volcanics.

Copper-Gold

Although none are being mined at present, there are numerous Cu-Au prospects and occurrences. The majority of these are associated with magnetite-rich bodies (e.g Wilkins and Green and Gold Prospects), and magnetite-rich units associated with felsic volcanics of the Basso Suite (e.g. Walparuta Mine, shaft near Calico Bore on Bimbowrie Station).

The EXCO Resources NL White Dam Au (Cu) deposit (7.3 million tonnes @ 1.09g/t Au; i.e. 257,400 oz Au) is hosted by quartz-feldspar-biotite gneiss, with much of the mineralisation associated with leucosome lenses, a style similar to that at Wilkins Prospect. The inference is that Cu-Au was carried and deposited by metamorphic fluids, a general conclusion arrived at by Rutherford (in this volume).

Ethiudna Subgroup

Numerous small pits in the Ethiudna Subgroup demonstrate its significance as a Cu-Au source. Some deposits appear to have a lithological association, others a structural control.

Cathedral Rock Formation Copper-Gold ± Barite

The Cathedral Rock Formation is the basal unit of the Ethiudna Subgroup where it overlies the George Mine Formation. Locally it is present above the Tommie Wattie Formation but is not as thick. Locally there are ‘chemical’ units consisting of: quartz + magnetite, quartz-magnetite + barite, quartz + magnetite + barite + sulphide. The latter is best represented by the Mount Mulga Barite Mine where a 20 kg chip sample gave 1.53 g/t Au and 0.42% Cu. Similar lithologies are known from Meningie Well, Ameroo Hill and Walparuta Inlier areas.

Pits and shallow shafts of the Putts Mine on Bimbowrie Station are developed along a single quartzite unit at the base of the Ethiudna Subgroup.

Volcanic-associated Copper-Gold Mineralisation

The Basso Suite volcanics (i.e. Abminga Subsuite) are generally enriched in iron in the form of both magnetite and pyrite, and frequently have associated iron formation-like metasediments. Volcanic units in the Ethiudna Subgroup on both limbs of the regional-scale isoclinal syncline on Old Boolcoomata Station are significantly Cu-Au mineralised. Reports for the historic Woman-in-White Mine (Brown, 1908) indicate a grade approximating 15 g/t Au; a similar value was obtained from a pit in the same stratigraphic unit geology within the opposing eastern limb.

Fracture-controlled Copper-Gold Mineralisation of the Peryhumuck Formation

Fracture-controlled Cu-Au mineralisation in the vicinity of the historic Waukaloo Mines was in part responsible for the current phase of mineral exploration. The Waukaloo Cu-Au Prospect is focussed upon calc-albitite of the Peryhumuck Formation with mineralisation being concentrated in fractures and small breccia zones.

The Walparuta Mine on Weekeroo Station is developed in brecciated albitite with a biotite-magnetite-sulphide-barite matrix. The Mount Howden Copper Mine, in the eastern limb of the Mount Howden syncline, comprises a set of shallow excavations along a mineralised breccia zone that crosses obliquely from the Peryhumuck Formation and into the Bimba Formation.

Portia Formation, ?Cues Formation Equivalent

Lead-Zinc

The Pb-Zn component of the Mulyungarie Domain is likely to be syngenetic. Mineralisation in the Polygonum Prospect area is distributed over 800m of section, but mainly in two thick intervals. The lower unit, the ~250 m thick Portia Formation (sometimes included with the Bimba Formation) is characterised by calcareous lithologies, mainly metasiltstone but with some thin marble units. The dominant sulphide species are pyrite and pyrrhotite that commonly form fine laminae, but also locally massive sulphide bodies. Sphalerite is the main early economic sulphide, and is present along laminae or is disseminated. Dating of tuff units at the Portia Prosect (Teale 2000, Jagodzinski – this volume) indicates a 1705-1700 Ma age, which is possibly equivalent to the Cues Formation in the Broken Hill Domain.

Copper-Gold

Significant Cu-Au mineralisation is present in two stratigraphic situations. The lower is the magnetite-bearing succession forming the footwall to the Portia Formation (Leyh and Conor, 2000). Mineralisation is generally fracture, vein or breccia controlled.

The Portia Formation is the principal host to epigenetic vein, breccia and replacement Cu-Au mineralisation in the western part of the Mulyungarie Domain, and is being actively explored by Havilah Resources both regionally, and at the Portia group of prospects and Kalkaroo Prospect.

A 'likely' Au resource estimate for high grade gold at the North Portia Prospect at the base of the Tertiary is indicated in the 2005 Havilah Resources prospectus as ~60,000 oz in rock grading better than 4 g/t. However there is considerable difficulty at determining the size of the Au resource, and this Havilah Resources is addressing via different sampling techniques. A recent statement (ASX 09/08/2006) is as follows: "Preliminary estimates indicate that the potential volume of mineralized bedrock material at Portia is of the order of 8 million tonnes of as yet uncertain grade, lying immediately beneath the Base of Tertiary mineralisation".

Resource figures for Kalkaroo Prospect to 230 m depth is 70 Mt @ 0.47% Cu, 0.46 g/t Au and 124 ppm Mo. In addition a western fault controlled extension to Kalkaroo is being investigated; mineralisation is present as stratabound (the principal style at the main Kalkaroo deposit) and breccia-hosted.

Saltbush Group

Lead-zinc

The Saltbush Group of the Olary Domain (Conor – this volume) is the stratigraphic equivalent of the combined Broken Hill and Sundown Groups of the Broken Hill Domain. The Bimba Formation (Larry Macs Subgroup) is a unit of regional extent, even extending into the Broken Hill Domain (Ettlewood Calc-Silicate Member). In subcrop it is easily followed as a zone of gossan or gossanous rubble that marks underlying disseminated or massive pyrite-pyrrhotite bearing-units. The Bimba Formation is anomalous with respect of Pb-Zn-Ag-W-Co, mineralisation that is generally considered to be syngenetic. Local Cu-Au anomalism is possibly epigenetic. Although there are numerous small pits there are few larger workings of note, examples are Ethiudna, Bimba and the Mount Howden Cobalt mines.

The Raven Hill Subgroup is interpreted to be the stratigraphic equivalent of the Purnamoota Subgroup, which hosts the Broken Hill lodes, and thus has to be considered prospective for BHT-mineralisation. In the Olary Domain no Pb-Zn mineralisation has been reported from this unit although the rusty colouration of schists suggests the presence of oxidise sulphide, and a thin gossanous interval has been noted recently.

The interpreted equivalent of this unit in the Mulyungarie Domain is of great interest as it contains a great thickness of Zn (Pb) mineralisation. In the eastern part of the Mulyungarie Domain in the Polygonum area the upper psammopelitic Zn-Pb anomalous unit approximates 400m thickness. In the west the downward encroachment of the overlying Strathearn Group is responsible for variable thinning of this Broken Hill-equivalent unit.

Copper-gold

Malachite highlights copper mineralisation in or near a light-coloured feldspathic psammite in the otherwise dark-coloured Black Maria Formation (Raven Hill Subgroup). It is in this material that the inclined shafts of the Black Maria Mine (Bimbowrie Station) were sunk. Nearby is the Lady Louise Mine, also developed on malachite showings. Samples from both the Black Maria and Lady Louise mine dumps have shown anomalous U (70-105 ppm), sampling has not been extended to determine whether the host stratigraphic units are also U anomalous.

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Lithostratigraphy of the Olary and Mulyungarie domains – 2006

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Subdivision of the Curnamona Province

In order to assist discussion, the Palaeo-Mesoproterozoic Curnamona Province is subdivided into the following eight domains listed from south to north (see Preiss, this volume for more detail): Olary, Broken Hill, Redan, Mulyungarie, Mudguard, Eurudina, Quinyambie, and Moolawatana domains. The subject matter of this presentation relates to the first mentioned four, which together make up the southern Curnamona Province.

Lithostratigraphy of the Olary Domain

The lithostratigraphy of the Willyama Supergroup of the Olary Domain is now better understood due to recent geochronological investigations (Conor & Fanning, 2001; Page & Conor, in prep.; Jagodzinski, in prep.), and geological mapping stemming from the Broken Hill Exploration Initiative (BHEI). The development of the new scheme follows-on from important early work, such as Campana and King (1958), Talbot (1967), Forbes and Pitt (1980), the exceptional work of Esso Minerals and Carpentaria Exploration Company (referred to here as Cotton, 1980), Clarke et al. (1986), Laing (1996) and Conor (2000) in South Australia, and also the seminal work of the NSW Geological Survey (e.g. Stevens et al., 1983) in NSW.

The current version of the stratigraphic scheme for the Olary Domain is summarised in Table 1. In Figure 1 it is compared with the stratigraphy of the Broken Domain, with both schemes being broadly related to a time scale. The latter demonstrates the advance in understanding resulting from the BHEI geochronological program, especially with respect to the discontinuous nature of deposition in the Olary Domain and a more complete record in the Broken Hill Domain.

1998 saw the inception of the BHEI geochronological program, the principal aim of which was to locate chronostratigraphic ties between the Olary and Broken Hill Domain. This aim was realised with the recognition of the following two chronostratigraphic markers:

- ≤1693±3 Ma volcaniclastic Plumbago Formation above the Bimba in the Olary Domain, and a lithologically similar metasiltstone overlying (and perhaps interbedded with) the Ettlewood Calc-Silicate Member in the western Broken Hill Domain
- ≤1651±7 Ma tuffaceous part of the Mooleulooloo Formation (Olary Domain), the interpreted equivalent of the <1655±4 Ma Bijerkerno Metasediments (Broken Hill Domain). Dating of these formations also demonstrates a temporal similarity with the Mount Isa Group (Queensland).

Curnamona Group

Buckley (1993) recognised felsic volcanic units interbedded within metasediments of the Willyama Supergroup. The age of these was shown to approximate 1700 Ma, and their chemistry to be of A-type composition, a characteristic shared with certain bodies of granite gneiss (Ashley et al., 1996). Subsequent extensive geochronology has shown that the felsic volcanics (including volcaniclastics) range in age from 1719 to 1713 Ma (mainly 1718-1715 Ma) and the granite gneisses are somewhat younger at ~1711 Ma (Page and Conor, in prep.). These A-type igneous rocks are assigned to the Basso Suite, and it is this suite that characterises the Curnamona Group (Conor, 2000).

It is now known that the Curnamona Group has no outcropping representative in the Broken Hill Domain; even the oldest date obtained from the Redan Gneiss (1710±4 Ma) is younger than any volcanic unit detected in the Olary Domain, but is similar to the intrusive part of the Basso Suite, i.e. the ~1711 Ma Ameroo Subsuite. By contrast none of the Broken Hill stratigraphy from below the Ettlewood Calc-Silicate Member appears to be present in the Olary Domain – a ~20 million year gap. This interval is represented in the Mulyungarie Domain (see below).

The lower part of the Curnamona Group is called the Wiperaminga Subgroup and is essentially equivalent to the 'Quartzofeldspathic Suite' of Clarke et al. (1986). It is subdivided into three formations as shown in Figure 1 and Table 1.

The Ethiudna Subgroup comprises a highly varied set of metasediments that overlies the Wiperaminga Subgroup (Figure 1, Table 1). It is in general equivalent to the 'Calcsilicate Suite' of Clarke et al. (1986), and as indicated by Cook and Ashley (1992) parts of it at least (e.g. Peryhumuck Formation) are evaporitic. The basal part of the Ethiudna Subgroup appears to be different where it overlies different formations of the Wiperaminga Subgroup. Laing (1996) noted that the Ethiudna Subgroup (his Peryhumuck and Weekeroo Formations) overlie lithologically distinct units, i.e. the George Mine and Tommie Wattie Formations, and on the strength of this defined two subdomains, i.e. Bulloo and Outalpa Subdomains (Figure 2). Laing attributed this stratigraphic anomaly to juxtaposition of different facies across the sheared axial planes of nappe-scale folds proposed. An alternative interpretation, which is currently being investigated, is that that the quartzites of the Cathedral Rock Formation were deposited upon a surface eroded into the George Mine Formation at the flank of a syn-depositional half-graben; with the Tommie Wattie Formation, above which the Cathedral Rock Formation is absent or poorly developed, representing the rift fill.

Conor (2000), following the lead of earlier workers (e.g. Cotton, 1980), included the well-known Bimba Formation within the Ethiudna Subgroup. This however was at odds with interpretations of the stratigraphic position of the Ettlewood Calc-Silicate Member within the Broken Hill Group (Stevens et al., 1983). Subsequent dating of the Plumbago Formation (Page et al., 2005; Conor, 2004) and the Bimba Formation (Page & Conor, in prep.) has supported the Broken Hill interpretation, and thus has necessitated reorganisation of the Olary scheme. This scheme places the Bimba Formation as the basal unit of the Saltbush Group, the latter being elevated from subgroup status to be equivalent to the combined Broken Hill and Sundown Groups. The Saltbush Group is generally preserved only in early-formed tight synclinal cores.

The Bimba Formation is a marker unit in the Olary Domain, apparently extending into parts of the Broken Hill Domain as the Ettlewood Calc-Silicate Member near the base of the Broken Hill Group. Also it is possible that the Bimba Formation is in part equivalent to the lithologically similar 250m thick Portia Formation of the intervening Mulyungarie Domain (Zang and Conor in this volume). In outcrop the Bimba Formation forms a laterally continuous unit that is generally less than 50m thick, It is commonly psammitic, but characteristically also is carbonate-bearing. It is of economic importance because it is iron sulphide-rich and highly anomalous with respect to such elements as Pb, Zn, Ag, W and Co. The Bimba Formation is the lower unit of a thin, but regionally extensive, lithostratigraphic couplet named the Larry Macs Subgroup, which includes the overlying Plumbago Formation.

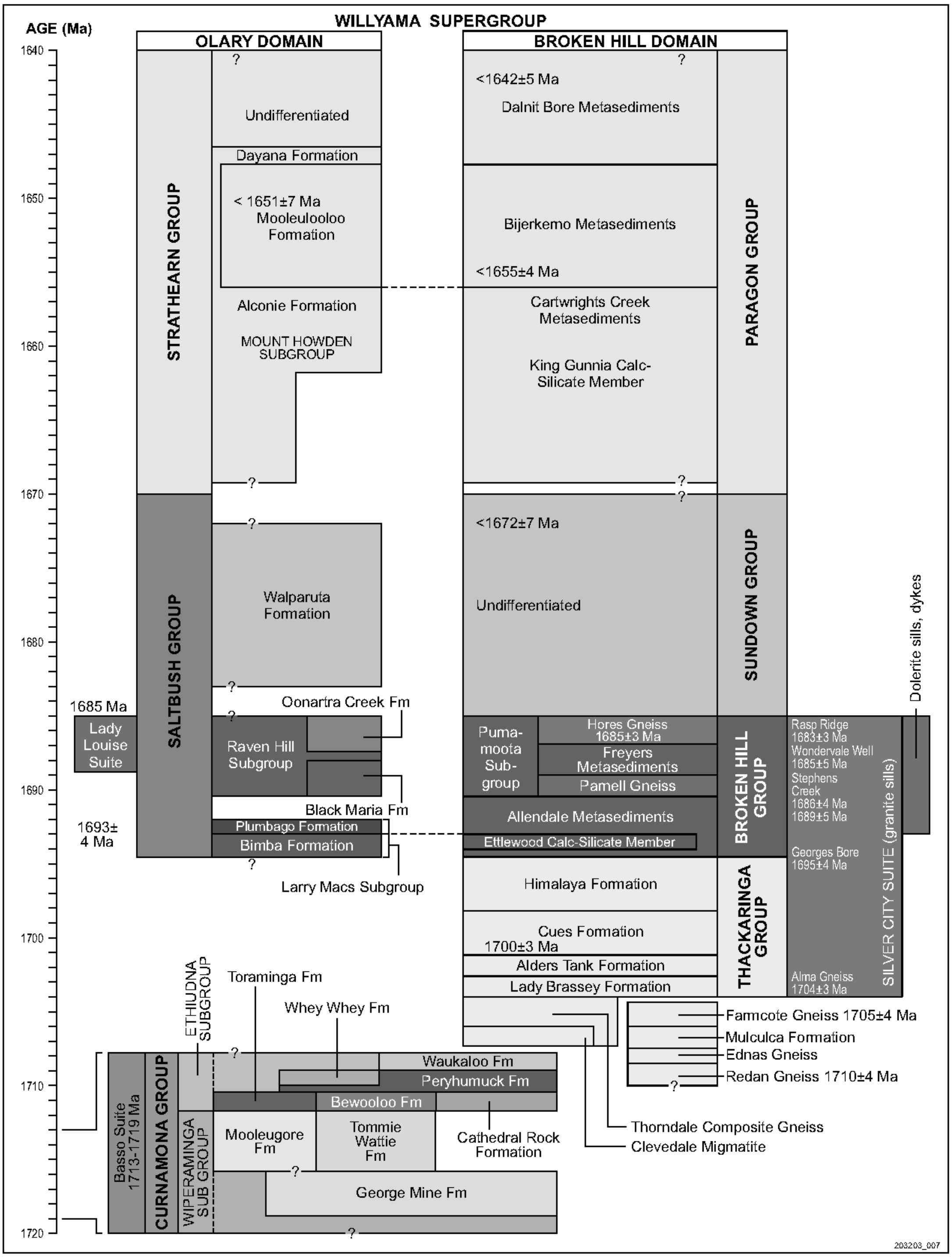

Figure 1. Lithostratigraphy of the Olary and Broken Hill Domain compared.

GROUP	SUBGROUP	FORMATION	AGE Ma	DESCRIPTION	EQUIVALENCE
STRATHEARN (largely undifferentiated)	Mt Howden	Dayana		Fine-grained sillimanite-andalusite-staurolite schist	Dalnit Bore Metasediments
		Mooleulooloo	<1655	Albitic psammite, locally tuffaceous	Bijerkerno Metasediments
		Alconie		Graphitic chiastolite pelite & metasiltstone	Cartwrights Creek Metasediments
SALTBUSH		Walparuta		Pelite & psammopelite with minor psammite layers	?Sundown Group
	Raven Hill	Oonartra Creek		Pelite & psammopelite with minor psammite layers & coticule lenses	?Purnamoota Subgroup
		Black Maria		Psammite, psammopelite & pelite, locally graphitic & locally with calcsilicate elipsoids	
	Larry Macs	Plumbago	~1693	Tuffaceous biotite psammite	Allendale Metasediments
		Bimba		Pyritic, marble, calcsilicate, micaceous psammite	Ettlewood Calc-Silicate Member
CURNAMONA	Ethiudna	Waukaloo		Fine grained psammitic schist	None
		Peryhumuck	~1715	Calc-albitite metasiltstone, locally pseudomorphs after carbonate and others.	None
		Toraminga	<1719	Psammitic schist with occasional albite granofels and calcsilicate. Mixed unit of Esso (1980)	
		Beewooloo		Psammitic schist with mafic lava, volcanic conglomerate, polymict conglomerate, quartz-grunerite-garnet 'exhalite'.	None
		Cathedral Rock	<1718	Quartzites, locally volcaniclastic	None
	Wiperaminga	Mooleugore		Psammitic schist with clean epidotic cross-bedded quartzite	Middle schist of Esso (1980)
		Tommie Wattie	~1718	Thick upward fining package from psammites, showing sedimentary structures, to andalusite pelite. Volcanic interbeds (Abminga Subsuite)	None
		George Mine	~1718	Pelite, psammopelite and psammite, but characterised by albite granofels. Contains numerous magnetite-rich units. Volcanic interbeds.	None

Table 1. Lithostratigraphic and lithological summary of the Olary Domain

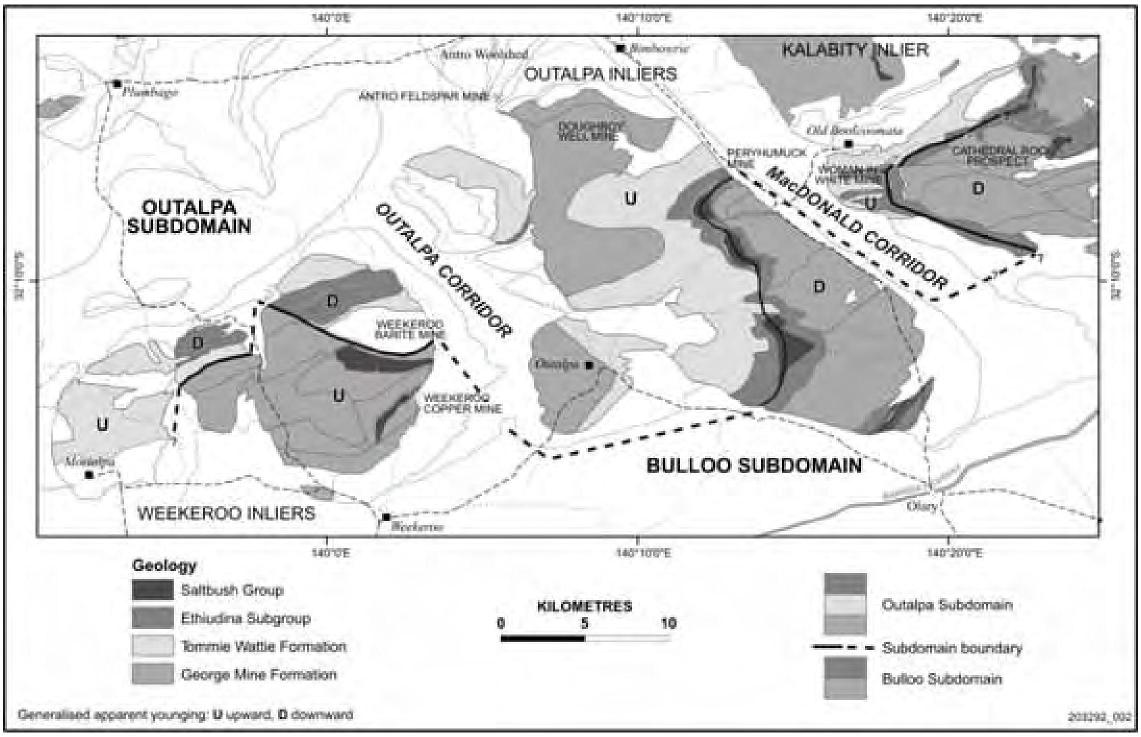

Figure 2. Summary geology of a portion of the Olary Domain (based upon Laing, 1996) showing the proposed Bulloo Subdomain (Ethiudna Subgroup overlying George Mine Formation) and Outalpa Subdomain (Ethiudna Subgroup overlying Tommie Wattie Formation).

In conjunction with the recognition of the thin volcaniclastic Plumbago Formation as a chronostratigraphic marker (Page et al., 2005), geological mapping indicated that in different places it was overlain by very different lithostratigraphic units, i.e. upper Allendale Metasediments in the Ettlewood area, lower part of the Saltbush Group in the Mount Mulga are, the upper part of the Saltbush Group at Weekeroo and Ameroo Hill, and Strathearn Group at Mount Howden and Alconie Hill. This stratigraphic morphology has been interpreted as sporadic onlap of sediments from the rift centre (Broken Hill Domain) onto the rift flank (Olary Domain) (Conor & Page, 2003). There is a complication in that, in spite of a specific search, the Plumbago Formation has not been detected in the intervening Mulyungarie Domain (see Jagodzinski et al., this volume).

It has come into general acceptance that the Broken Hill Group above the Bimba Formation is not present in the Olary Domain, but this is not true. There is a set of units in the Mulga Bore – Meningie Well area that are lithologically similar to parts of the Broken Hill Group (Laffan, 1994; Lottermoser & Ashley, 1996). These units, the Black Maria and Oonartra Creek formations make up the Raven Hill Subgroup, and like the Purnamoota Subgroup these units contain mafic sills, iron formation, Mn-rich garnet quartzite and locally numerous calcsilicate nodules.

Younger than the Saltbush Group, rocks of the Strathearn Group (redefined) are generally not seen in contact, largely because in the north, where outcrop becomes sparse (e.g. Mount Howden and Alconie Hill), pelites of the Strathearn Group rest directly upon the Plumbago Formation thus showing that the Saltbush Group to be missing. An exception is Wiperaminga Hill where a critical section displays Saltbush Group psammopelites being overlain by graphitic chiastolite-bearing pelites of the Strathearn Group.

The Strathearn Group (redefined to exclude the Saltbush Group) is the direct equivalent of the Paragon Group, and the Strathearn – Paragon Groups represent the only known through going lithostratigraphic unit of the Willyama Supergroup (although it is possible that the Curnamona

Group is, but is buried below the rocks of the Broken Hill Domain). The Strathearn Group includes rocks of the Mount Howden Subgroup (Table 1), and also a presumed considerable thickness of pelitic metasediment in the Mulyungarie Domain. The psammitic Mooleulooloo Formation (Bijerkerno Metasediments equivalent) is apparently extensive and, in returning ~1655 Ma U-Pb ages, provides a chronostratigraphic conjunction with the Mount Isa Group in Queensland (Page et al., 2005).

From isotopic evidence Barovich (2003) has suggested that a change in the source of sediment supply is registered within the Strathearn–Paragon Groups. She demonstrated that the lower part of the Willyama Supergroup is characterised by highly negative initial ε_{Nd} values (– 4.0 to – 6.8), and more recently has pointed out that the fluctuating change occurs within the Cartwrights Creek Metasediments (K. Barovich, pers comm. 2005). By contrast ε_{Nd} values of rock higher in the succession (i.e. upper Cartwrights Creek Metasediments upwards) are less negative, being more typical of average upper continental crust (– 0.2 to – 1.4). At Mount Howden it would appear that the lower part of the Alconie Formation (equivalent to the Cartwrights Creek Metasediments) is missing because it is both relatively thin and initial ε_{Nd} values are similar to those of the upper part of the Paragon Group in the Broken Hill Domain (K. Barovich, pers comm. 2005).

Lithostratigraphy of the Mulyungarie Domain

Apart from the granite at Mundearno Hill the only outcrop in the Mulyungarie Domain is that which forms the Mooleulooloo Hills, and so this unit is called the Mooleulooloo Formation. Elsewhere the Mooleulooloo Hills range is buried, but forms a continuous gravity anomaly that not only outlines the complex structure of the Mulyungarie Domain (Figure 3), but also indicates that the Strathearn Group is both laterally continuous and significantly thick.

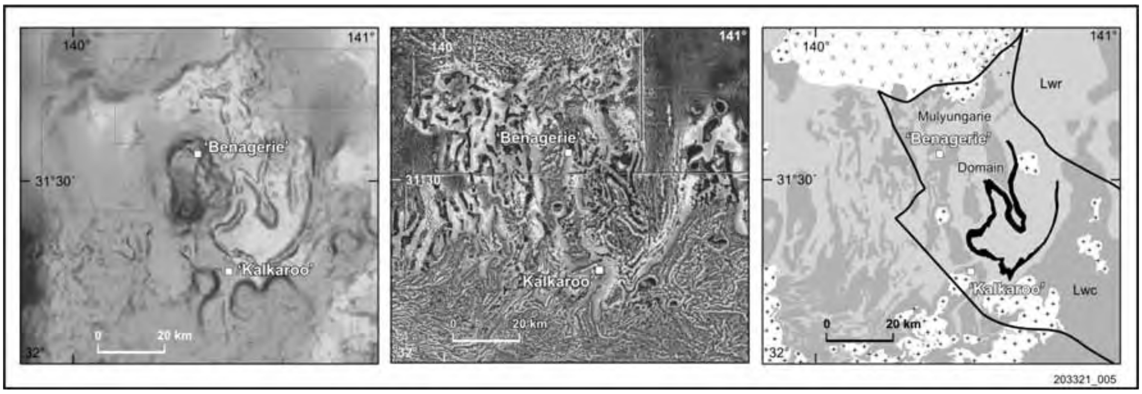

Figure 3. South Australian part of the Mulyungarie Domain. Gravity image, 1VD aeromagnetic image, and solid geology: Lwc = Curnamona Group, Lwt = Combined Portia Formation, Saltbush and Strathearn Groups, Black unit = Mooleulooloo Formation, + = Mesoproterozoic granite, V = volcanics of the Mudguard Domain.

The Mulyungarie Domain is important because it contains a laterally extensive mineralised sedimentary succession of great thickness. In the vicinity of the Polygonum Prospect in the east magnetite-bearing albitic metasiltstone, which is sporadically Cu-Au mineralised, forms the magnetic footwall to 800m of Pb-Zn anomalous sediment. An upper psammopelite dominated package, which includes a 90m thick amphibolite sill, is equated with the Broken Hill Group (W. Leyh, pers comm. 2004). Judging from the relative positions of the overlying Mooleulooloo Formation (regional gravity anomaly) and the magnetic footwall to the Portia Formation (regional aeromagnetic gradient feature), the thickness of the Broken Hill Group-like package is highly variable west of the Polygonum region, and in places might be absent.

At Polygonum a 100-150m thickness of underlying barren pelite and graphitic metasiltstone separates the Broken Hill Group-like rocks from a 250 m thick calcareous metasiltstone package, which is also Pb-Zn mineralised. This calcareous package is pyrite-pyrrhotite – rich, locally containing lenses of massive sulphide, and is equated with the mineralised succession at the Portia and Kalkaroo Prospects in the western part of the Mulyungarie Domain. Because of its pyritic and calcareous nature it is commonly assumed by explorers that this package is equivalent to the Bimba Formation. However such a correlation is uncertain, and hence this unit is given the separate name of Portia Formation.

Uncertainties stem from lack of geochronological control. The age of tuffs from the North Portia Prospect has been determined by U-Pb SHRIMP dating at 1702±6 Ma (C.M. Fanning, in Teale, 2000) and 1705±4 Ma (Jagodzinski, in prep.; and this volume), which is some 10 million years older than the Plumbago Formation that directly overlies the Bimba Formation and at least 10 million years younger than the Curnamona Group. Also no zircons of Plumbago Formation age (i.e. 1693±3 Ma) have as yet been detected in the black Plumbago Formation-like metasiltstone unit that overlies the Portia Formation at Polygonum Prospect.

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A magmatic–hydrothermal origin for the Broken Hill ore bodies?

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I focus on the concordant gabbroic (now amphibolite to granulite) sills in the Willyama Supergroup, demonstrating that compositional variations due to in-situ fractionation in the thicker sills (>~40m thick) provide reliable and unambiguous 'way-up' indicators in regions where the high-grade metamorphism has obliterated other useful markers. Along the Broken Hill line of lode are more Fe-rich than regional Willyama Supergroup mafic sills. I present a number of transects across outcropping sills both regionally, and along the line of lode and adjacent areas, demonstrating the utility of this approach.

Building on existing studies of the metabasic rocks in the Willyama Supergroup, I show that these are typical rift tholeiites, with a significant percentage of evolved ferrobasaltic compositions. The latter are ubiquitous along the line of lode, and I show that this Fe-enrichment, to striking levels as much as 21% Fe2O3 in some sill chilled margins, is not due to pervasive Fe-metasomatism as has been previously claimed. My study demonstrates that advanced crystal fractionation is responsible for the Fe-enrichment, and supported by other major and trace element data.

Why should the Fe-enriched magmas be dominant along the line of lode? I draw an analogy with gabbros drilled from the ultra-slow spreading centre at the SW Indian Ridge during ODP Site 735B. This 1500m-deep drill hole sampled oceanic lower crust produced adjacent to a major extensional shear zone, and was characterized by remarkable amounts of oxide-rich gabbros that crystallized from exceptionally Fe-rich magmas. Such magmas were generated by fault movement squeezing out residual intercumulus melt from underlying gabbros, and this very Fe-rich magma percolated up the fault, often crystallizing as foliated oxide gabbros.

Advanced fractionation of relatively dry tholeiitic magmas is well known to lead to strong enrichments in Pb and Zn, but Cu decreases during fractionation (e.g. of MORB suites) as Cu is partitioned into magmatic fluids throughout the fractionation episode. Thus strong crystal fractionation is a very effective way to separate Cu from Pb and Zn.

All S isotope data for Broken Hill Pb-Zn ores show typical magmatic values around 0. I propose that massive Pb, Zn and H_2O enrichment by synkinematic fractionation existed in oxide gabbros developed below the major extensional shear zone along which the line of lode now occurs. Exsolution of late magmatic fluid provided the hydrothermal fluids responsible for the Pb-Zn mineralisation, metals being leached from the Pb-Zn enriched magmatic rocks along the shearzone. Sulfur isotope values of major Broken Hill Pb-Zn ores cluster around 0, indicative of a magmatic source for the sulfur, and I believe also of the Pb and Zn. Ilmenites in oxide gabbros typically have 1-2% MnO, and their alteration by such hydrothermal fluids provided the abundant Mn and Fe that characterizes alteration assemblages in the felsic gneisses around the ore bodies.

This model, involving extensive fractionation of mafic magmas, demands a massive cumulate complement to the Fe-rich magmas that formed the sills in the line of lode region. I argue that the large Thorndale gravity high just southeast of the line of lode reflects this mass of gabbroic rocks, and that the combination of abnormally Fe-rich tholeiities and a significant adjacent gravity high may be useful exploration vectors for Broken Hill-type ore bodies.

Tectonic synthesis of the Curnamona Province, southern Australia, using a time-space framework

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Introduction

Geoscience Australia, through its Proterozoic Synthesis Project, is developing Time-Space-Event Plots to compare the depositional, metamorphic, magmatic, deformational and metallogenic history of Australian Proterozoic provinces. This information is being used to formulate an integrated geodynamic model of Proterozoic Australia and a greater understanding of the genesis and distribution of major mineral deposits formed during this Era. The information is being extracted from the published literature, GA databases such as OZCHRON and OZCHEM, and other sources and is being archived in the GA Provinces, and Events databases. We present here a summary of data from the Curnamona Province, discuss interpretations of the geodynamic setting, and implications for the genesis of known and probable mineral deposits in the region.

Basin fill

The Proterozoic Curnamona Province covers an area of approximately 80,000 km^2 extending across South Australia and New South Wales with exposure in the Olary and Broken Hill Domains in the south separated by the Mundi Mundi Fault, and in the Mt Painter and Mount Babbage inliers in the north. Much of the province, however, is obscured by younger sedimentary cover. Basin fill consists of Palaeoproterozoic Willyama Supergroup (~1720 to ~1640 Ma), metasedimentary, metavolcanic and meta-intrusive rocks, and is overlain by Mesoproterozoic volcanics, sedimentary rocks with granitoid intrusives. The presumed thickness of the Willyama Supergroup is ~7 km (Stevens et al. 1988). Building on earlier investigations, the stratigraphy in the Broken Hill Domain (BHD) was established by mapping in the 1970's and 1980's (e.g. Willis et al., 1983a; Stevens et al., 1983) and the correlative stratigraphy of the Olary Domain (OD) was compiled by Laing (1996). The lower Willyama Supergroup consists of an oxidised and albitised succession including granitic gneisses, amphibolite sills, and psammitic, pelitic, and calc-silicate rocks. The upper succession is dominated by metapelites with graphitic layers deposited in a reducing environment. Extensive zircon SHRIMP U-Pb dating (e.g. Page et al., 2000, Page et al., 2005a) has constrained the timing of Willyama Supergroup deposition. Reported dates include maximum depositional ages based on the youngest detrital zircons, minimum depositional ages established from ages of intrusives, and depositional ages determined from tuffaceous units.

Basement rocks to the Willyama Supergroup are not exposed, but inheritance indicates the presence of Archaean and older Palaeoproterozoic crystalline crust. The lower units of the Willyama Supergroup in the BHD are the basal Clevedale Migmatite, Thorndale Composite Gneiss and Redan Gneiss, dated at ~1710-1705 Ma (Page et al., 2005a), and consist of migmatitic metasedimentary rocks, metasedimentary composite gneiss, Na-plagioclase-quartz rocks and amphibolite to basic granulite. The basal Curnamona Group in OD has been correlated in part with these units, but also includes rocks as old as 1719 Ma (Conor, this volume, Page & Conor, in prep.).

Overlying the basal BHD units is the Thackaringa Group consisting of leucocratic quartzo-feldspathic gneiss, and magnetite rich quartz-feldspar rocks and amphibolite to basic granulite, representing felsic and basaltic volcanics and intrusives. The basal Lady Brassey Formation and overlying Cues Formation are age constrained by intrusion of the felsic Alma Gneiss and Farmcote Gneiss dated at ~1704 Ma (Page et al., 2005a). A correlative in the OD, the Basso Suite, intrudes the basal Curnamona Group and has the same age, within error. The uppermost unit of the Thackaringa Group, Himalaya Formation, is age constrained by the intruded Rasp Ridge Gneiss dated at 1683±3 Ma (Page et al., 2005a). Correlative intrusions in the OD are the Lady Louise Suite including the Woman-in-white Amphibolite of the same age, within error. The Thackaringa Group is overlain by the Broken Hill Group, consisting predominantly of quartz-rich psammitic and pelitic metasedimentary rocks. Basal units, the Allendale Metasediments and Ettlewood Calc-Silicate Member, have been dated at 1693±4 Ma (Page et al. 2005a) from a grey graphitic unit interpreted as tuffaceous. The overlying Parnell Formation includes metabasite, and garnetiferous quartzo-feldspathic gneiss, overlain by Freyers Metasediments consisting of pelitic and psammopelitic units. The uppermost Hores Gneiss consists of garnet-biotite–rich (Potosi-type) and felsic (quartzo-feldspathic) gneisses, intercalated with metasedimentary rocks and interpreted as mass-flow acid volcanics and psammopelites. These have been dated at 1685±3 (Page et al., 2005a) and are considered to be the volcaniclastic equivalent of the intrusive Rasp Ridge Gneiss. The Hores Gneiss contains the Broken Hill Line of Lode and also the redox boundary within the Willyama succession. In the OD, the Bimba and Plumbago Formations (Saltbush Subgroup, Strathearn Group) are correlated with the Ettlewood Calc-Silicate Member.

The Sundown Group of the Willyama Supergroup represents a major change in the BHD, with deposition of largely pelitic and psammitic units in a reducing environment. These are thin bedded, commonly graded and with intercalated calc-silicate nodules, interpreted as medial to distal turbidites with some contourite reworking. Maximum depositional ages of 1688±6 Ma were determined in the Euriowie Block and 1672±7 Ma in the Monuments area (Page et al., 2005a). These are overlain by pelite, psammite, calc-silicate rocks and graphitic schists of the Paragon Group. Basal units are Cartwrights Creek Metasediments, including King Gunnia Calc-Silicate Member, overlain by Bijerkerno Metasediments dated at 1655±4 Ma and 1657±4 Ma (maximum depositional ages, Page et al., 2005a), and Dalnit Bore Metasediments dated at 1642±5 Ma by Page et al. (2005a). In the OD, the upper Saltbush Subgroup, Walparuta Formation consists of similar pelitic and psammitic sedimentary rocks overlain by the Mt Howden Subgroup (upper Strathearn Group) consisting of Alconie Formation, Mooleulooloo Formation and the uppermost unit Dayana Formation. A tuffaceous bed from the Mooleulooloo Formation was dated at 1651±7 Ma by Page et al. (2005b), within error of the age of Bijerkerno Metasediments in the BHD with which the unit is correlated. The upper surface of the Willyama Supergroup in BHD and OD is erosional so the youngest beds and true thickness are unknown. In the Mount Painter and Mount Babbage inliers in the north of the Curnamona Province, exposed metasedimentary rocks had previously been correlated with the Willyama Supergroup in the BHD and OD by Teale and Flint (1993). Fanning et al. (2003) reported that the quartzites and metasedimentary rocks contained youngest detrital zircon peaks dated 1590-1580 Ma. These units are overlain by Mesoproterozoic metavolcanic, metasedimentary and felsic intrusive rocks.

Interpretations of sedimentary environments

The Willyama Supergroup is considered to be deposited in a deepening intracratonic rift basin (Willis et al., 1983a) or back arc basin (Giles et al., 2002, 2004) with the lower succession deposited in a fluvio-deltaic and lacustrine or coastal sabkha environment with associated mafic and felsic intrusions and volcanic rocks. Albite alteration of the lower succession is considered by Stevens et al. (1988) to be due to an alkaline sodic environment most commonly in sabkha and playa lake evaporitic settings. The upper Willyama succession was considered by Stevens et al. (1988) to represent a post-rift sag phase, during which thermal subsidence and deposition on a continental platform environment took place. Wright et al. (1987) considered the Sundown Group to be deep water sediments, but Stevens et al. (1988) suggested continued deposition of shelf muds and silts, occasional storm-surge turbidite sands, and thick, shallow marine sheet sands. The Ettlewood Calc-Silicate Member may represent intertidal dolomitic sediment with chert laminae or a shallow-marine deposit. The overlying Paragaon Group was interpreted by Willis et al. (1983b) as deep water, but Stevens et al. (1988) considered these also may be shallow water deposits with shelf muds, delta-front sands and silts and minor intercalated dolomitic marl, but in the upper unit (Dalnit Bore Metasediments) fine-grained silty and muddy turbidites indicate deeper water. Stevens et al. (1988) suggested the rift may have had similar morphology to the present day Salton Sea, with the possibility of one end open to the sea. Deposition of the Willyama Supergroup was followed by basin inversion, polydeformation and metamorphism, although the timing of these events is debated, as outlined below.

Magmatism

Three main phases of Palaeoproterozoic intrusive and extrusive magmatism are apparent in the Curnamona Province. In BHD, the earliest phase is represented by A-type granites dated at ~1705 Ma (Page et al., 2005a) including Alma Gneiss and Farmcote Gneiss. The equivalent in the OD is the felsic Basso Suite dated ~1715 - ~1710 Ma by Page et al. (2005b). The Montstephen Metabasalt has been considered likely to be part of the Basso Suite, so the youngest part of this event at least is bimodal (Conor et al., 2004). The second magmatic phase is definitively bimodal, dated at ~1685 Ma by Page et al. (2005a) and in the BHD the highly fractionated S-type Rasp Ridge Gneiss, considered to be derived from melting of Willyama sedimentary rocks (Conor et al. 2004; Greenfield, 2003) and Hores Gneiss, the volcaniclastic equivalent. In the OD the similarly dated correlative is the Lady Louise Suite which includes the Woman-in-White Amphibolite. The mafic component of this phase is high Fe-Ti. The third phase, dated 1590-1580 Ma (Page et al., 2000; Raetz et al., 2002) is the S-type Mundi-Mundi granite in the BHD and intrusive rocks in OD including the Bimbowrie Supersuite and granites at Triangle Hill and Crockers Well. These are of similar age to the voluminous Hiltaba Suite and Gawler Range Volcanics of the Gawler Craton. Detailed dating by Page et al. (2003) found no evidence of the I-type felsic magmatism reported to be 1640-1620 Ma by Fanning et al. (1998). At Mount Painter and Mount Babbage A-type Mesoproterozoic granites (1590 Ma and younger) intrude early Mesoproterozoic sediments (Teale and Flint, 1993). Geochemistry of the felsic igneous rocks provided no support for the presence of a magmatic arc at any stage of the development of the Curnamona Province.

Interpretations of magmatism

A-type granites are generally associated with elevated temperatures and high geothermal gradients and are often considered to be sourced from lower crustal melting (Wyborn et al., 1988). A-type magmatism is often associated with the onset of continental rifting (Ashley et al., 1995; Gibson and Czarnota, 2003), and hence supports the interpretation of an active rift basin for deposition of the Willyama succession. In the later phase of intrusion and volcanism, the felsic component is S-type and interpreted to be the product of melting of deeper Willyama sedimentary rocks supported by inherited Sm-Nd, and Hf. The final post-orogenic phase appears to be part of the voluminous widespread bimodal Hiltaba event in the adjacent Gawler craton covering some 25,000 km^2 (Wyborn, et al. 1988), which may represent renewed extension.

Rutherford et al. (2006) identified the first two magmatic phases described above (dated at ~1700 Ma and 1685 Ma) as intruded Mg-rich and Fe-rich metatholeiites that were considered to have been extracted from a depleted mantle in the BHD. In the OD these have been derived from a variably enriched, heterogeneous sub-continental lithospheric mantle. These metatholeiites were most likely to have been intruded in a back-arc basin or intracontinental setting, with the geochemically enriched mantle component derived from subduction related processes.

Deformation and metamorphism

The Willyama Supergroup has been complexly deformed and metamorphosed but there has been considerable debate about field observations of fold interference patterns, timing of deformation and metamorphism, which has repercussions for interpretation of the geodynamic environment and genesis of mineral deposits. Early structural models (e.g. Laing et al., 1978, Marjoribanks et al., 1980) proposed large nappes which overturned regional stratigraphy and were associated with amphibolite-granulite facies metamorphism. These nappes were refolded by two later events followed by the development of retrograde shear zones. Detailed mapping in 1970's and 1980's (e.g. Willis et al., 1983a) was interpreted to indicate that, in spite of this complex deformation, the stratigraphic succession was not greatly disrupted. White et al. (1995) proposed a different interpretation, attributing the outcrop pattern to a series of discrete thrust packages separated by high temperature thrust zones, which represented early thrust movement during high grade metamorphism, and they supported early suggestions that the tectonic transport direction was towards the southeast. The generally favoured model recognises three events F_1 to F_3 with associated foliations S_1 to S_3. The S_1 foliation was considered to be parallel to S_0 by Marjoribanks et al. (1980) and axial planar to F_1 nappes which overturned stratigraphy. Nevertheless few, if any, fold closures have been found and these are essentially inferred structures. The F_1 axial plane has been variously described as dipping to the east (Hobbs et al., 1984; Stevens et al., 1988) or to the west (Laing and Barnes, 1986). Marjoribanks et al. (1980) proposed a zone of upright F_1 folds in the Mount Darling Range area southeast of Broken Hill forming a 'root' zone between two areas of nappe-like F_1 folds. This involved diverging tectonic transport, with nappes travelling either to the northwest or southeast. Some authors (e.g. Marjoribanks et al., 1980; Hobbs et al., 1984; Haren et al., 1997), considered the F_1 axes had been rotated into parallelism with F_2 and hence were coaxial, but later workers suggested a high angle interference pattern and that they were not coaxial. S_2 foliations were similar in mineralogy to S_1 (e.g. fibrolite aggregates) but were oblique and overprinting S_1, and found only in F_2 hinge zones. F_2 folds have been described as tight to isoclinal in the north and open in the south, trending northeast, plunging moderately to the southwest, with axial planes dipping steeply to the northwest. S_3 foliations are subvertical and axial planar, formed by crenulation of earlier schistosities, associated with retrograde metamorphism. The strike of the S_3 foliation has been reported as north to northeast and the trend of F_3 varied accordingly. The high grade rocks of the Willyama Supergroup are also cut by retrograde schist zones trending northwest, northeast or east, and these have been considered to have developed in the early stages of D_3 rotation but in places have offset F_3 folds. Dated biotite from these shear zones showed Delamerian Orogeny ages of 520±20 Ma (Pidgeon, 1967; Harrison and McDougall, 1981) and 460 Ma (Etheridge and Cooper, 1981), demonstrating later reactivation.

Metamorphism in the Willyama Supergroup ranges from greenschist facies in the north to granulite facies in the south. This high-T, low-P metamorphism has been considered to be associated with D_1 and D_2 events and to have taken place during the ~1600 Ma Olary Orogeny with crustal thickening and folding which was initially recumbent.

A different tectonic model has been proposed by Gibson et al. (2004) and Gibson and Nutman (2004). They accepted S_1 as a layer parallel fabric, but that it developed independent of any folding event. They suggest it was associated with bimodal magmatism and high-grade metamorphism producing regionally widespread andalusite- and sillimanite-bearing mineral assemblages. Gibson and Nutman (2004) dated zircons from three amphibolites, sills and dykes in the Clevedale Migmatite and Thorndale Composite Gneiss, at 1674±8, 1686±13, and 1691±9 Ma. Hornblende inclusions in these zircons were compositionally similar to metamorphic amphibole identified in the matrix, so these ages were interpreted as metamorphic. The possibility that the hornblende inclusions represented replacement of magmatic pyroxene, implying a much younger metamorphic overprint, was rejected as this would have produced radial fractures due to a resulting volume increase, and such fractures were not observed. There is little other isotopic evidence, however, for this early peak metamorphism. Gibson et al. (2004) and Gibson and Nutman (2004) dated this early (M1) event ~1690–1640 Ma which was occurring at deeper crustal levels at the same time as deposition of the upper Willyama sediments. Gibson et al. (2004) observed mylonitic shear zones with the upper units of the Broken Hill Group in BHD and Bimba Formation in OD, near the stratigraphic level of the redox boundary, and suggested these represented a major detachment surface between the lower and upper Willyama succession. This detachment zone, a response to a D_1 extensional event, was considered to be responsible for the juxtaposition of higher grade, lower succession rocks, which show evidence of bimodal magmatism against upper succession rocks where bimodal magmatism is absent. They considered that a later D_2 event, which was accompanied by further high grade metamorphism, occurred at ~1600 Ma. This inverted the detachment zone, produced northeast verging nappe folds, and also inverted the original D_1 thermal structure, so that sillimanite-grade lower plate rocks now lie structurally above andalusite grade rocks of the upper plate. A younger event D_3 produced northwest verging folds and southeast dipping thrusts.

Two deep seismic lines across the Curnamona Province provide some detail of deeper structures within the Willyama Supergroup (Gibson et al., 1998; Goleby et al., 2006; Korsch et al., this volume). In the east, moderately southeast dipping shears extending into the lower crust are interpreted as thrusts. In the west, structures are shallower with similar southeast dips and sole onto a decollement at about 6-9 km depth. Associated northwest verging folds show typical fault propagation geometries. These observations are consistent with interpretations of D_3 forming northwest verging folding and southeast dipping thrust faults.

Deciphering PTt paths of the metamorphism in the Willyama Supergroup has proved difficult. Based on mineral equilibrium assemblages, it is difficult to distinguish between prograde and retrograde assemblages and define the metamorphic event to which they belong. Significant also is the stratigraphic level and hence the depth at which the measured event occurred. Stüwe and Ehlers (1997) suggested peak metamorphism of 4-5 kbar and 650° C which was associated with the ~1600 Ma shortening event and which they labelled M_2, and a younger, 4-5 kbar and 650° C, event (M_3) which they suggested could be Grenville (~1100 Ma) or Pan-African/Delamerian (550-500 Ma) in age. The latter was observed overprinting a foliation associated with upright folding. They acknowledged the possible presence of an earlier M_1 metamorphic event. Swapp and Frost (2003) suggested a clockwise PTt path for their M_1 metamorphism, with pressures as high as 9 kbar, assuming temperatures of 775° C, and a younger M_2 event with peak conditions of 6.5-5.5 kbar and 750°C. Forbes et al. (2005) studied an early high temperature shear zone in the southern Broken Hill Block and suggested the presence of two tectonothermal events. M_1, 2.8-4.2 kbar and 600°C involved heating to attain a raised geothermal gradient of ~ 41-61 °C/km. It was interpreted to be due to rifting at ~1.69–1.67 Ma or 1.64–1.61 Ga. A second event M_2, 5 kbar and 750°C, immediately followed and was considered responsible for a lithology-parallel and regionally pervasive S_2 fabric which was terminated by crustal shortening during the Olarian Orogeny. Frost et al. (2005) determined peak metamorphic conditions of 5-7 kbar with temperatures exceeding 850°C in pelitic and psammitic gneisses hosting the Broken Hill orebody and suggested that a polymetallic melt persisted at Broken Hill for up to twenty million years after peak metamorphism.

Interpretations of deformation and metamorphism

Observational data of the Willyama Supergroup supports the interpretation that it has been deposited in a rift environment (Willis et al., 1983a) with probable half graben morphology (Plimer, 1986), and a back-arc setting has been suggested (Giles and Nutman, 2003, Rutherford et al., 2006). Two main models have been suggested for the tectonic development during and following deposition. One widely held view is that the high-grade, high-T, low-P metamorphism resulted from crustal shortening and thickening, commencing with onset of the Olarian Orogeny at ~1600 Ma. Earlier magmatic intrusion at ~1700 Ma and ~1685 Ma is not considered to be linked to the observed metamorphic grades. An alternative view is that metamorphism took place much earlier ~1690-1640 Ma and was associated with crustal thinning. This model suggests intrusion of tholeiitic magma, partial melting and unroofing of the lower crust producing bimodal intrusion and volcanism, elevated temperatures with a high geothermal gradient, and an early high-grade metamorphism. This is consistent with observed early (~1700 Ma) higher temperature A-type magmatism of Alma Gneiss, Farmcote Gneiss and Basso Suite. But the model also requires bimodal magmatism. There is agreement that the later (1685 Ma) S-type Rasp Ridge Gneiss and Lady Louise Suite are bimodal, but the older event appears largely felsic. Recently however it has been suggested that Montstephen Metabasalt is likely to be part of the Basso Suite, so the youngest part of this event at least is bimodal (Conor, 2004).

Mineral deposits

The Broken Hill Line of Lode is located within the Hores Gneiss, dated at 1685±3 Ma, on the overturned limb of an interpreted early nappe fold. In addition, there are a number of BH-type deposits which are stratigraphically at the same level or below the Broken Hill ore body. Parr et al. (2004), using Pb isotopes, suggested that these ore systems developed in separate pulses over as much as 10 million years. Greenfield (2003) undertook a recent synthesis of ore deposit models for the Broken Hill deposit, noting the following models: ore fluids derived from the mantle (Plimer, 1985); ore fluids from highly fractionated crustal magmatic fluids (Parr and Plimer, 1993); leaching of metals from basin sediments by hydrothermal basin formation waters or circulating seawater (Lydon, 1983; Garven and Bull, 1999), or leaching of metals by hydrothermal metamorphic fluids (Fontaine-Geary et al., 1995).

Syn-metamorphic leaching of metals from feldspars in sediments had been considered inefficient because the most efficient stage of leaching of Pb, Zn, Na and so on, is during late diagenesis. But in the case of Broken Hill this assumes metamorphism with onset of the Olarian Orogeny. If metamorphism occurred earlier as suggested by Gibson et al. (2004), the proposed metamorphic leaching fluids would have closely followed diagenesis of the succession underlying the Hores Gneiss. A crustal magmatic metal source has been considered unlikely as Rasp Ridge Gneiss is an S-type granite and unlikely to yield sufficient base metal content during exsolution of the vapour phase (Wyborn et al., 1998). Metal leaching of the quartz-albite rocks of the lower succession has been calculated to require ~8000 km^3 of source rock (Huston et al., 1998). Stable isotopes D/H, O, C, B, S and Sr indicate a lack of seawater (Shaw, 1968; Cartwright, 1999). Uniform Pb isotope signature of the Broken Hill lode suggests a uniform source with a mantle component, compared to subsequent hydrothermal pulses that suggest a mixture, possibly leached, signature.

Greenfield (2003) concluded that the metals were most likely sourced from the mantle or lower crust, possibly with leached metals in the later stages of a hydrothermal system. A deep seated source requires a major discharge fault in the proximity of the ore deposit. Gibson and Nutman (2004) suggested that their proposed detachment surface could provide a pathway for metamorphic mineralising fluids.

Geodynamic models

A model of the geodynamic history of the region suggested by Betts and Giles (2006), was that the Curnamona Province was part of the North Australian Craton (NAC) until ~1470 Ma, and was rotated ~52° such that the western margin of the Curnamona originally faced south. Support for the connection is that the Willyama Supergroup is coeval in part with North Australian basins such as Mt Isa (Betts and Giles, 2006). Palaeomagnetic data by Wingate and Evans (2003) from the ~1600–1590 Ma Gawler Range Volcanics and McArthur Basin provide support for this model. North-dipping subduction was interpreted to be responsible for back arc development in the Curnamona Province as well as in the attached southern NAC. Subduction was proposed to have culminated by collision with the Gawler Craton as part of the Mawson Craton during the Kimban Orogeny at about 1710-1690 Ma. This model is speculative and conflicts with evidence of extension in the Curnamona Province at this time.

An alternative model suggests that a subduction zone existed to the present east of the Curnamona Province and that direct evidence, including the associated arc, has been removed by later rifting. This model proposes back arc development above a steeply dipping subduction margin. Slab rollback caused crustal extension and basin development in the overlying plate, with the Willyama Supergroup deposited in the extending basin. The subduction angle is interpreted to have then shallowed, possibly in response to subduction of more buoyant crust, followed by subduction hinge advance. The basin then passed into a contractional phase with initiation of folding and crustal thickening in the Olarian Orogeny at ~1600 Ma. Initiation of the Hiltaba magmatic event may signal a return to steep subduction, slab rollback and crustal thinning in a renewed extensional back arc basin.

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A comparison of geochemical exploration techniques at prospects in the Curnamona Province

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Introduction

Stratiform and stratabound Pb-Zn and Cu-Au mineralisation are commonly associated with a regional redox boundary within the Willyama Supergroup. This boundary can be identified regionally, from aeromagnetic data, although the rocks are mostly covered by 10-150m of transported regolith. Discovery of new mineral deposits in the area would be enhanced by an effective surface geochemical technique that allows detection of mineralisation through this thick cover. PIRSA as part of a CRC LEME project, are investigating techniques at the Kalkaroo (Cu-Au-Mo), Polygonum (multi-element) and Christmas Ball (Cu-Au) Prospects within the Curnamona Province.

A number of geochemical techniques were investigated including: partial leach soil geochemistry – aqua regia, Deep Leach 11, 20 and 26 (Amdel Ltd), MMI-M (WAMTECH) and electrogeochemistry – CHIM.

Samples were collected from 10-25cm and 60-300 cm (auger) below the surface. Deeper samples targeted the zone of maximum evaporation associated with the precipitation of calcium carbonate and sulphates (gypsum). All samples were sieved using an 80# screen and pH and conductivity measured.

CHIM (CHastichnoe Izvlechennye Metallov) is an electro-geochemical method for the measurement of ions. Appropriately prepared electrodes were placed in 20cm deep pits, nitric acid added and the pits filled in. A current was applied for 48 hours, after which time the electrodes were exhumed and the coatings carefully removed and analysed. Soil samples were taken from each set of electrode pits.

Geochemical Surveys

Kalkaroo Prospect

Samples at 20m spacing were collected along two survey lines of 500m. Mineralisation being targeted on each traverse was located approximately from 110m below the surface and beneath 50-60m of transported regolith.

Line A

Of the methods used, CHIM most accurately indicated the area overlying the highest grade mineralisation (elevated levels of Cu, Au and U). Soil samples produced quite different results to the CHIM. Deep Leach 26 analysis on soil samples collected by auger gave a one point Zn-Pb anomaly over the zone of mineralisation. A corresponding Zn anomaly was seen in surface soil results using Deep Leach 11 and 26. MMI-M in addition to elevated Zn values displayed a 'rabbit ear' anomaly in U.

Line B

A W-Au CHIM anomaly was found over inferred primary mineralisation but not over identified supergene mineralisation. Although some soil anomalies have been obtained using W, the mineralisation is not known to contain appreciable W (Law, 2002). Elevated Zn over the same zone was evident in many of the techniques trialled. Near-surface soil results gave an intense Mo-Au-Cu-U anomaly to the east of known mineralisation. The anomaly may result from drilling contamination, although, lies directly over the extension of mineralisation to the base of cover. This anomaly was not visible in the CHIM or deeper soil sample results. Interestingly, Ag in all soil samples, highlighted a change in the underlying rock unit with a general trend of elevated response over pelitic hanging wall rock units.

Polygonum Prospect

Success had been reported in previous geochemical surveys using carbonate zone samples at the Polygonum Prospect in spite of over 100m of transported cover (Hedger and Dugmore, 2001; Leyh and Corbett, 2001). To reproduce the anomalies and determine if surface soil sampling could be as effective a sampling strategy, a 3500m survey line (50m sample spacing) was laid out.

Mineralisation at the Polygonum Prospect occurs at a variety of stratigraphic levels and includes four styles of mineralisation. These are:

1. Stratiform to stratabound Cu-Au-Mo zone in albitic +/- magnetite metasediments,
2. Stratiform to stratabound Zn-Pb-Ag (Mn, W, Mo, As, Co, Cu) zone in interbedded calc-silicate and albite-altered metasediments,
3. Broken Hill-type (BHT) Pb-Zn-Ag in fine-grained, garnet-rich interbedded pelite and psammite,
4. Inferred McArthur River-Mt Isa-style Zn-Ag-Pb (Cu), stratigraphically above the other target zones in pelitic rock units.

Geochemical anomalies were obtained for 3 of the 4 styles of mineralisation, confirming the anomalous zones defined in previous surveys. Using Deep Leach 11 and samples from the top of the carbonate zone, a broad and locally intense Ag-Co-Zn (Cr, U) anomaly over the stratigraphic position prospective for McArthur River style mineralisation was evident (Figure 1; Leyh and Corbett, 2001). A lower magnitude Ag anomaly over the same zone was recorded using Deep Leach 11 on surface soil samples.

Broad, low-order, multi-element anomalies were obtained using surface soil samples and these outlined both BHT and stratiform to stratabound Zn-Pb-Ag mineralisation identified in drilling. Deep Leach 11 was moderately effective in highlighting the zone over BHT style mineralisation, as was Deep Leach 26 and MMI-M for the stratiform to stratabound Zn-Pb-Ag mineralisation (Figure 1). Results from soil samples from the top of the carbonate zone were only barely anomalous over the same intervals.

Christmas Ball Prospect

Unlike the other prospects, the Christmas Ball Prospect has limited transported cover (<2m) with weak mineralisation from 33m and highest grades from 100m below the surface (Law, 2002).

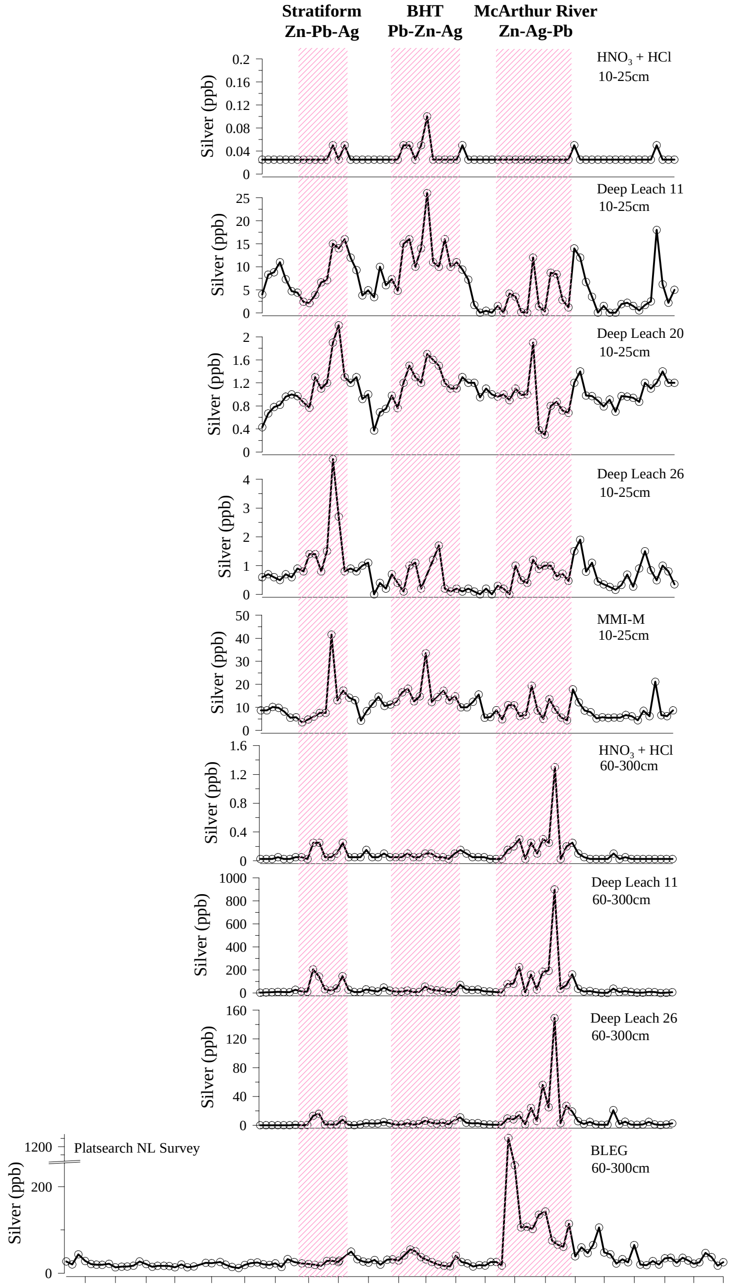

Figure 1. Comparison of geochemical techniques for the element silver, at the Polygonum Prospect, Curnamona Province.

Soil samples collected from both sampling intervals were moderately useful in detecting the underlying mineralisation. Deep Leach 11 was the preferred digest with elevated levels of Co-As-Ag in shallow samples and Pb-Bi-Mo (Co, Ag) from the deeper sample interval. Deep Leach 26 analysis of soils from both sample intervals was also able to highlight mineralisation with elevated levels of Ag. A broad zone of increased conductivity in soil samples outlined the area of mineralisation. Higher pH values were obtained from the fringes of the mineralisation. This may correspond to the 'rabbit ears' described by Govett et al. (1976), attributed to electrochemical dispersion of H^+ ions from an ore body.

Conclusion

Considering the difficult geochemical circumstances, no method was necessarily expected to produce a satisfactory result. It is therefore not surprising that many of the methods did not clearly reflect mineralisation. However, easily the most outstanding anomaly was that of the Ag at the Polygonum Prospect from the top of the carbonate zone which was many times background and similar to the previous survey of Platsearch NL (in joint venture with Inco Limited; Leyh and Corbett, 2001).

Elsewhere, less clear-cut anomalies were obtained which may be improved by the use of different soil size fractions or extractants. These include a CHIM W-Au anomaly obtained on 'Line B' of the Kalkaroo Prospect, Ag-Pb-Co (U) anomalies at Polygonum Prospect using Deep Leach 11 on surface soil samples and Cu anomalism at Kalkaroo Prospect 'Line A' using the CHIM.

Although not universally applicable, Deep Leach 11 clearly was the most effective digest, although MMI-M and Deep Leach 26 showed promise. Soil sampling gave quite different element patterns to the CHIM method reflecting the fundamental differences in the methods.

Near-surface sampling produced better results than samples collected using an auger at the Kalkaroo Prospect, although, survey lines did not extend far enough over background.

Soil samples from the near surface and 'top of carbonate zone' were both required to outline the broad spectrum of mineralisation identified at the Polygonum Prospect. Concerns as to the origin of these soil anomalies remain, due to the possibility of mineralised colluvium from the Barrier Ranges.

Soil surveys did not clearly show mineralisation at the Christmas Ball Prospect as hoped. Samples collected from the top of the carbonate zone most accurately indicated the known location of mineralisation. Conductivity and pH measurements outlined the zone of mineralisation and along with surface soil results, suggest additional mineralisation exists to the north.

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The Ninnerie Supersuite – Mesoproterozoic igneous rocks of the Curnamona Province

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Introduction and definition

The Curnamona Province is host to several Mesoproterozoic granite and volcanic suites, which are distributed extensively across the whole province. These suites range in age from ~1575 to ~1600 Ma, and represent several episodes of granite emplacement. The Ninnerie Supersuite is the proposed name to cover all early Mesoproterozoic granites and related rocks that were intruded or extruded syn-late to post Olarian Orogeny. Geochemical and compositional differences within the Ninnerie Supersuite encourage subdivision, in which at least six separate sets or suites are included. These include the 2-mica, regional granites of the Bimbowrie Suite, sodic to biotite only granites of the Crocker Well Suite, intermediate intrusives coeval with the Crocker Well Suite and locally other S-type granites, A-type felsic porphyritic volcanics of the Mudguard Domain, buried non-magnetic or reversely polarised granites of the Mulyungarie Domain and syn-Olarian Orogeny granites of the Broken Hill Domain.

Subdivisions

The Bimbowrie Suite is the most extensive granitoid suite in the Olary Domain, being present in all inliers (Ashely et al., 1994). The Bimbowrie Suite intruded between 1580 and 1600 Ma. Bimbowrie Suite granites are 2-mica granites with S1 affinities (Barovich & Foden, 200;, Stewart & Foden, 2003), although they contain accessory magnetite, hence are variably magnetic, and have average Na/K ratios of 0.85 (Conor, 2004). They are relatively leucocratic, pink to buff muscovite-biotite monzogranites and share many similar geochemical characteristics across the domain (Ashley et al., 1994).

The Crocker Well Suite includes biotite-bearing S2-type granites and sodic granites found only in the Crocker Well–Billeroo region (Ashley, 1984; Stewart & Foden, 2003). Crocker Well Suite granites are pink to buff, medium to coarse grained and biotite bearing. Reported ages for the Crocker Well Suite are 1579±2 Ma (Ludwig and Cooper, 1984) and ~1580 Ma (Ashley et al., 1994). The distinctive group of sodic granites associated with the Crocker Well Suite comprise leucocratic phlogopite trondhjemites (Ashley et al., 1997), granodiorite, adamellites and alaskites.

Intrusives of intermediate composition coeval with the Crocker Well Suite and locally other S-type granites are predominantly biotite and hornblende-bearing monzodiorite to biotite granites (Conor, 2004). They are generally visible as enclaves within S-type granites, but locally show magma mingled textures.

The A-type felsic porphyritic volcanics of the Mudguard Domain are homogeneous, medium to coarse grained volcanics with phenocrysts of embayed quartz, sericitised plagioclase and turbid corroded K-feldspar (Giles & Teale, 1979). Interpretation from geophysical imagery suggests they comprise a thick, flat-lying sheet which overlies Willyama Supergroup metasedimentary rocks.

Granites of the Mulyungarie Domain are known only via geophysical imagery. On magnetic imagery they are identified as discrete circular to lobate shapes, but are inferred to be plunging cylindrical or tabular bodies from gravity imagery and seismic data.

Origin

The intermediate intrusives and A-type volcanics of the Mudguard Domain show evidence of a mantle component. The majority of the Ninnerie Supersuite are of S-type composition and have been interpreted to have been sourced from anatexis of Willyama Supergroup metasedimentary rocks or from underlying crust of similar composition (Barovich & Foden, 2002). Melting of the metasediments may have been induced by an external heat source related to the emplacement of the intermediate granites in the Crocker Well region. The Crocker Well Suite and Bimbowrie Suite likely represent separate magmatic events or sources, illustrated through both spatial and temporal distribution, and geochemical and compositional differences.

Mineralisation

The Ninnerie Supersuite is of extreme importance in regards to mineralisation, especially where granites are directly related to uranium mineralisation in areas such as Crocker Well (Ashley, 1984) and Radium Hill. Uranium prospects include the Crocker Well Group of Prospects, Mindamereeka Prospect, Mount Victoria Prospect, Windamerta North and South Prospect, Spring Hill Prospect and the historic Radium Hill Prospect. Of equal importance is Cu-Au-Mo mineralisation in the Portia-Kalkaroo region, where there is a strong but indirect relationship of granites and mineralisation. Disseminated molybdenite has been reported from at least one granite body (Rock Wallaby granite of the Bimbowrie Suite).

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Geological implications of new exploration results from the Benagerie Ridge

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Introduction

Havilah Resources' PACE assisted exploration drilling of the Benagerie Ridge over the past two years has confirmed several important geological observations in this area of almost non-existent outcrop:

1. A remarkably consistent stratigraphy with several key marker units that can be recognized throughout the area.
2. Several major structural domes with thick sequences of pelites developed in the intervening basinal areas.
3. Ubiquitous generally near circular granite plutons, frequently lying in or near to the cores of the domes (eg Benagerie Dome and Mulyungarie Dome).
4. Four main types of mineralization comprising from lower to upper:
    - A. Largely stratabound Cu-Au-Mo, which appears to have replaced calc-pelite and evaporitic sediments in the transitional zone between footwall albitites and hangingwall pelites (eg Kalkaroo and North Portia). In detail the best mineralisation is typically found in cross-cutting veins and breccias.
    - B. Micro-fracture controlled Au, that has been extensively upgraded by deep weathering and supergene enrichment (eg Portia and Shylock)
    - C. Quartz breccia vein hosted Au, that has formed in major regional fault zones (eg West –Central Kalkaroo)
    - D. Stratabound Pb-Zn hosted by hangingwall pelites of Broken Hill age and isotopic signature (eg Hunters Dam-Mc Brides, Deep Well)

It is evident that the Benegerie Ridge is a lower metamorphic grade remnant of the Olary Domain that has escaped the intense deformation and extensive partial melting of similar age rocks elsewhere in the Curnamona Craton. The geological setting of reactive rock sequences draped over structural domes that are intruded by high level granites has been very conducive to the generation, migration and entrapment of hydrothermal fluids into the roof zones of the domes. Mineralization has deposited in open brittle fractures and chemically reactive units or a combination of both in the roofs and flanks of the domes. The metal association (Cu, Au, Mo, Bi) and up-sequence zonation (Cu-Mo-Au to Au-As to Pb-Zn) is typical of high temperature igneous metal mineralizing systems. The evidence for operation of large scale mineralizing systems underscores the high potential for world class mineral discoveries in this region.

Acknowledgements

Havilah Resources acknowledges the contribution of PIRSA whose PACE grants have assisted with much of the drilling, upon which the above observations are based. The interpretations presented here may not necessarily be shared by PIRSA geoscientists.

The Curnamona under cover

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The problem – most of it is buried!

Less than 25% of the Palaeo- and Mesoproterozoic rocks of the Curnamona province are exposed (and that using an exceptionally generous definition of 'exposed'). These rocks contain an impressive inventory of mineralisation, dominated by the Broken Hill Main Lode but including a number of smaller occurrences of Broken Hill-type Ag-Pb-Zn and structurally controlled Cu-Au deposits. Mineralisation occurs within a background of widespread and intense hydrothermal alteration spanning at least 100 million years, from the formation of the basin to the late stages of orogenesis – a setting of undoubted mineral potential. It is little surprise that the exposed rocks have been well-explored and are considered by many to be mature - to the point of old age. But what of the remaining three quarters of the province (totalling some 36,000 km^2) that does not stick out of the ground?

Even a relatively superficial analysis of the covered regions of the Curnamona reveals a number of important points; 1) both the basement and cover rocks are prospective, 2) the most prospective rocks for Cu-Au and SEDEX style systems occur under cover; 3) we have barely scratched the surface of the covered regions in terms of drilling depth or density. In this talk I will highlight some of the mineral potential of the covered regions of the Curnamona province and suggest some strategies that may build our confidence in exploring the basement rocks.

Prospectivity

Despite their demonstrable prospectivity the covered regions of the Curnamona province are immature in exploration terms. The majority of drilling in the covered regions of the Curnamona province does not penetrate more than 200m into the cover rocks and does not sample the Proterozoic basement (Fig. 1). What we know about the basement geology is rudimentary and relies on a few drill holes, extrapolation of the exposed geology and analysis of the geophysical data. Nevertheless, the little we do know should be cause for optimism amongst explorers, namely:

- The interface between the lower and upper Willyama Supergroup is a significant locus of hydrothermal alteration and is prospective for a number of styles of mineralisation (BHT, Cu-Au). This interface has a mappable expression in the magnetics and is thus a useful marker in constraining the structural geometry. Much can be learned from known occurrences (for example Kalkaroo, Portia and Thunderdome) that can be applied to the 1000s of line kilometres of this contorted and fault diced horizon.

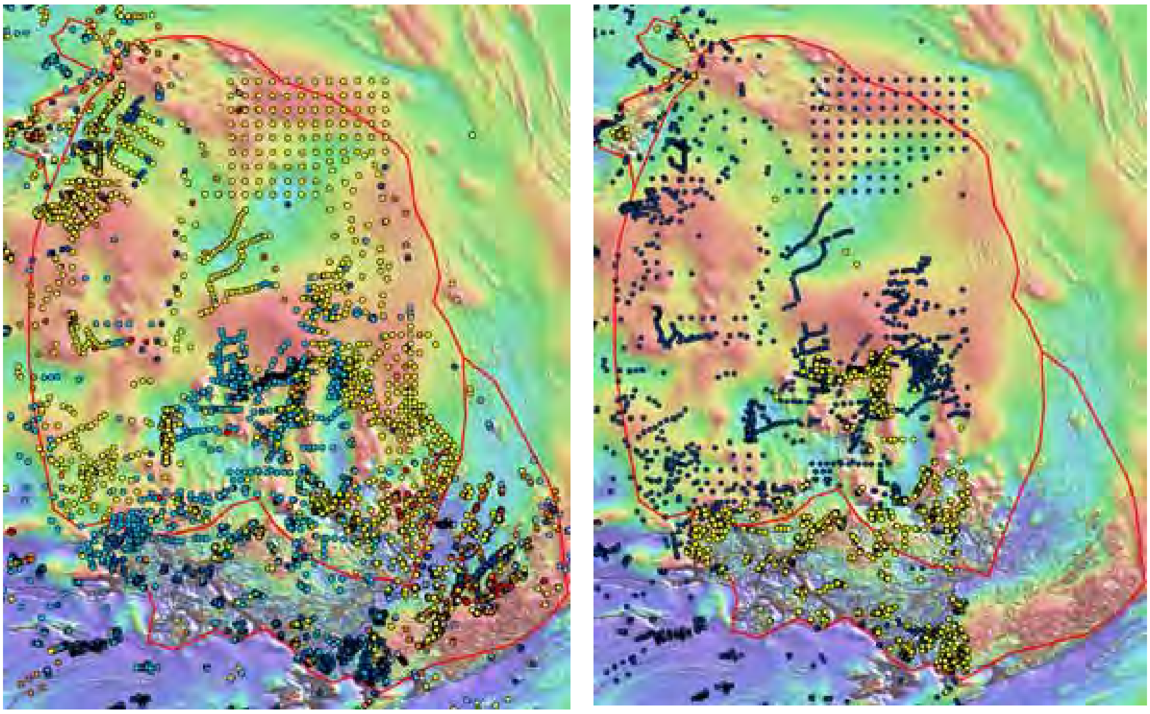

Figure 1. Total magnetic intensity images of the Curnamona province, overlain (on the left) by drill holes coloured by depth (dark blue < 20m, light blue 20-100m, yellow 100-200m, orange 200-500m, red >500m), from PIRSA and GSNSW databases and (on the right) by drill holes coloured by success (yellow) or failure (dark blue) to intercept the Proterozoic basement, from PIRSA database.

- The greater volume of metasedimentary rocks in the covered area belong to the upper Willyama Supergroup and are of equivalent age and depositional setting to the base-metal prospective rocks of the Isa Superbasin on the North Australian craton (Page et al., 2005). Using the Isa Superbasin as a template we can expect that the location of Pb-Zn mineralisation in the upper Willyama Supergroup will be broadly controlled by stratigraphic architecture and the basin-phase fault network (Betts et al., 2003).

- The central part of the province is dominated by volcanic and intrusive rocks of comparable age and chemistry to the Gawler Range volcanics and Hiltaba granites of the eastern Gawler Craton (Burtt et al., 2004). Moreover, there is a spatial relationship between this magmatism and magnetic alteration systems (Fig. 1) comparable to those associated with IOCG deposits in the eastern Gawler Craton. There is a now well-established (and successful!) template for IOCG exploration under cover on the Gawler Craton (crustal architecture, gravity, magnetics, IP) that can and should be applied to the Curnamona.

What can make a difference?

In each of these three examples mineral explorers have a well-established set of criteria for targeting and prioritising drill holes – given a minimum background knowledge of geologic fundamentals. The most important of these are; the distribution of rock types, the architecture of potential fluid plumbing systems, the depth and topography of the basement / cover interface, the chemistry of basement rocks (even if they are apparently unmineralised) and the chemistry of the basement / cover interface. So how do we increase our confidence in these fundamentals?

The distribution of rock types, depth to basement and fault architecture can be modelled to a first order using the existing potential field datasets (see for example the PIRSA 3D Curnamona model, available via the SARIG website) combined with extrapolation of exposed geology and the depth constraint provided by the recent Curnamona seismic line. There is more that can be done with these baseline data (see for example Williams and Betts, in press), however the next level of resolution in our geologic models will require more close spaced potential field measurements and an independent means of determining the basement topography (for example, shallow seismic).

With these datasets in hand, we can be more confident in siting drill holes and pushing them through to targets in the basement. Then, by dealing with these precious intercepts in a considered and consistent way we can rapidly build a picture of the extent and importance of mineral systems in the basement. There is a wealth of chemical, petrophysical and spectral data that can be extracted from ‘unsuccessful’ drill holes. These data can help us to understand potential field datasets, map alteration systems and plan future drilling thus maximising the value of drilling, both to the individual explorer and to the exploration community. In addition, the basement / cover interface represents an important but seldom analysed location of physical and chemical dispersion which effectively increases the target size and potentially provides a vector to mineralisation.

There is not much new in a strategy of detailed geophysics, deep drilling and maximising drilling value in areas of deep cover. There are, however, no shortcuts or cheap options on offer. Exploration in the covered regions of the Curnamona province requires a significant investment in time and resources - the long-term value of which can only be judged by each explorer. What we *can* offer is a commitment from government and academia to participate in and provide infrastructure for the type of research that will make a difference. Examples of this include, identifying cryptic alteration features in drill core (in part using the Hylogger technology), building a centralised petrophysical database with which to constrain geophysical modelling, mapping the basement / cover interface using shallow seismic methods, and continuously refining geological models as more detailed geophysics and basement intercepts become available.

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The Broken Hill Exploration Initiative – Twelve Years of Collaboration

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This is the seventh conference since the Broken Hill Exploration Initiative (BHEI) was established in May 2004. The BHEI is a collaborative venture between the NSW Department of Primary Industries, Primary Industry and Resources South Australia, and Geoscience Australia in support of increased mineral exploration in the Curnamona Province. The BHEI resulted from concern by governments that the both the Broken Hill and Port Pirie economies were at serious risk if new ore was not discovered and developed at Broken Hill or in the Curnamona region. Also associated with the BHEI are the Cooperative Research Centres for Landscape, Environment and Mineral Exploration and Predictive Mineral Discovery (CRCLEME and **pmd***CRC).

New South Wales has supported geoscience programs under the BHEI through its exploration initiatives Discovery 2000 and Exploration NSW. The more recent Exploration NSW initiative has been a seven year $30 million program to promote increased mineral and petroleum exploration investment in New South Wales. In the 2006-2007 New south Wales budget new initiative funding has been allocated for two years under the banner “New Frontiers”.

BHEI has proved to be an outstanding success, producing vast new datasets and knowledge, and generating industry enthusiasm for exploration in the Curnamona region. It has also proved to be a success story in science collaboration between the two states and the Commonwealth. A feature of this collaboration has been the BHEI conference. These conferences are key events for the release of new breakthroughs in mineral exploration-related research in the Broken Hill region and adjacent areas in South Australia.

When considering progress under the BHEI, it is worthwhile reflecting on the fact that 2006 was to be the year mining ceased on the Line of Lode. In the nineties, Pasminco was only extracting ore from the southern operations and was also the only producer on the Line of Lode. In recent years we have seen mining reinvigorated with Perilya producing from both ends of the field, and both Perilya and CBH Resources advancing on ambitious development plans on what remains the most fabulous ore deposit ever discovered. It is timely to remember that Broken Hill spawned the two behemoths of the global mining industry. Coupled with this Line of Lode success is a regional exploration effort that is, arguably, stronger and more diverse in 2006 than at any time in the past.

Clearly the international metal market has driven this major exploration revival. BHEI, however, has created a vast geoscience knowledge framework, which together with this increased exploration investment augurs well for increasing mining-generated prosperity in the Curnamona region.

A New South Wales perspective

Over the past twelve years in New South Wales, BHEI has provided us new high-resolution geophysical coverages, new hyperspectral mapping, airborne gravity gradiometry, regolith mapping and characterisation, research on structure and controls on mineralisation, geochronology and isotopic studies. All these studies have taken understanding of the Broken Hill mineral systems to a new level. The information coverages now available over the Broken Hill region have set a new global standard.

Broken Hill has been the tested for new exploration and mining technologies since its early days. NSW Government support for innovative BHEI programs has continued this. The application of BHP Billiton FALCON™ system is a case in point. The release of this Broken Hill data late in 2003 was the first public release of any FALCON™ survey data. This survey was conducted in collaboration with pmd*CRC and has contributed to a refinement of a three dimensional model of the Broken Hill Block as well as identifying arrange of major drill targets, for example Goldfinger.

BHEI geochronology studies have provided a major breakthrough in the understanding of the fourth dimension of Broken Hill geology. These studies have validated and calibrated the stratigraphic sequence developed by the Geological Survey of NSW in the 1970s and 1980s. Furthermore, we 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. Correlations between various levels of the Broken Hill and Olary stratigraphies are now firmly established, including that between the base metal and tungsten-bearing Bimba Formation of the Olary Block and the zinc-tungsten bearing Ettlewood Calc-Silicate Member some 500metres stratigraphically below the Broken Hill orebody.

Lead-isotope studies by ***pmd****CRC*-CSIRO and supported by BHEI have set 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 - McArthur River – Century group of world-class deposits.

Exploration NSW has also allowed us to dramatically improve geoscience and mineral exploration datasets over the Broken Hill region.

Global promotion of exploration investment in Australia is now an essential element of a national strategy under the “Team Australia” banner. The states join with the Commonwealth at national and international conferences and trade shows such as the Prospectors and Developers Association of Canada Conference in Toronto, Canada, to promote international investment in the Australian exploration scene. The Curnamona Province continues to feature prominently in these promotions as a collaborative promotion between NSW and South Australia.

NSW achievements since 2003

- Numerous papers and the results of studies have been published in the past three years. Major works on Curnamona geochronology have now been published in *Economic Geology*. A lead isotope study of mineralisation in the Broken Hill Block has been published in *Geology*. This proposes a combined inhalative-exhalative model for the Broken Hill type ore systems. Preliminary findings of a sedimentology study of the block are now available as a Geological Survey report. There also has been robust discussion of tectonic models published in the *Journal of the Geological Society of London* and *Tectonics.*

- A recurring issue at BHEI conferences has been the concern about reconciling the results of the deep seismic survey program conducted over the Broken Hill Block in 1997 with the geology as mapped at surface. In order to provide shallow seismic data to provide a continuum for interpretation from surface to the deep seismic data a trial high resolution seismic program was conducted in 2005. This was conducted immediately north of Broken Hill and along 16km of the old seismic line.

- A program of reviewing the world-class 1:25,000 scale geological coverage of the Broken Hill Block has commenced, with a Rockwell Sheet pilot project completed and drafted. This involves informing the Geological Survey 1970s and 1980s vintage mapping with the BHEI geophysical coverages. A new 1:100,000 scale interpretation map will also be produced and augmented by results of the high resolution seismic line and cross section studies through the Block.

- The way forward for the Broken Hill region is a vastly improved three dimensional understanding of the distribution of rock packages in this extremely complex setting. Preliminary attempts to create validated and detailed geological cross-sections have highlighted how little we know of that critical third dimension of Broken Hill geology. Efforts continue to construct three-dimensional models using potential field data informed by surface geology and the limited three-dimensional geological data.

- Since 2003 there has been an increased focus on enhancing geoscience understanding of the unexplored and underexplored rock packages lying outboard of the Broken Hill Block. This has been assisted by major Exploration NSW geophysical programs (airborne and seismic) in 2005 to image the major frontier terranes in the northwest and southwest of NSW. Geological and regolith mapping programs have extended 1:100,000 coverages north beyond the Koonenberry area into the Tibooburra region.

- The Loch Lilly-Kars Belt 1:250,000 interpretation map is now available.

An audit and gaps analysis of geoscience coverages in the Curnamona Province was conducted by pmd*CRC in 2003 at the behest of the BHEI partners. This study catalogued the richness and diversity of geoscience available over the Broken Hill Block. The study also identified opportunities for further work. Progress has been made on some of these and competing priorities have limited progress on others.

The need for a regional core storage facility at Broken Hill has long been seen by industry as an important contribution that the NSW Government could make to promoting exploration success in the region. A new facility has now been constructed. This will initially hold up to 80,000 metres of drill core and will include a core preparation room, core viewing facilities, and office facilities with fast internet connection to the Department's minerals databases. Mineral explorers will be able to view core stored in the facility "on-demand" as well as have on-site access to DPI's web-based database technologies.

Much has been achieved over the past twelve years and this has built on an outstanding geological mapping framework as well as generations of mine-scale and regional exploration. There also has been much done in the way of quality geoscience research at Broken Hill which has constrained the options in relation to the origin and evolution of the Broken Hill mineral system. The BHEI has proved to be a productive collaboration which will provide benefits long into the future and underpin exploration and discovery in this richly mineralized region.

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Geophysics at Broken Hill – what works and what doesn’t

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Regional Exploration Geophysics

Geophysics has the potential to play a vital role in the Broken Hill terrane in both discovery and resource definition. On the regional scale, Broken Hill type deposits such as Aggeneys-Gamsberg, Cannington, and even possibly Zinkgruvan are visible in the magnetic field, though the difficulty lies in distinguishing the mineralisation response from other magnetic units. The amphibolite grade metamorphism means that mineralisation will probably not be directly detectable, Broken Hill, Cannington and Zinkgruvan (Aggeneys-Gamsberg unknown) all lie on the flank of a large gravity high which may be significant. Around Broken Hill, the overburden is relatively thin, though usually conductive. Variations in thickness and/or conductivity and, possibly shear zones, may give spurious responses, but the highly resistive host rock means that even weakly mineralised horizons may be mapped with EM.

Prospect Geophysics

On the prospect scale, ground magnetics can detail magnetite rich lithologies/pyrrhotite rich lode and assist mapping. It is simple, easy, and cheap and should be applied even if just to help routine mapping. Gravity can be expected to react to dense lode, and new down-hole gravity probes hold promise for locating mineralisation not visible with DHEM. EM response depends on the lithology, but can penetrate to +200m for ground EM, 1000m for CSAMT, and ~100m off-hole for DHEM. All Broken Hill ore types should be polarisable, with the exception of pure sphalerite, and IP has improved significantly over the last five years with the development of 3D IP and better inversion giving depth penetration of at least 500m in Broken Hill type terrains.

Several less-used techniques can also play important roles. Broken Hill ore is commonly ribbon-like and electrically continuous over significant distances. Thus applied potential can indicate extensions to intersected mineralisation. Applied potential was very successful at locating the unexposed near-surface mineralisation which eventually developed into the Potosi Mine. It has also helped determine the extent of the mineralisation, or lack thereof, in some of the prospects near the Pinnacles. Down-hole magnetometric resistivity has also proved more useful than DHEM at defining the low-conductivity sphalerite mineralisation in the Potosi to Flying Doctor prospects.

Mine Geophysics

On the near mine scale, geophysics should also be regarded as one of the essential tools in the mine geologists’ tool box. Methods such as radar, radio imaging topography and EM can provide information to help drive design, and even highlight missed mineralisation.

Orogenic gold in the Tibooburra area north of Broken Hill – an extension of the Victorian goldfields?

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Summary

In the Tibooburra area, within the northeastern Koonenberry Belt, geological mapping has delineated a sequence of marine sediments, interbedded with distal airfall tuffs that have been dated at between 508-496 Ma. These rocks were strongly deformed at approximately 440-420 Ma, producing tight east verging folds and reverse faults, and a penetrative west-dipping cleavage. The sequence was intruded by post-kinematic monzodioritic sills and dykes (~423-416 Ma) and the geochemically-related I–type Tibooburra Granodiorite (412±10 Ma).

Gold mineralization in the Tibooburra goldfields is associated with syn-kinematic crack-seal quartz veins which were injected mainly parallel to cleavage and form long narrow stringer zones. Auriferous fluids were probably oxidized, low-sulphide, CO_2-bearing fluids produced during peak metamorphism. Two types of gold-associated alteration are present: narrow phengite–chlorite–pyrite–carbonate halos around quartz veins, and carbonate–sericite 'bleached' zones extending kilometres along strike.

The style and timing of gold mineralization and the structural history of the Tibooburra goldfields has strong similarities to the Victorian goldfields within the Western Lachlan Orogen and Delamerian Orogen of Victoria. However, there are significant differences in the interpreted tectonic setting between the two areas which have implications for the development of the Gondwana margin and mineral exploration.

Introduction

In 1995, the NSW Geological Survey began a mapping and research program in the Koonenberry Belt as part of the 'Exploration NSW' Initiative. The aims of the project included understanding the tectonic and metallogenic evolution of the belt, and using this knowledge to assist mineral exploration.

New information from geological mapping, whole rock geochemistry and zircon dating suggest that the northeastern Koonenberry Belt (Tibooburra goldfields, Figure 1) was primarily deformed during the Delamerian Orogeny (511-497 Ma; D1), but following erosion and deposition of a marine basin suffered a second deformation event associated with gold mineralization in the Late Ordovician to Early Silurian (D2). This orogenic event is contemporaneous with the Benambran Orogeny in the Lachlan Orogen, and may represent the collision of part of the Thomson Orogen with the east Gondwana margin.

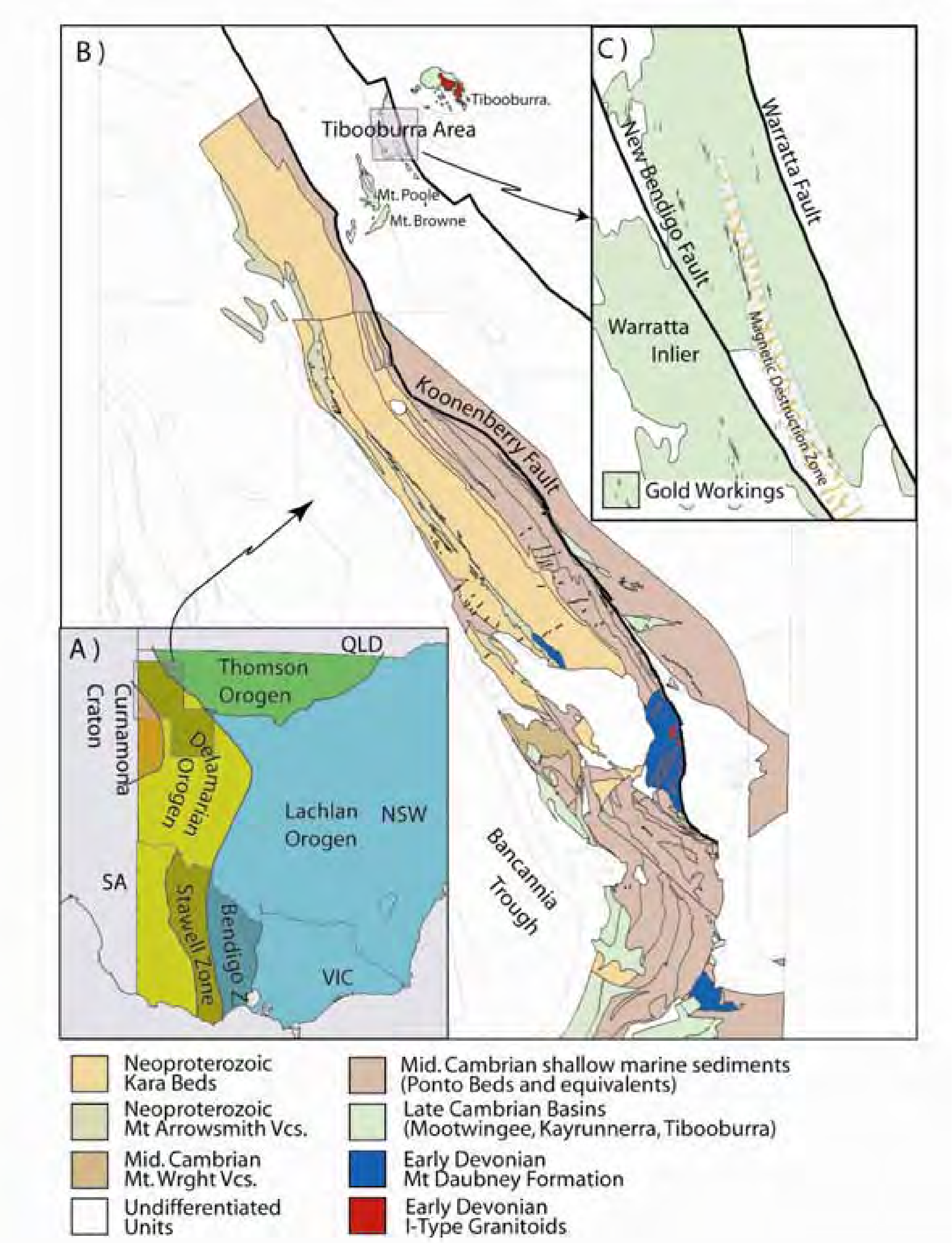

Figure 1. Locality diagram. a) Major geological elements of southeastern Australia. b) Pre-Middle Devonian simplified geology of the Koonenberry Belt. c) Outline of Warratta Inlier showing gold workings (pits and shafts) and magnetic low (approximately -40 nT anomaly) interpreted as a magnetite destruction zone.

Mapping and whole rock geochemistry have also helped to characterize orogenic gold mineralization in the Tibooburra area that formed late in the second deformation cycle (D2). The alteration style and structural controls on the mineralization are typical of turbidite hosted orogenic gold deposits (Bierlein et al. 1998) and bear particular similarity to the Bendigo Goldfield (e.g. Li et al., 1998).

Despite these similarities, there are important differences in the interpreted lithotectonic evolution of the early Palaeozoic Gondwana margin between the two areas. The inversion of a continental shallow marine basin in an intra-plate setting is inferred for the northeastern Koonenberry Belt during the Benambran Orogeny which differs from the subduction/accretionary prism model proposed for the same period in the Western Lachlan Orogen by Gray and Foster (2004) and Miller et al. (2005).

Regional geology

The Koonenberry Belt is located on the northeastern margin of the Curnamona Province (Figure 1). The western half of the belt, bounded by the Bancannia Trough and Koonenberry Fault, comprises a Neoproterozoic shallow marine sequence of sandstone and siltstone with minor interbedded quartzite and limestone (Kara beds). Within the Kara beds is a transitional alkaline mafic to ultramafic igneous suite, including sills and submarine to emergent lavas and volcaniclastics, dated at 586 ± 7 Ma (Mt Arrowsmith Volcanics; Crawford et al., 1997). This sequence is interpreted to be related to extension during the breakup of the Rodinia supercontinent (Crawford et al., 1997).

Early to Middle Cambrian calc-alkaline bimodal volcanic rocks of the Mt Wright Volcanics (Crawford et al., 1997) are fault bound against the Kara beds and interpreted to represent a continental margin volcanic arc (Mills, 1992). Middle Cambrian sedimentary rocks to the east consist of marine sandstone and siltstone with tholeiitic basalt extrusives and distal airfall felsic tuffs (Ponto Group and age equivalents). The felsic tuffs give a mean age of 511.1 ± 1.7 Ma (Black, 2006).

The eastern half of the Koonenberry Belt is bound by the Koonenberry Fault to the west and the Thomson Orogen to the east (Fig. 1). The sequence in the southeast consists dominantly of deep marine turbidites (Eastern Teltawongee beds). In the Tibooburra area, a correlated sequence also contains reworked felsic tuffs (Depot Glen beds) dated at 504.5 ± 2.6 Ma (Black, 2006).

Strong deformation across the whole belt occurred during the Delamerian Orogeny (D1). A felsic dyke that cuts the folded Ponto Group rocks has been dated at 497.5 ± 3.3 Ma (Black, 2006). These dates bracket the Delamerian Orogeny throughout the Koonenberry Belt to approximately 511-497 Ma. Denudation of the resultant highlands was probably quite rapid, with the development of molasse fluvial to shallow marine sedimentary basins, calc-alkaline bimodal volcanics and related intrusives by the Late Cambrian (Kayrunnera Group, Mutawintji Group and rocks of the Warratta and Tibooburra inliers).

A structurally-controlled Late Silurian to Early Devonian intermontane basin (Mt Daubeny Formation) developed in the southern Koonenberry Belt was intruded by I–type granites and related intrusives, dated by SHRIMP U–Pb at 413.8 ± 2.7 Ma (Black, 2006). Similar age monzodioritic sills and dykes intruded most inliers across the Tibooburra area, and have been dated by SHRIMP U–Pb to between ~423-421 Ma (Black, 2006). The I–type Tibooburra Granodiorite (Figure 1) was dated by Rb–Sr at 412±10 Ma (Shaw, in Cooper and Grindley, 1982).

Geology of the Tibooburra Goldfields

The Tibooburra goldfields (Figure 1) are contained within a series of early Palaeozoic inliers comprising the Depot Glen beds (Mt Poole and Mt Browne inliers), and the Jeffreys Flat and Easter Monday beds (Warratta and Tibooburra inliers respectively; Figure 1). They consist mostly of strongly cleaved, greenschist facies phyllites intruded by granodioritic to monzodioritic dykes, sills and stocks. Provenance appears broadly similar among the inliers, with sub-arkosic to lithic compositions and detritus suggesting mixed continental sources including acid volcanics and sandy immature sediments, in addition to a more distal plutonic/metamorphic terrain (Stevens and Etheridge, 1989).

Despite these broad similarities the Jeffreys Flat and Easter Monday beds are interpreted to have been deposited after the Depot Glen beds and following the Delamerian Orogeny. This is based on the Middle Cambrian age of tuffs in the Depot Glen Beds (504.5 ± 2.6 Ma), the late Cambrian age of tuffs in the Easter Monday beds (tuffaceous mudstone dated at 497.2 ± 2.6 Ma; Black, 2006) as well as the appearance of rounded boulders of folded felsic tuff in the Jeffreys Flat beds (dated at 510.4 ± 3.0 Ma; Black, 2006).

Approximately 1870 kg of gold was won from the Tibooburra goldfields from 1881 to 1901; however 85% of this was derived from nuggetty gold in the quartz-rich basal lag of a Cretaceous cover sequence (Kenny, 1934). Inspection of gold nuggets recovered from the basal lag suggests they are locally derived, probably from the adjacent inliers (Gibbons, 2005). Auriferous quartz vein networks were mined via shafts (down to 67 metres), pits and adits by early prospectors. Despite rich rock-chip gold values and an overall mined grade of 23.5 g/tonne, the primary ore system has never been tested below the water table (approximately 50-70 m depth) in over 100 years of sporadic exploration.

The majority of primary gold production was from the Warratta Inlier (Figure 1), and the following section focuses on the geology and mineralization style found in this inlier.

Geology of the Warratta Inlier

The Warratta Inlier generally contains finer-grained and less quartz-rich metasedimentary rocks than the adjacent inliers, in an exposed 2 km thick sequence informally called the (Figure 2).

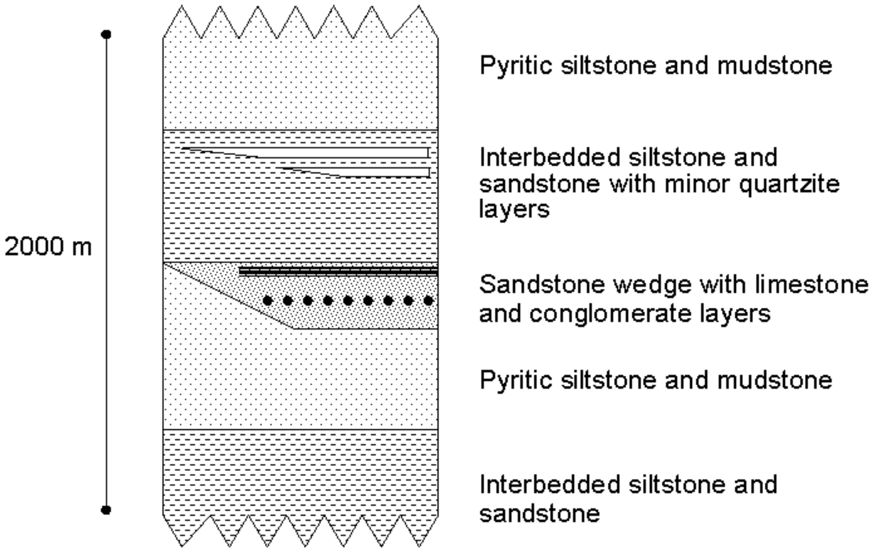

Figure 2. Simplified stratigraphic column for the Jeffreys Flat beds in the Warratta Inlier.

The pyritic siltstone units have small pyrite cubes (mostly weathered to limonite) located along bedding planes and are assumed to be diagenetic. A 1–2m thick impure limestone unit contains

<25% quartz (–feldspar) sand and angular pebbles of chert. The ~25 m thick conglomerate unit is sandy- and rarely muddy-matrix supported with well-rounded cobbles and pebbles of quartzite, felsic tuff, sandstone and leucogranite. Interbedded siltstone–sandstone units are consistent in composition, defined as litharenites or arkosic sandstones, with quartz (<70%), feldspar and plagioclase (<20–25%), and minor lithic clasts.

The sequence has been intruded by porphyritic monzodioritic to rhyolitic sills and dykes. They clearly postdate cleavage development, but have been themselves folded by D2.

Quartz vein networks are abundant in the inlier, with 761 distinct bedding–cleavage parallel veins or vein network mapped in 70 km2 of outcrop. The vein networks are persistent up to several kilometres, but generally traceable over 100–200 m. The vein networks consist of 5–10 m wide zones altered country rock and massive to laminated quartz veins (<40 cm wide, <1 m long). Veins are generally parallel to S1, although locally cutting across it. Cleavage intensity increases towards the vein margins. Most veins have narrow, fine-grained columnar quartz margins with grainsize increasing towards massive cores. Some veins have a laminated appearance due to white mica and fluid inclusion trails, orientated parallel to cleavage (Thalhammer, 1992). Veins consist, in order of abundance: milky quartz, albite, host rock fragments, pyrite, white mica, carbonate, chlorite, arsenopyrite and gold. The vein systems are commonly associated with distinct <3 m wide halos of phengite–chlorite–pyrite (<3 cm cubes)–carbonate (siderite–ankerite–calcite)–hematite. It is not clear whether hematite is a primary alteration mineral.

The Warratta Inlier contains over 200 shafts and pits sunk into bedrock, mainly worked in the 1880's. These concentrated on several large quartz vein network systems, the largest being the Pioneer–Phoenix Reefs. This system is over 5 km long and includes a <300 m wide zone of bleached pyritic siltstone–mudstone and minor sandstone. The bleaching gives a distinct pale colouring to the rocks, and thin sections reveal increased carbonate (mainly siderite spots and disseminated calcite), phengitic sericite, and iron oxides in these zones. A well developed quartz vein network extends along strike, with veins concentrated on the eastern limb of a large, shallowly plunging, east-verging anticline.

The Pioneer–Phoenix Reefs are also coincident with a 15–20 km long and 500–1000 m wide magnetic low (Figure 1). It is at least 40 nT below the surrounding rocks. We interpret this as a magnetite destruction zone, and may have caused the bleached alteration zone surrounding the reefs.

Two whole-rock K–Ar dates from Thalhammer (1992) on quartz-vein alteration halos in phyllites from the Pioneer–Phoenix Reefs gave dates of 441 ± 5 Ma, and 438 ± 3 Ma. In the same study, a phyllite from outside the alteration halo gave an age of 424 ± 4 Ma.

Structural Geology

The earliest penetrative deformation identified in the Tibooburra area is the Delamerian Orogeny that is inferred to have affected rocks in the Depot Glen beds (D1). The first and main deformation event recognized in the Jeffreys Flat beds is characterized by strong penetrative cleavage, concertina-style folding and steep reverse faulting (D2). This second deformation event is interpreted to be broadly coaxial with D1 (σ1 for both events inferred to be WSW–ENE).

The S2 cleavage is defined mainly by shape orientation and white mica, and is axial planar to fold hinges. The cleavage dip is mainly 70–80° to the west-southwest, with σ1 interpreted to be approximately horizontal and parallel to this dip direction.

F2 Folds observed in the field are generally upright to east-verging, tight to very tight, and display a flattened chevron form, with long straight limbs and interlimb angles of 20–40°. Wavelengths measured in the field vary from 100–200 m, but are parasitic to (or coaxially refolded by) major open folds with wavelengths of up to 2 km. The enveloping surfaces are generally flat and major fold amplitudes varying to ~2500 m in the Warratta Inlier (~500 m in the Mt Poole inlier). Folds are doubly plunging but generally plunge shallowly to the north, with axial traces persisting for several kilometres.

Major faults are generally parallel to cleavage with reverse kinematics. They are observed to cut across fold noses, producing hangingwall anticlines and footwall synclines. Active to at least post-Pleistocene, the major Warratta and New Bendigo Faults (Figure 1) have evidence of a long history, with fold and cleavage intensity increasing toward these structures, and mylonitic fabrics within the fault zones. They are interpreted to have been active during late D2, with subsequent reactivation. Faults parallel to quartz vein networks occur on the eastern limb of some anticlines, although the kinematics are unclear.

A second deformation event (D3) refolded F2 folds, quartz-vein networks and S2 cleavage. The event is characterized by kink-banding and mesoscopic F3 chevron folding in discrete domains. $\sigma1$ is broadly coaxial with D2, although an unconstrained amount of transpression is also evident in fold and fault patterns. D3 intensity is greatest at major fault margins, resulting in locally overturned F2 folds. Minor tension quartz–calcite veins have injected along kink bands and as minor en-echelon arrays in monzodiorite sills/dykes, but limited rock-chip assays indicate they are not auriferous.

Lithotectonic history

In the Tibooburra area, continental provenance and shallow marine setting of the Late Cambrian sedimentary rocks suggest deposition on a continental platform or shelf. Sedimenation closely followed the Delamerian Orogeny (D1; 511–497 Ma), and may have sourced detritus from the Delamerian Highlands to the west (Scheibner and Basden, 1998). In the southeast of the Koonenberry Belt, Late Cambrian fluvial to shallow marine molasse basins of the Kayrunnera Group unconformably overlie the Delamerian-deformed turbidites of the Eastern Teltawongee beds. The contemporaneous shallow marine sediments of the Tibooburra inliers, 70 km along strike to the north, may similarly have been deposited on Delamerian-deformed continental crust.

Based on the K-Ar data, D2 deformation of the Jeffreys Flat beds was contemporaneous with the Benambran Orogeny in the Lachlan Orogen (~440-420 Ma). The flat enveloping surface of the folds also corresponds to a flat magnetic profile and monotonous lower greenschist facies metamorphism, suggesting a thin-skinned fold-thrust regime (Cox et al., 1991). The vergence of the fold-thrust belt in the Tibooburra area is away from the craton. This is in contrast to the westerly vergence of the fold-thrust belt west of the Koonenberry Fault (Direen and Crawford, 2003).

Pre-tectonic basaltic andesites and syn- to post-tectonic monzogranites and related dykes/sills intruded across all the Tibooburrra inliers. The alkaline major-element chemistry, relatively high Nb/Y ratios plus other trace element data from the pre-tectonic suite suggest an intraplate setting. The syn- to post-tectonic intrusions also show geochemical evidence of an intraplate setting but with evidence of variable crustal contamination and these rocks have been dated at between ~423-421 Ma (Black, 2006).

Comparison with Victorian Goldfields

Structural, petrographic, temporal and tectonic features of the Tibooburra goldfields are comparable to the Victorian goldfields of the Western Lachlan Orogen (Table 1, Figure 3).

Some of the features such as bedding–cleavage concordant replacement veins, quartz–albite–pyrite–arsenopyrite mineralization and carbonate–sericite alteration are typical of turbidite-hosted orogenic gold deposits worldwide (Bierlein et al., 1998) and are not exclusive features of the Victorian gold deposits. These features indicate mineralization pulses in both terranes were probably caused by fluid overpressure during late orogenesis, associated with low sulphide, CO2-rich aqueous ore fluids (Bierlein et al., 1998).

Description	TG	VG	Notes
Gold Mineralization			
Replacement style, bedding/cleavage concordant, auriferous quartz–albite–pyrite–arsenopyrite–chlorite vein networks	yes	yes	Arsenopyrite more abundant in VG
Metre-scale alteration halos containing phengite-sericite, chlorite, pyrite, arsenopyrite, carbonates (siderite–ankerite, calcite)	yes	yes	Hematite present in TG
Zones of bleached country rock are associated with sericitization and carbonatization, and generally define a broad alteration halo around auriferous veins	yes	yes	
Both hydrothermal and sedimentary (diagenetic?) pyrite recognized	yes	yes	Framboidal pyrite in VG
Elevated arsenic and lead in altered country rocks	yes	yes	
Auriferous quartz vein networks located on the eastern limbs of anticlines	yes	yes	Not exclusively. Only recognized in two prospects within TG
Auriferous quartz veins in saddle reefs	no	yes	Not recognized in TG
Magnetic low associated with main mineralization trend that envelops boundaries of bleached zones mapped in outcrop	yes	no	Not recognized in VG
Lead isotope values close to crustal growth curve	yes	yes	TG and most VG values within error
Sulphur isotope values peak close to 0‰	yes	yes	Peak values between 1-3‰
P-T conditions during gold mineralization ~350º C and 300 Mpa	yes	yes	Illite crystallinity and fluid inclusions
Structural Geology			
Doubly plunging, tight to isoclinal, upright to inclined, chevronic folding	yes	yes	Chevron hinges not as sharp in TG
Folds have flat enveloping surface 1-2km thick	yes	yes	
Fold axes doubling plunging but overall shallow plunge to the north	yes	yes	TG D_2 σ_1 closer to WSW–ENE
Fold tightness increases towards major faults, locally overturned	yes	yes	
West-dipping reverse faults, developed late during fold growth	yes	yes	
Approximately 60–70% shortening across terrane	yes	yes	
Vergence of the fold-thrust belt away from the craton	yes	yes	Only in Bendigo Zone (VG)
Cleavage very strong and pervasive throughout all lithologies	yes	no	In BG, cleavage is pervasive in pelite and weakly developed in psammite
Cleavage is axial planar	yes	no	In BG, cleavage fans around fold hinges.
Tectonic Setting			
Thin skinned deformation regime	yes	yes	
Craton-verging fold-thrust belt in dominantly Delamerian-deformed rocks, opposite vergence in dominantly Benambran-deformed rocks, separated by major west-dipping fault	yes	yes	Avoca Fault in Western Victoria, Kooonenberry Fault in northwest NSW
Timing of metamorphism and gold mineralization is late D_1	yes	yes	
Post-tectonic I-type magmatism	yes	yes	Also S–types in VG.
Host sedimentary sequences underlain by oceanic crust	no	yes	See text

Table 1. Comparison of mineralization, structure and tectonic setting between the Tibooburra goldfields (TG) and the Victorian goldfields (VG). References for Victorian goldfields are Cox *et al.* (1991), Gray and Foster (2004), Bierlein *et al.* (1998) and Li *et al.* (1998), and are mainly focused on Bendigo Zone for mineralization and structural geology. References for Pb and S isotope data and P-T conditions are from Thalhammer (1991).

Comparable structural features between the Tibooburra area and the Bendigo Zone, such as the thin-skinned fold-thrust regime verging away from the east Gondwana craton, may bear only superficial comparison. The structural setting in the Bendigo Zone has been used to infer thin skinned deformation above a horizontal detachment in the Victorian goldfields (Cox et al., 1991). However, in Tibooburra, a shallow marine basin overlying folded Delamerian basement is very different to the Ordovician deep water turbidite rocks of the Bendigo Zone, which are interpreted to have been underlain by oceanic crust (Gray and Foster, 2004). The interpreted lithostratigraphy for the Tibooburra area is more comparable to the Stawell Zone, which is interpreted as a Delamerian fold belt reworked during the Benambran Orogeny (Miller et al., 2005). There is no convincing evidence to suggest that an oceanic basin developed east of the Koonenberry Fault subsequent to the Delamerian Orogeny, or that the Benambran Orogeny in the Tibooburra area was related to a subduction/accretionary prism setting proposed for the same period in the Western Lachlan Orogen by Gray and Foster (2004) and Miller et al. (2005). In contrast, the geochemical data of pre-, syn- and post-tectonic magmatic activity suggests an intraplate tectonic setting.

Both the Victorian and Tibooburra goldfields developed along the eastern margins of the Delamerian Orogen, and the main phase of syn-orogenic gold mineralization in both terranes is dated at approximately 440 Ma (Figure 3, Gray and Foster, 2004). This is coincident with a major mineralizing event throughout the Tasmanides (Scheibner and Basden, 1998). Both terranes were intruded by Late Silurian to Early Devonian granites, although plutonism in the Victorian goldfields continued until the late Devonian (Gray and Foster, 2004). The period between the Benambran Orogeny and magmatism in the Tibooburra area was shorter than the corresponding gap in the Victorian goldfields (Figure 3).

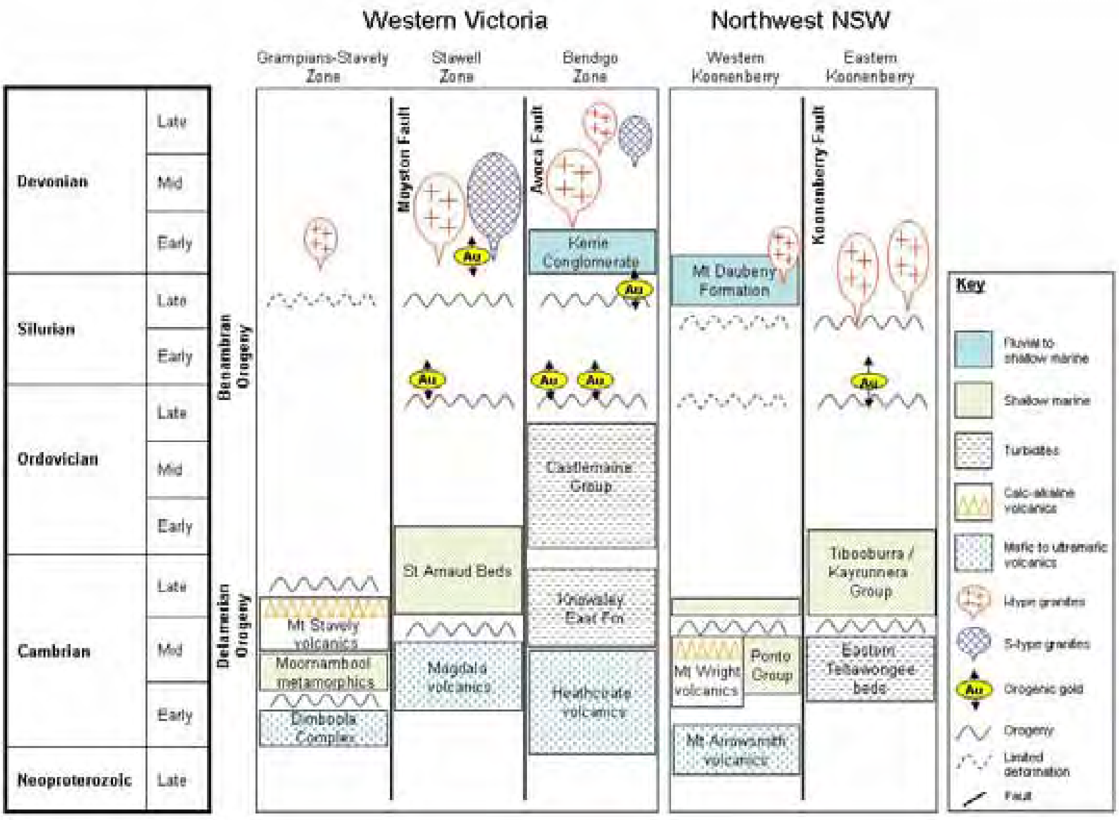

Figure 3. Time-space plot, comparing the simplified geology of Western Victoria with northwest NSW. Data mainly from Glen (2005), Gray and Foster (2004) and Miller et al. (2005).

A significant and poorly constrained aspect of the tectonic setting is the timing and influence of inferred docking of the Thomson Orogen to the Gondwana (Koonenberry)–Lachlan margin. The inferred northerly dip of the Olepoloko Suture suggests the Thomson may have been thrust over the Lachlan (Glen, 2005). Correlation with north–south shortening during the early Silurian Rodingan Movement in central Australia, suggests at least one stage of the collision of the Thomson Orogen with the Gondwana (Koonenberry)–Lachlan margin may have been of Early Silurian age (Gray and Foster, 2004), coincident with the Benambran deformation event in the Tibooburra area.

Conclusions

- Mineralization in the Tibooburra goldfields is classified as an orogenic gold province, and is typical of turbidite-hosted/slate-belt gold provinces.
- Mineralization timing, style and structural development of the Tibooburra Goldfields is very similar to the Victorian Goldfields in the Western Lachlan Orogen.
- The Tibooburra area sedimentary rocks were most likely deposited in an intraplate continental basin setting onto a Delamerian Orogen basement.
- These data provide the potential to apply Victorian orogenic gold exploration models to other segments of the eastern margin of the Delamerian Orogen, and suggest these deposit types may have developed in a variety of tectonic settings.

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Improved map and genetic implications of the Mount Mulga barite-iron-oxide-copper-gold-deposit – preliminary results

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Introduction

The aim of the project is to provide an improved map of the Mount Mulga Mine (barite – magnetite – copper – gold) and the hosting rock sequences, to determine geochemical relationships of the mineralised units to the country rock, and compositional variations along strike to establish whether the deposit is syngenetic or epigenetic. This work includes whole rock XRD and XRF analyses, sulphur isotope analyses for barite and chalcopyrite, strontium isotopes for barite, EDX and electron microprobe studies of individual mineral phases.

The Mount Mulga Mine is situated on Bimbowrie Station, near Old Boolcoomata, 30km north of Olary on the Barrier Highway, 160 km west of Broken Hill. Intensive workings for copper are reported from the beginning of the 20th century from the Mount Mulga deposit, but the main mining period was between 1962 and 1985 when 18 705 t of low quality barite were mined from an open cut (Ashley et al., 1998a). The resources of barite ore were estimated to be 89 000 t (Olliver, 1977).

The deposit is situated within the lower parts of the Palaeoproterozoic Willyama Supergroup close to the contact of the Wiperaminga and Ethiudna Subgroups. The barite-bearing units are in quartzite, magnetite-rich quartzite, albitite, migmatitic gneiss and mica schist of the Ethiudna Subgroup. Directly below the barite deposit the Wiperaminga Subgroup is represented by migmatitic gneiss with albitic layers. Pegmatites, consisting of feldspar, quartz and Fe-tourmaline are very abundant and often have a sill-like, locally cross-cutting appearance.

Sulphur and strontium isotopic data for barite in Lottermoser and Ashley (1996) indicate Proterozoic seawater as a source for these elements. A chalcopyrite sample from Mount Mulga has a significantly lower δ^{34}S value than the coexisting barite.

Trace element data (Millar, 1994) show low concentrations of base metals except copper, and the uranium content is very low. REE patterns for the barite at Mount Mulga (Lottermoser and Ashley, 1996), as well as the very similar occurrences at the Peryhumuck Mine and Ameroo Hill (Middleton, 1993), show low REE concentrations, a positive Eu anomaly and a depletion of HREE compared to LREE. Because these patterns are very similar to those from metalliferous hydrothermal sediments of the East Pacific Rise, Bierlein (1995) interpreted the barite seams as the result of precipitation from hot reducing fluids near a hydrothermal vent system.

Three barite units can be distinguished at the Mount Mulga Mine. They appear to be stratiform and consist mainly of coarse-grained, pale whitish or pinkish barite, quartz and, up to centimetre-sized, magnetite grains (partly martitised). The main barite body measures approximately 120m along strike and at maximum about 10m wide. In the central section the barite body contains sulphidic Cu-Au mineralisation along its margins.

The second barite unit has a maximum width of c. 5 m. It runs parallel to the main barite unit within the migmatitic gneiss of the Ethiudna Subgroup, which also contains small separate schlieren of barite. This seam-like body can be followed for several hundreds of meters to the southeast of the mine, where the barite content gradually decreases until the unit resembles a quartz-ironstone (Ashley et al., 1998b). In parts of the seam a vertical zonation can be observed with coarsely crystalline barite at the bottom, a quartz rich section in the middle and laminated ironstone at the top.

A third barite – quartz – iron-oxide body occurs south of the mine running parallel to the second body at a distance of 10 – 20 m as a thin layer, but then ends about 300 m southeast of the mine, where it defines the boundary between the Ethiudna and Wiperaminga Subgroups.

Polished sections show complex genetic relationships of chalcopyrite – bornite grains with dissolution/exsolution as well as replacement textures suggesting a paragenetic assemblage. These sulphides are partly replaced by secondary covellite. Also a few grains of native gold can be observed (up to 0.1mm) included in the Cu-sulphides. EDX analyses show that the gold grains contain around 16% silver. Electron microprobe analysis was used to determine the composition of the gold and sulphide grains (see poster). The petrographic setting of sulphides along fractures in magnetite suggests that the Cu-S mineralisation post-dates the formation of the barite-magnetite host rock. Accessory minerals in the barite are biotite, manganiferous siderite, barium-feldspar and pitchblende. Quantified whole-rock XRD analysis of barite samples from the mine showed a composition of up to 98% barite, the remainder being magnetite, quartz, biotite and chalcopyrite.

XRD analysis of a quartz-ironstone sample from the seam 1 km from the mine shows a composition of nearly 80% quartz, the rest are iron-oxides (mainly hematite through martitisation) and approximately 1% barite. In part this unit is accompanied by a layer of an epidote + quartz + biotite + chlorite rock (around 80% epidote), the barite – quartz – iron-oxide rock itself being epidotised in some places.

At Mulga Bore Creek c. 2 km north of the mine, there is a second occurrence of malachite-stained barite in the study area. This barite unit is still part of the Ethiudna Subgroup, but, being just below the Bimba Formation, is at a stratigraphically higher level than that at the Mount Mulga deposit. There are two thin layers having a maximum width of 30 cm that are composed of barite, quartz and in places biotite. Iron-oxides are not part of the mineralogy of these layers, a significant difference from the Mount Mulga Mine barite. One layer can be followed approximately 400 m along strike, the second is continuous for only about 100 m.

Also at Mulga Bore Creek a third locality of copper-sulphide mineralisation is found. Here, in a metavolcanic-bearing horizon of the Ethiudna Subgroup (1713 Ma, zircon U-Pb, Conor 2004), mineralisation is present as chalcopyrite and secondary Cu-minerals like malachite, azurite and chrysocolla, and Au-grades are significantly elevated. In addition to these two examples of Cu-mineralisation at Mulga Bore Creek the whole Ethiudna Subgroup is Cu-anomalous in the area of study, as evident from frequent occurrences of secondary Cu-minerals in the gneiss and schist.

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An Integrated Geophysical Approach to BHT Exploration

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Introduction

In June 2005 the Japan Oil, Gas and Metals National Corporation (JOGMEC) signed an agreement with Minotaur Exploration over the Border Project Area west of Broken Hill. The Joint Venture is actively exploring in the project area for Broken Hill Type Pb-Zn-Ag Mineralisation.

Exploration Strategy

The Joint Venture is targeting areas of previously underexplored Broken Hill Group Stratigraphy. Prospective areas are interpreted using the regional aeromagnetic and gravity datasets. Individual targets are generated using a combination of the geological, geochemical and geophysical techniques. The presence of large amounts of historic data means that very little new regional data has to be acquired. At the prospect scale, gravity and electrical geophysical data are critical for drill targeting.

Example - White Roo Prospect

This Prospect (Figure 1) was generated from regional gravity and airborne TEM datasets. The Prospect is interpreted to occur within Broken Hill Group equivalent stratigraphy. Initial drill testing confirmed the presence of zinc-anomalous strata. Follow up ground geophysical surveys (Moving Loop TEM, Fixed Loop TEM, Ground Magnetics, Down hole SIROTEM, Down hole CRONE) detected a complex of bedrock conductors and allowed these to be located in 3-D space with greater precision than original airborne data. Subsequent drilling intersected a pyrrhotite/chalcopyrite mineralising system within a mafic gneiss basement sequence.

Acknowledgements

Thanks to Minotaur Exploration and JOGMEC for allowing data to be presented. PACE funding from PIRSA helped fund the drill-testing at White Roo.

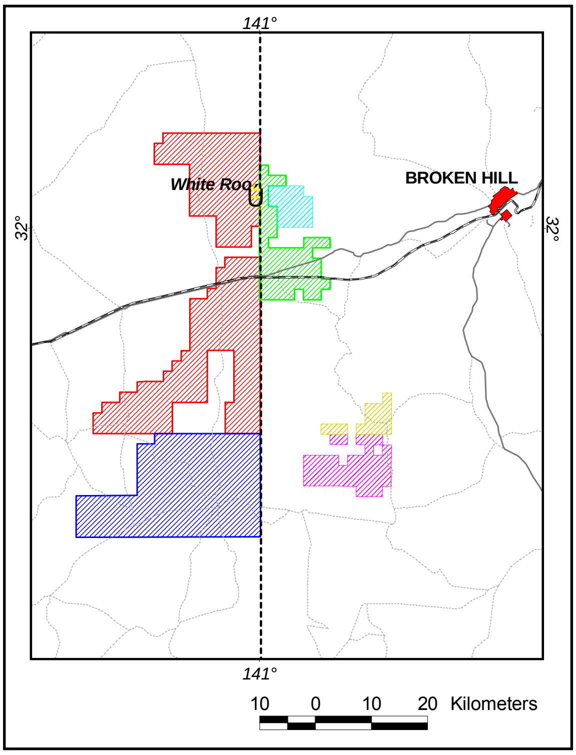

Figure 1. Location of Border Project tenements and White Roo Prospect**.**

The Grasmere and Peveril copper deposits – emerging VMS deposits in the Koonenberry Belt, NSW

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Introduction

Black Range Minerals holds a 100% interest in two exploration licences covering 579km^2 at the southern end of the Koonenberry Belt, approximately 100km east of Broken Hill in New South Wales. The historic Grasmere Copper Deposit lies within these licences. Secondary copper ore was mined from this deposit in the late 1800's and early 1900's.

Previous explorers identified gossans containing secondary copper mineralisation over some 4km of strike. Only limited drilling had been undertaken prior to Black Range's involvement, most recently by Rio Tinto in 1991. This resulted in delineation of a small high-grade massive pyrite-chalcopyrite-sphalerite lode down dip from gossans at the Grasmere Deposit.

Since October 2005 Black Range Minerals has completed two drilling programmes totalling more than 11,000 metres, together with ground EM and gravity surveys. An extensive massive-sulphide mineralised system has now been delineated over more than 4,000 metres of strike, to depths greater than 450 metres. The mineralisation has many affinities to the Besshi-type VMS deposits. Mineralisation remains open in all directions.

Significant thickening of the mineralisation is evident at both the Grasmere Copper Deposit and the newly discovered Peveril Copper Deposit, located 2.5km along strike from the Grasmere Copper Deposit. Intersections in drilling include 11 metres at 2.02% copper from 52 metres, 9.75 metres at 2.25% copper from 120 metres, and 8.5 metres at 2.95% copper from 58 metres.

As at July 2006 the JORC-compliant resource at the project stands at **5.75 million tonnes at 1.03% copper, 0.35% zinc, 2.30g/t silver and 0.05g/t gold**, containing approximately 60,000 tonnes of copper. There is considerable potential to increase the resource base with further exploration.

Geochemistry of garnet-rich rocks, southern Curnamona Province, Australia: genesis and implications for Broken Hill-type mineralisation

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Introduction

Garnet-rich rocks are spatially associated with the Paleoproterozoic Broken Hill (BH) Pb-Zn-Ag deposit and hundreds of smaller Broken Hill-type (BHT) deposits, but they are also present as minor occurrences unrelated to sulphides throughout the southern Curnamona Province (SCP), Australia. The origin of these rocks remains a subject of considerable debate due to the structural and metamorphic complexity of the SCP. Although the geology and geochemistry of garnet-rich rocks in the BH deposit have been a focus of attention (e.g., Spry and Wonder, 1989; Lottermoser, 1989; Plimer, 2006), the geology, geochemistry, and exploration significance of garnet-rich rocks elsewhere in the SCP, particularly in the Olary Domain is more limited (e.g., Laffan, 1994; Pierini, 1994; Lottermoser and Ashley, 1996). Here we present major and trace element [including rare-earth element (REE)] compositions of garnet-rich rocks as well as individual garnets from Cathedral Rock, Meningie Well, Polygonum, Hunters Dam, Weekeroo, Doughboy, Thunderdome, Mutooroo, and Iron Blow prospects, and from the BH deposit. The first seven locations were metamorphosed at upper greenschist to upper amphibolite facies whereas the last three occurrences were subject to granulite facies. The objectives of the study are to determine:

1. The origin of garnet-rich rocks in the SCP;
2. Geochemical differences between garnet-rich rocks from the BH deposit and elsewhere in the SCP;
3. The physicochemical conditions of formation of garnet-rich rocks; and
4. Guides in the exploration for BHT deposits in the SCP and elsewhere.

Geological setting and description of garnet-rich rocks

Garnet-rich rocks are intercalated with metasedimentary rocks at various stratigraphic levels in the Willyama Supergroup, amphibolites are generally proximal, but felsic volcanic rocks are more restricted. The studied areas in the Saltbush Group near Cathedral Rock and Meningie Well South are equated with the Broken Hill Group (Laffan, 1994; Lottermoser and Ashley, 1996; Page et al., 2005). Garnet-rich rocks are primarily quartz garnetite and lesser garnetite (> 80 % garnet) at BH, Iron Blow, Thunderdome, and Mutooroo, whereas quartz-garnetite is the only garnet-rich rock present at Cathedral Rock and Polygonum. At Thunderdome, quartz-garnetite and garnetite usually contain magnetite and grade into iron formation. Garnet-rich rocks at Weekeroo and Meningie Well consist of garnet and amphibole and locally grade into amphibole-rich rocks and silicate-facies iron formation. At Polygonum, garnet-rich laminae are intercalated with garnet-poor pelitic layers. Garnet-rich rocks in all localities are conformable with bedding in the enclosing metasedimentary rocks. Exceptions to this include the cross-cutting, so-called "remobilized" quartz-garnetite and garnet envelope of Spry and Wonder (1989) at BH, which formed during the third deformation event that affected the Willyama Supergroup.

Table 1. Stratigraphic relations of garnet-rich rock locations in the SCP

LOCALITY	STRATIGRAPHIC GROUP	FELSIC VOLCANIC	AMPHIBOLITE	SIGNIFICANT SULPHIDE
Broken Hill	Broken Hill	S-type volcaniclastic	sills	yes
Thunderdome	Broken Hill		sills	yes
Mutooroo	Broken Hill		sills	yes
Cathedral Rock	Broken Hill equivalent		sills	
Meningie Well	Broken Hill equivalent		sills	
Iron Blow	Thackaringa		sills	yes
Doughboy	Curnamona	A-type ?lava		yes
Weekeroo	Curnamona		yes - lava	

Models for the formation of garnet-rich rocks

The origin of garnet-rich rocks at BH has centred on three main concepts: 1. Metamorphism of Mn-rich exhalites mixed with aluminous detrital/pelagic sediments (e.g., Lottermoser, 1989; Spry and Wonder, 1989; Plimer, 2006); 2. Syn- to post-peak metamorphic/metasomatic interaction of Mn between the BH deposit and the aluminous wall rocks (e.g., Hodgson, 1975); and 3. Reaction between partially molten Mn-rich sphalerite in the lodes and the pelitic wall rocks during peak metamorphism (Mavrogenes et al., 2004). The second and third conceptual models both require the presence of Mn within the sulphide deposit to have reacted with the aluminous wall rocks at some time during the prograde/retrograde metamorphic history. Clearly, this was not the case since Mn-rich garnet rocks are found throughout the SCP unrelated to sulphides. Although concerns relating to the partial melt model at BH are discussed elsewhere in this volume, the presence of garnet-rich rocks metamorphosed to greenschist-amphibolite facies in the SCP cannot be explained by this model because the temperature was too low for melting of sulphides to have taken place. Furthermore, mass-balance considerations of the volume of garnet-rich rocks at BH relative to the amount of sphalerite in the orebodies would require the MnS content of sphalerite to be >20 mole %, which has not been reported in any known sulphide deposit. Given the above mineralogical and textural considerations, the most likely scenario for the formation of the garnet-rich rocks in the SCP, especially garnetite and massive and laminated varieties of quartz-garnetite, is for the protolith to have formed by exhalative/inhalative processes whereby Mn-Fe-bearing hydrothermal fluids reacted with aluminous sediments of pelagic/detrital origin.

Chemistry of garnet-rich rocks

Garnet-rich rocks in the SCP are dominated by Mn, Fe, Si, Al, and Ca. Away from the BH deposit the MnO content of garnet-rich rocks varies from 0.2 wt.% MnO at Iron Blow to 7.22 wt.% MnO at Cathedral Rock. Garnetite and quartz garnetite from BH contain up to 26.4 and 19.3 wt.% MnO, respectively. Fe/Mn ratios in garnetite and quartz garnetite from BH range between 0.3 (garnetite) and 13.5 (quartz garnetite), whereas those in garnet-rich rocks from elsewhere in the SCP range from 1.25 (Thunderdome) to 69.2 (Iron Blow). The major element composition and Cu-Co-Ni content of garnetite and quartz garnetite in the SCP when evaluated in terms of Al-Fe-Mn, Fe/Ti versus Al/(Al+Fe+Mn), and Fe-Mn-[(Cu+Co+Ni)x10] show that there was a roughly equal amount of hydrothermal and detrital components in the protolith, with a relatively minor hydrogenetic contribution Although BIF from BH and garnet-amphibole rocks from Meningie Well show a higher hydrothermal component (>80%) in the source rock than garnetite and quartz garnetite, some amphibole-garnet rocks from Weekeroo show a considerably higher detrital component. The rocks from Weekeroo and garnet-pyroxenoid rocks at BH are among the most Ca-rich garnet-bearing rocks in the SCP and may have contained carbonate mud in the protolith. Quartz garnetite and garnetite from BH show higher average values of K, Rb, Mn, S, Ga, Cs, Eu, Sn, U, W, Cu, Pb, Zn, As, Cd, Sb, Ag, and Au than garnet-rich rocks from Mutooroo, Iron Blow, Cathedral Rock, Meningie Well, and Weekeroo. Compared to garnetite and quartz garnetite from BH, garnet-rich rocks from these sites possess higher average contents of Fe, Ca, P, Sr, Y, C, Co, Ni, and Bi. Higher average Co+Ni values in garnet-rich rocks from Meningie Well, Cathedral Rock, and Weekeroo, compared to the other occurrences in the SCP, suggest a higher hydrogenetic component to their protoliths.

In evaluating the controls on the fractionation of isovalent trace elements in magmatic and aqueous systems and their various precipitates (chemical sediments and hydrothermal minerals), Bau (1996) showed that elements of similar charge and radius, such as the Y-Ho and Zr-Hf twin pairs, should display coherent behaviour and display close to chondritic compositions (so-called "CHARAC" behaviour). Most garnet-rich rocks in the SCP plot within the CHARAC field; however, some rocks plot close to, but outside of, the CHARAC field.

Chondrite-normalized REE patterns of Mn-poor, Fe-rich quartz garnetite and blue quartz-garnet-gahnite (BQGG) rocks from BH and Mn-poor garnet-rich rocks in the SCP away from the BH deposit generally show light REE (LREE) depletion, heavy REE (HREE) enrichment, flat to decreasing HREE trends, and negative Eu anomalies (Eu/Eu* < 1), whereas Mn- and Ca-rich garnetite and garnet-pyroxenoid rocks from BH show positive Eu anomalies (Eu/Eu* > 1). The LREE patterns contrast to those for individual garnets obtained by LA-ICP-MS techniques. Garnet in garnet-rich rocks throughout the SCP exhibit low LREE/HREE ratios and flat HREE signatures, typical of garnet in metamorphic terranes elsewhere. HREEs are incorporated in garnet whereas LREEs likely occur in intergranular material between garnet grains and in monazite, xenotime, and apatite inclusions in garnet or along grain boundaries. Garnet in garnetite and quartz garnetite from BH show Eu/Eu* > 1 and Eu/Eu* < 1, respectively. Exceptions to these patterns occur for metasomatic garnet in remobilized quartz garnetite, garnet envelope, and garnet in some BQGG from BH, which show arcuate HREE signatures.

Discussion and conclusions

Positive and negative Eu anomalies in garnet-rich rocks (including garnets extracted from the same samples) have previously been interpreted as reflecting high T-low fO_2 and low T-high fO_2 conditions in the hydrothermal fluids responsible for their formation in settings proximal and distal to BH, respectively (e.g., Lottermoser, 1989; Bierlein; 1995, Lottermoser and Ashley, 1996). However, samples with a high detrital component will yield Eu/Eu* < 1 whereas those with a high hydrothermal component should produce Eu/Eu* > 1. The positive and negative Eu anomalies found for garnetite and quartz garnetite, respectively, cannot be explained by differences in the relative contribution of detrital to hydrothermal components because Al/(Al+Fe+Mn) ratios are the same for both and Fe/Ti is higher in quartz garnetite than in garnetite, indicating that garnetite contains a higher detrital component than quartz garnetite.

Plimer (1979) and Spry and Wonder (1989) showed that there is an overall increase in the Mn/Fe ratio of the ore from the stratigraphic footwall (C and B lodes) to the hanging wall (2 and 3 lenses) at BH. This concept is supported by the composition of garnet-rich rocks which show the highest Mn/Fe ratios in samples from 3 lens relative to those in B and C lodes. Garnetite also contains higher Mn/Fe and (Mn+Ca)/Fe ratios than quartz garnetite. Furthermore, there is a strong positive correlation among Eu/Eu*, Eu, Mn, and Ca. If Eu^{2+} showed stronger sorption on Mn-rich oxides/hydroxides/carbonates in the protolith than Fe-rich oxides/hydroxides/

carbonates, this may explain the Eu/Eu* > 1 in samples of garnetite and the Eu/Eu* < 1 for quartz garnetite. Alternatively, since Eu^{2+} has an ionic radius to more similar to Ca and Mn than Fe, Eu^{2+} will preferentially substitute for Ca and Mn in the lattice of Mn oxides/hydroxides/carbonates and calcite in comparison to Fe oxides/hydroxides /carbonates.

Chloride species are common in fluids derived from modern hdrothermal vents (e.g., Red Sea) spatially associated with Mn-Fe precipitates and may explain the CHARAC behaviour of most garnet-rich rocks. However, it is noted here that fluorite is abundant in the BH deposit (particularly 3 lens), and that fluorapatite is common in BIF and some samples of garnet-rich rock in the SCP. The presence of fluoride species, in addition to chloride species, may account for the slightly high Y/Ho ratios of some garnet-rich rocks. However, another reason why most garnet-rich rocks show CHARAC behaviour is because the clays that interacted with the Mn-bearing exhalative fluid likely possessed CHARAC compositions. This concept is supported by the observation of Bau (1996) that both Phanerozoic and Proterozoic shales plot within the CHARAC field. Y/Ho and Zr/Hf ratios near chondrite and the Eu/Eu* > 1 and high Mn/Fe ratio in garnetite and garnet-pyroxenoid rocks, and the high Mn/Fe ratio of garnet-rich rocks, coupled with the paucity of Cu in the BH deposit, suggest that ore fluid at BH had a high Cl^-/F^- ratio, and was between 250° and 300°C. Lower Mn/Fe ratios and Eu/Eu* < 1 suggest that quartz garnetite at BH, garnet-rich rocks in smaller BHT deposits, and those unrelated to sulphides also formed at T >250 °C. Garnet-rich rocks spatially associated with the BH deposit are enriched in K, Rb, Mn, Ti, S, Ga, Cs, Eu, Sn, U, W, Cu, Pb, Zn, As, Cd, Sb, Ag, and Au relative to rocks that show no spatial association to sulphides or to minor amounts of sulphides. These elements, along with the presence of Eu/Eu* > 1 in garnet-rich rocks, constitute an exploration guide to BHT mineralization.

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Exploring within and through transported cover in the Curnamona Province and Thomson Orogen: results from animals, vegetables and minerals

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Introduction

CRC LEME assists mineral explorers by improving the understanding of regolith processes, both on a regional and local scale, so current mineral exploration techniques can be refined and new ones developed. A particular focus of the Centre's research is on landscapes containing transported material where traditional exploration methods have been ineffective. Some of the outcomes and highlights of this research from the Curnamona Province and Thomson Orogen include:

- Discovery of extensions of the Pinnacles Mine lode rocks under alluvial sediments of Pine Creek using river red gum leaf biogeochemistry;
- The use of the biogeochemistry of chenopod shrubs (saltbush and bluebush) to represent mineralisation beneath sheet flow sediments at White Dam and other Cu-Au prospects in the Curnamona Province;
- Identifying that acacias such as mulga, contain detectable levels of Au and other pathfinder elements when located over Au mineralisation and associated alteration zones and dispersion trails in the Tibooburra – Milparinka district;
- Observing that vertical root penetration (10s of metres) through transported cover by plants such as the widespread prickly wattle (*Acacia victoriae*) and by spinifex in the northern Flinders Ranges, resulting in their plant biogeochemistry providing a surficial chemical expression of buried bedrock or deep regolith materials;
- Identification of regolith-interfaces, such as the sub-Mesozoic palaeosurface and associated basal sediments, as constrained chemical and physical traps for metals and pathfinder elements within basin settings and their margins;
- Understanding that a regolith-landform mapping and landscape evolution framework provides a context for regolith materials in areas of extensive transported cover. In particular, neotectonics have greatly altered palaeo-dispersion pathways such as those associated with palaeodrainage systems.

Regolith and Landscape Evolution Framework

Regolith-landform maps

Following the initial regional regolith-landform mapping (e.g. Gibson & Wilford, 1996; Gibson, 1996; Hill, 2001; 2002; Gibson, 2002), CRC LEME has been involved in producing more detailed and focussed regolith-landform maps to provide a framework for its key study sites. Firstly this resulted in the publication of a series of 1:25,000 from the southern Broken Hill Block, including the Kinalung-Quondong (Brachmanis et al., 2001a), Redan (Brachmanis et al., 2001b), Balaclava (Foster et al., 1999), Triple Chance (Debenham et al., 2001), Pinnacles (Senior et al*.,* 2002), Wahratta (Foster & Hill, 2002), and Mt Gipps (Lewis et al., 2002) sheets. A 1:25,000 regolith-landform map was also published of the Tibooburra Inlier (Chamberlain et al., 2002), and 1:100,000 maps of Wonnaminta (Gibson, 2001), and Teilta (Hill, 2005a). Later, more detailed regolith-landform maps have included the Flying Doctor Prospect (Thomas et al*.,* 2003; Hill et al., 2005); White Dam Prospect (Brown et al., 2003), the White Dam to Luxemberg area east of Olary (Lau et al*.*, 2004).

Palaeodrainage and palaeo-dispersion

Geochemical signatures of mineralisation have been dispersed vertically and laterally through the regolith of the region since at least the Mesozoic. Important expressions of some of this palaeodispersion can be seen in remnants of palaeodrainage systems. Most notable here are palaeodrainage systems associated with:

- Basal Mesozoic palaeodrainage that predates the sediments of the Cretaceous marine transgression across much of the basin area. This palaeodrainage has interacted extensively with a weathered, bedrock-dominated landscape and locally contains high concentrations of Au in the Tibooburra district, and may contain chemical expressions of other buried mineralisation within basin areas;
- Palaeogene palaeodrainage typically associated with the Eyre Formation and equivalent sediments. This palaeodrainage has mostly reworked Mesozoic sediments within basin areas and contains local expression of bedrock mineralisation on the basin margins, or where suitable groundwater aquifers are hosted within the sediments;
- Neogene palaeodrainage that is typically associated with the Namba Formation and younger sediments (e.g. Willawortina Formation and Pooraka Formation and their equivalents). This tends to include a greater component of lithic fragments associated with the uncovering of bedrock in the basin margins; and,
- Contemporary drainage systems that have mostly reworked a combination of the palaeodrainage sediments and aeolian, sheet flow and weathered bedrock regolith.

Neotectonics

Tectonism has been a major control on the regolith and landscape evolution of the region, particularly since the mid-Palaeogene. That resulted in contemporary regolith dispersion pathways that are different from earlier ones due to major changes in topographic relief. It has long been established that much of the uplift of the northern Flinders Ranges has taken place in the later parts of the Cainozoic, but Cainozoic tectonism is also very significant within the Barrier Ranges (Hill & Kohn, 1999; Hill et al*.* 2003) and further north through the Grey Ranges near Tibooburra (Anderson et al*.,* 2004; Hill, 2005; Davey & Hill, 2005; McAvaney & Hill, in prep.).

Regolith Geochemistry

Soils and stream sediments

Soils and stream sediment geochemistry applications for mineral exploration in the district have been problematic due to the transported nature of the surface materials. For example, widely sourced aeolian materials comprise a major component of the surface regolith, and are typically poor at hosting locally derived chemical signatures of buried mineralisation. Brown and Hill (2004) have shown that effective use of these materials can only be achieved in conjunction with detailed regolith-landform maps that show changes in the major characteristics of the regolith and detail local dispersion vectors particularly related to the landform expression.

Indurated Regolith

The region hosts a wide array of indurated (cemented) regolith materials (Hill, 2000; 2005). One of the most widespread and abundant is calcrete and other regolith carbonate materials.

These have proven useful for providing a broad expression of mineralised areas near Broken Hill (Hill et al., 1999; McQueen et al., 1999; Senior & Hill, 2002; Hill, 2005b), as well as near Olary (Wittwer et al., 2004) and the Tibooburra-Milparinka district (Gibbons & Hill, 2005). A detailed chemical and Sr-isotopic study of calcretes from the region indicates a dominant marine source of Ca rather than the alternative bedrock weathering source. Potential Ca source areas include the southern continental shelf and the extensive calcareous dunes along the coastal regions. Atmospheric processes such has aeolian dust and rain, have resulted in the transportation of these materials inland. (Dart et al., 2004, 2005). Ferruginous regolith has not been widely used as an exploration sampling medium in the district largely because of its relatively limited distribution; however potential exists for developing silcretes as an alternative regional exploration sampling medium in basin areas (Hill, 2005a; b).

Biogeochemistry of Plants

In recent years a range of regolith biogeochemistry research projects have been undertaken in the Curnamona Province and the immediately adjacent areas of western New South Wales and eastern South Australia (Hill, 2002; Hill & Hill, 2003).

Chenopods – bluebush and saltbush

Many of the chenopod shrubs appear to be chemical amalgamators of the regolith substrate overlying bedrock. Examples include black bluebush (*Maireana pyramidata*) at the Flying Doctor Prospect (Hill et al*.,* 2005), and to some extent bladder saltbush (*Atriplex vesicaria*) at the White Dam prospect, although this also appears to gain chemical signatures from below the base of the transported regolith interface (Brown & Hill, 2004).

Acacias

Two of the best examples of plants that are deriving chemical signatures from weathered bedrock underlying shallow transported regolith are the prickly wattles (*Acacia victoriae*) at the Flying Doctor Prospect (Hill et al*.,* in press), and the mulgas (*Acacia aneura*) within Tibooburra Inlier (Hill, 2003), the New Bendigo Inliers (Tucker & Hill, in prep.) and Thackaringa Serpentinite (Hill, 1998). In these cases the surface and near surface regolith materials have either a poor or insignificant chemical expression of the underlying bedrock, however the trees here appear to have ‘penetrated’ this shallow (< 5 m thick) regolith and contain chemical signatures indicative of the underlying bedrock. This characteristic suggests that these trees can be better sampling media than surface transported regolith materials and shallow drilling and costeans.

River Red Gums

River red gums form extensive riparian woodlands along many of the major drainage lines in the region. Their root systems extend for many 100s of metres laterally and 10s of metres vertically, where they may interact with regolith substrates (mainly stream sediments), shallow aquifer systems and the underlying bedrock (Hulme & Hill, 2003; 2004; 2005). The very high polymetallic composition of the leaves near the Pinnacles Mine, and the decrease in metal contents to eventually reach background levels (typically below detection limits) downstream, highlighted the potential for this area to host further buried mineralisation. Further research by Karen Hulme has resampled leaves from these trees and the further assays not only repeat earlier results, but better constrained discrete areas of elevated, subsurface metal contents. Recent excavation under some of these trees with high metal contents has found extensions of the Pinnacles mineralisation lodes beneath the alluvial sediments of Pine Creek.

Biogeochemistry of Animals

Kangaroo scats have been sampled as part of a pilot study in the Broken Hill region (Hill, 2004). This study found that an area with a radius of about 20 km and centred on Broken Hill contained elevated Pb, Zn, Cd and Sb contents within the vegetation-roughage fraction of the scats. Uranium contents in the plant roughage increased towards the west of Broken Hill.

Education & Training

CRC LEME provides world-class education and training in regolith geoscience to the Australian and international scientific community. A range of regolith geology field courses are run each year in the Fowlers Gap area, north of Broken Hill. These provide students with experience in regolith geology, including mapping and field sampling, as well as allowing CRC LEME staff to showcase some of the major research outcomes from the region. Detailed (1:12 500 scale) regolith-landform mapping of paddocks within Fowlers Gap Arid Zone Research Station has been a further output from this combination of teaching and research (Hill & Roach, 2004; Hill & Roach, 2005a; Hill & Roach, 2005b).

Undergraduates

Second year undergraduate students from the University of Adelaide, as well as third year students from ANU spend a week in July examining the regolith at the Fowlers Gap Arid Zone Research Station and Broken Hill. This provides an introduction and foundation for their knowledge of this field of geoscience as well as necessary skills that are useful for mineral exploration under cover.

Honours and post-graduates

Shortcourses run through the Minerals Council of Australia (MCA) Minerals Tertiary Education Council (MTEC) are hosted in the Fowlers Gap-Broken Hill region. These include a one week regolith mapping camp typically held for Honours students in March, and a two week Masters course that is also held once a year at Fowlers Gap.

Shortcourses for Professionals

Professionals are welcome to attend any of the MTEC-related courses (ie, Honours and Masters courses) in the region. The Masters course in particular has received enrolments from the minerals industry, where they receive course information drawing from the latest research discoveries made from the region.

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Mount Painter region keeps PACE with exploration

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Introduction

The Mount Painter region (MPR), as described here, is the area covered by the 1:125,000 Mount Painter Special Series Geological Map (Coats et al., 1969) and is centred on the predominantly Mesoproterozoic Mt Painter (MPI) and Mt Babbage Inliers (MBI). These inliers represent a relatively small northwestern exposure of the Curnamona Province that are flanked to the west and south by Adelaidean succession of the Adelaide Geosyncline, and to the north and east by Mesozoic and Tertiary sediments.

An active exploration program for uranium, base metals and geothermal energy by the EL holders in the MPR (e.g. Heathgate Resources Pty Ltd, Quasar Resources Pty Ltd, Alliance Resources Ltd, Marathon Resources Ltd and Petrotherm Ltd) are reporting encouraging results. The region has an established uranium producer in Heathgate Resources Pty Ltd with their operation - the Beverley Uranium Mine, which produced ~ 2.1m lbs of U_3O_8 in 2005.

Coinciding with the recent worldwide upturn in interest for commodities and increased company exploration in the MPR, the Division of Mineral and Energy Resources (MER) has initiated a number of projects, many funded by the State Governments' Plan for Accelerating Exploration (PACE). These are in addition to the ongoing work in the area by MER, and are designed to increase the understanding of the overall geology and potential mineralising systems of the area.

The projects include funding to exploration companies drilling programs, acquisition of "Quickbird" satellite imagery, geochronology, land-based gravity survey and Hylogging of drill-core. Value-adding to existing data-sets includes the processing of Hymap data and sample collecting for spectral-truthing, capture of 8,000 stream sediment sample points into SA_GEODATA , rectification of open file company mapping and selective field mapping areas with the aim to update the geological map of Coats (1969).

Project Details

PACE Drilling Programs

In the MPR four drilling programs have been assisted with PACE funding:-

(1) Red Metals' potential IOCG target, Big Bang, located to the east of Moolowatana HS was drilled on a regionally significant, structurally controlled, moderate amplitude magnetic anomaly associated with a very high gravity response. It was drilled 592m through 256 metres of Tertiary and Mesozoic then in to intense calcsilicate-feldspar-magnetite altered basement rocks. Although no mineralisation was intersected, this

alteration is interpreted as typical of the early regional Na-Fe-Ca-K alteration seen in other prospective IOCG terrains around the world (Kary, 2005).

(2) Petratherm Ltds' first geothermal energy hole, Yerila-01, is located approximately 20 kilometres north of Moolawatana HS. Phase-1 was drilled to 693.5 metres to evaluate the geothermal potential of the region. The rate of temperature increase recorded down-hole is comparable to other "hot rock" provinces in the world. A second hole (not PACE funded), Paralana-1 has recently completed its second phase of drilling to a depth of 1,807 metres and hopes the temperature gradient already recorded in the initial drilling continues to increase (Kallis, 2006).

(3) PACE partially funded one of the three drill-holes at M2, Quasar Resources Pty Ltd high sulphide iron oxide Cu-Au target. M2 Prospect represents an intense aeromagnetic signature near the historic Yudnamutana copper workings. Prior to drilling the recorded geological stratigraphic subdivisions within the area were considered to represent metasomatic alteration of host rocks associated with IOCG mineralisation. The results of the multidisciplinary exploration program are currently being analysed and evaluated to determine the potential of the project.

(4) A new concept by Red Metal Ltd was to test the potential for valley-fill calcrete uranium deposits within younger Quaternary sediments near Lake Callabonna, to the north of Moolawatana HS. A total of 23 drill traverses across 11 separate channels were completed, which were shown to contain mostly sand and gravel. No significant accumulations of valley-fill calcrete favourable for uranium mineralisation were detected but analytical results are still pending (Rutherford, 2006).

"Quickbird" Satellite Imagery

Spatially rectified DigitalGlobe "Quickbird" high-resolution (60cm pixels) satellite imagery covering a greater potion of the MPR was purchased. The data were acquired during July to September 2005 and MER ground-truthed 30 control points during November that year. This provides an excellent spatially rectified base on which to plan, prepare and undertake drilling programs, field mapping, geophysical surveys and additional exploration tasks.

Geochronology

Published literature referring specifically to dating the Pepegoona Porphyry is limited to Rb-Sr data (Compston et al., 1966). Numerous authors have inferred a connection to the ~1575 Ma Mt Neill Granite. For example, Teale, (1993) reported an age of 1576 ± 2 Ma from a rhyolitic crystal tuff from Harts Creek, and equated this with the Pepegoona Porphyry and parts of Mt Neill Granite Porphyry.

Fanning (1987) dated an intensely deformed porphyritic rhyolite from the Gunsight Prospect at 1575 ± 14 Ma (U-Pb zircon) but did not specifically correlate this with the Pepegoona Porphyry.

A sample of the Pepegoona Porphyry recently collected south west of Pepegoona Well in the MPI was dated at 1582 ± 3.5 Ma (Jagodzinski and Hore, in prep.) confirming the age relationship between this extrusive and the Mt Neill Granite.

Gravity Survey

Nearly 2,000 gravity stations on a 2 x 2 km grid were acquired over the northern Curnamona Craton in early 2005. These data extend into areas of the MPR and their inclusion in the MER Gravity database will contribute to a more informed regional interpretation of the Curnamona Province as a whole.

Remote Sensing

A number of novel exploration methods have been recently used in the MPR. One such technique is hyperspectral airborne visible-infrared scanning (used by Anglo-American, and available through HyVista as Hymap, with various partners) previously discussed by Keeling and Mauger (1998). Infrared spectroscopy is useful in identifying minerals, particularly those having hydroxyl radicals such as clays and micas that result from alteration and weathering processes. Complementary technology employed by MER is the CSIRO Hylogger (Keeling *et al.*, 2004), which scans core at 10 mm resolution and, among other things, simplifies and accelerates the identification of many clay and carbonate species in core.

Stream Sediments

The company-generated stream sediment reconnaissance data for areas of the MPR have been collated by MER and converted from paper maps to a more versatile, digital form as a first step in both increasing their utility and permitting a more regional overview.

As the old geochemical maps are derived from aerial photographs, they have local distortions which prevent them from being simply overlaid onto modern maps without first having these distortions reduced by a process known as ‘rubber sheeting’. This provides a best-fit map for the area generally and while minor, local distortions remain it provides a suitable base for modern geochemical maps.

Once the geochemical data are stored in digital form, comparison with modern geological and geophysical information at various scales is possible, with improved overall positional precision. Statistical functions can be simply applied to selected data either as an end in itself or as a means of estimating thresholds or other geochemical parameters of value. Combinations of elements (or the same element determined by different methods) can also be compared, represented simultaneously or used as indices and related to features of interest. In this way, old data may give rise to new interpretations that in turn may lead to new discoveries (Hore et al., 2005). Over 8,000 were added to the MER database as a result of this process.

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Quartz-feldspar-kyanite veins within low-grade Adelaidean meta-pelites

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Introduction

The discovery of kyanite within quartz veins hosted in Neoproterozoic Adelaidean sediments at Wadnaminga, 40km to the southwest of Radium Hill, confirms that kyanite has developed either syn- or post-Delamerian Orogeny (~500Ma).

This is the first reported finding of kyanite in Adelaidean rocks of the Olary region and has important implications for estimating the pressure-temperature conditions for the region as a whole, either during or post, the Delamerian Orogeny.

Recent preliminary field mapping in the area has identified quartz-feldspar-kyanite veins in outcrop intermittently over a 14km SE-NW strike length in the Wadnaminga region.

Description of kyanite veins

The kyanite-bearing quartz veins are hosted by low metamorphic grade (greenschist facies) pelites of the Neoproterozoic Saddleworth and Craddock Formations. The veins are approximately one metre to three metres in length. They are generally concordant with bedding and are unaffected by a subtle Delamerian cleavage, indicating a syn- to post- Delamerian age. They are undeformed and contain euhedral kyanite blades, some up to 10cm in length, as well as aggregates of kyanite and some feldspar, which are all hosted in the quartz. Within the quartz veins the kyanite forms near the contact with the host rock and also as blades grouped together in the centre of the veins.

The contact margins of the metasediments with the quartz-kyanite veins reveal limited wall-rock alteration with no obvious kyanite growth within the host rocks. Not all of the quartz veins within the pelitic unit contain kyanite and it appears that the kyanite-bearing veins are limited to a particular (aluminium rich?) horizon.

Discussion

Large kyanite crystals occurring in quartz veins hosted by Neoproterozoic sediments located at Wadnaminga can be timed to a late stage of the Delamerian Orogeny or ?subsequent event.

The complete lack of kyanite growth in the chemically suitable, pelitic, wall-rock sediments implies that the chemical and pressure-temperature conditions favouring feldspar and kyanite growth in the quartz veins (of probable hydrothermal in origin), were confined to these quartz veins and did not significantly affect the enclosing host-rock sediments.

Resolving outstanding stratigraphic issues in the southern Curnamona Province through the application of SHRIMP U-Pb geochronology

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Introduction

Following the 1998-2004 BHEI geochronology program undertaken by Rod Page in collaboration with geologists of MER-PIRSA, NSW DPI-MR and GA, the complex history of the Curnamona Province is now better understood. The lithostratigraphy of the Olary Domain has been revised, and the current version is summarised by Conor (this volume). This paper reports our recent attempts to resolve some of the stratigraphic issues that remain outstanding at the conclusion of this study, mainly the question of the relationship of the outcropping Bimba Formation in the Olary Domain, the Portia Formation of the Mulyungarie Domain and the Ettlewood Calc-Silicate Member of the Broken Hill Domain. The paper illustrates the difficulties faced in dating these predominantly meta-sedimentary successions, where searching for horizons with a significant volcaniclastic component is a hit or miss affair.

Depositional age of the Bimba Formation

The Bimba Formation is a regionally important mineralised marker within the Olary Domain, comprising a thin, calcareous metasedimentary succession, historically correlated with the Ettlewood Calc-Silicate Member in the Broken Hill Domain based on their similar composition and appearance. The correlation has been supported by the equivalent maximum depositional ages (Dmax) of the overlying Plumbago Formation (1693 ± 3 Ma; Page et al. 2005), and a lithologically similar metasiltstone overlying (and possibly interbedded with) the Ettlewood Calc-Silicate Member (1693 ± 4 Ma; Page et al. 2005). The maximum age for deposition of the Bimba Formation is constrained by volcaniclastic units within the underlying Curnamona Group (*ca* 1713-1718 Ma). The interim ~ 20 million year period is represented by only 50 m of stratigraphy in the Olary Domain (c.f. hundreds of metres of stratigraphy in the Broken Hill Domain, comprising the Thackaringa Group and the underlying *ca* 1705-1710 Ma gneisses). Clearly there are significant time breaks within the Olary Domain during this period, although no unconformities have been recognised. Firmer age constraints are required to determine whether the Bimba Formation belongs within the Curnamona Group (≥ *ca* 1713 Ma), the Saltbush Group (< *ca* 1693 Ma), or somewhere in between; perhaps the temporal correlative of the Thackaringa Group, which currently has no recognised stratigraphic equivalent in the Olary Domain (see Fig. 2 in Conor, this volume).

Unfortunately, the Bimba Formation contains no obvious volcanic targets for dating. A distinctive, biotite-speckled psammite within the Bimba Formation, and quartzites marking a basal unconformity, and a quartzite unit within underlying metasediments, have been sampled in the hope that they might contain a significant volcaniclastic zircon component. Instead, their U-Pb zircon isotopic heterogeneity suggests a wide variety of clastic sources. Page et al. (2003)

reported preliminary results from the biotite-speckled psammite, indicating this horizon is no older than 1705 -1701 Ma (Fig. 1). Pooling the predominantly concordant analyses from the four samples produces an age of 1704 ± 6 Ma (Fig. 2). As all further efforts to locate volcaniclastic horizons in this part of the sequence have been unsuccessful, this remains our best constraint on the upper age limit of the Bimba Formation. The age is a good 10 m.y. younger than the ca 1713-1718 Ma Curnamona Group, indicating the Bimba Formation is temporally equivalent to the Thackaringa Group, or younger.

A pattern emerges in the Dmax ages for sample groups as we move up section (Fig. 2). The quartzites at the base of the Bimba Formation and below yield detrital ages ranging down to 3115 Ma with the youngest detrital peak at 1724 ± 4 Ma (Fig. 2d). The biotite-speckled psammite within the Bimba Formation yields a similar range of detrital ages, but in addition to the 1725-1730 Ma peak, it contains a younger group of predominantly concordant analyses at 1704 ± 6 Ma that is not recorded in the older quartzites (Fig. 2c). The 1693 ± 3 Ma zircons first appear in the overlying volcaniclastic rocks of the Plumbago Formation (Fig. 2b). The pattern of Dmax ages could suggest significant time breaks and unconformities below the Bimba Formation, and between the Bimba and Plumbago Formations, but this interpretation is equivocal.

Lithostratigraphy of the Mulyungarie Domain

The Mulyungarie Domain is an important mineralised region containing a number of Cu-Au and Pb-Zn prospects, e.g. Portia, Kalkaroo, Hunters Dam, McBrides, Polygonum, Thunderdome prospects. As the Willyama Supergroup is predominantly sub-cropping, stratigraphic control relies on U-Pb zircon dating to establish an absolute basis for drillhole correlations. Current understanding of the stratigraphy is summarised in Conor (this volume), but at present there is little geochronological control on lithostratigraphic correlations. The only ages available are from thin, tuffaceous bands within the mineralised sequence at Portia, which have been dated at 1702 ± 6 Ma (Teale, 2000) and 1705 ± 4 Ma (Jagodzinski et al., 2006). These ages suggest that the newly introduced Portia Formation (Conor, this volume) is temporally equivalent to the Thackaringa Group (Cues Formation = 1700 ± 3 Ma), and lend support to its current correlation with the Bimba Formation (Dmax = 1704 ± 6 Ma; Fig. 2).

Our aim is to establish more chronostratigraphic ties with the Olary and Broken Hill Domains, and initially the focus is on identifying cross-province markers such as the Plumbago Formation and Mooleulooloo-Bijerkerno marker, and a third potential marker recognised lower down in several drill holes in the eastern Mulyungarie Domain; a pink, cherty (possibly tuffaceous) psammite, presumed to be older than the 1702-1704 Ma tuffs at the Portia prospect. To date, our efforts have been unsuccessful. Three samples of Plumbago-like metasiltstone collected at Polygonum have failed to yield zircon (Jagodzinski et al., 2006). Two recently analysed samples of the pink, cherty psammite marker contained no significant volcaniclastic zircon component, and produced no definitive Dmax age (Fig. 3). Both samples contain a significant population of 1780-1790 Ma zircons. One sample also yielded younger apparent detrital ages of *ca* 1751 Ma and 1694 Ma, but these age peaks cannot be interpreted with confidence. One grain yielded apparent ages of *ca* 1691, 1753 and 1836 Ma suggesting significant isotopic mixing and/or Pb loss has affected the zircon. A second grain yielded duplicate, but discordant analyses of *ca* 1694 Ma. Because of discordance, this has to be considered a minimum detrital age (i.e. if non-recent Pb-loss has affected the grain, it could be older). If the 1694 Ma age is real, current understanding of the local stratigraphy will need to be revised. Further dating and possibly re-sampling of the unit is required to resolve this issue.

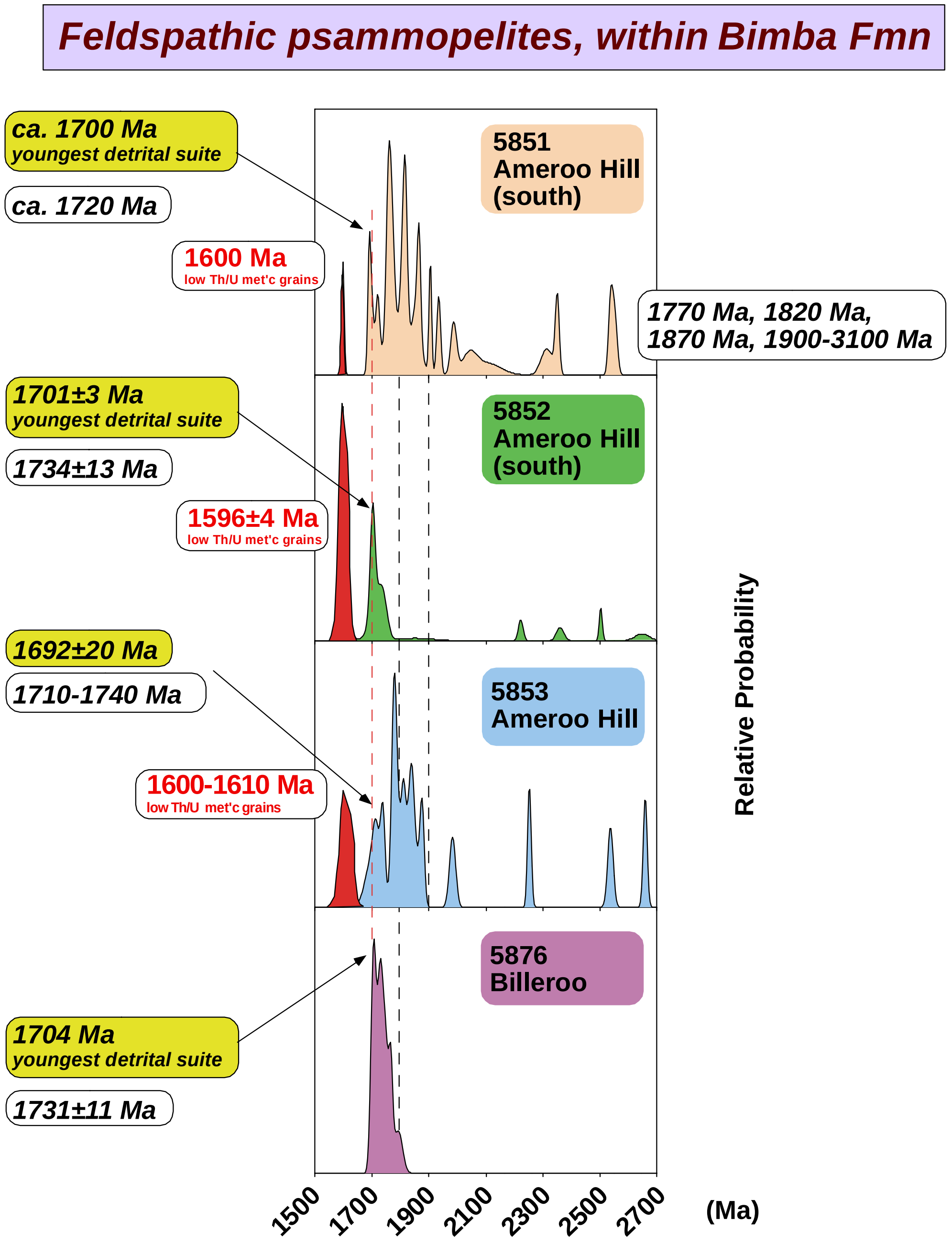

Figure 1. Probability density distributions for the biotite-speckled psammite in the Bimba Formation, reproduced from (Page and Conor, in preparation). All four samples contain a few grains (n = 2 - 9) that lie within the 1700-1705 Ma age range. Low Th/U grains and rims are attributed to growth of zircon during the ~1600 Ma Olarian Orogeny.

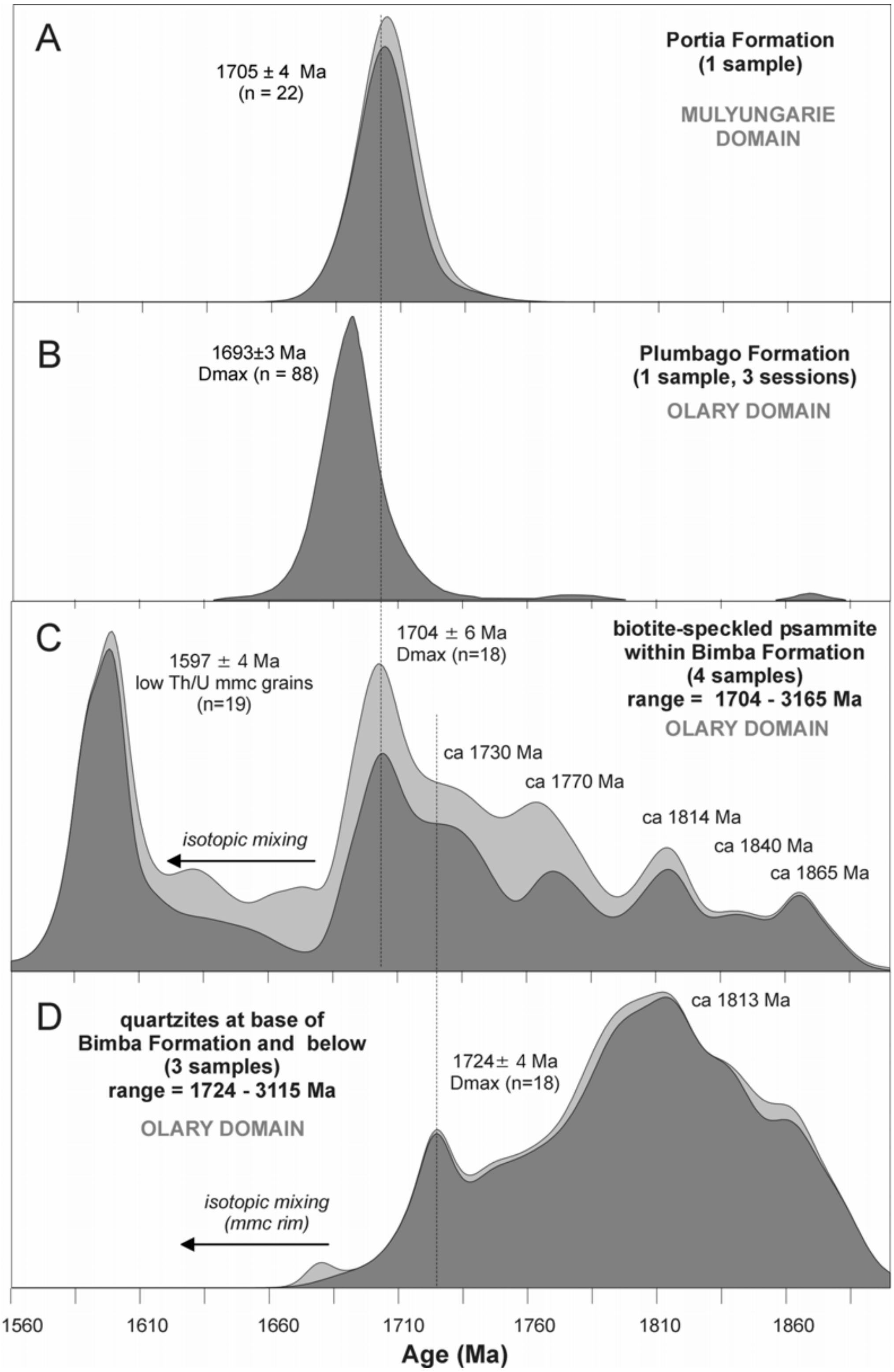

Figure 2. Probability density distributions for sample groups referred to in the text, generated using AgeDisplay (Sircombe, 2004). Dark grey curves illustrate the age distribution of concordance-filtered data at 95–105%. The lighter shaded PDDs include all data. NB: to highlight Dmax ages, the figures illustrate the 1560-1900 Ma interval rather than the full range of data. R.W. Page generated data for the Plumbago Formation and biotite-speckled psammites.

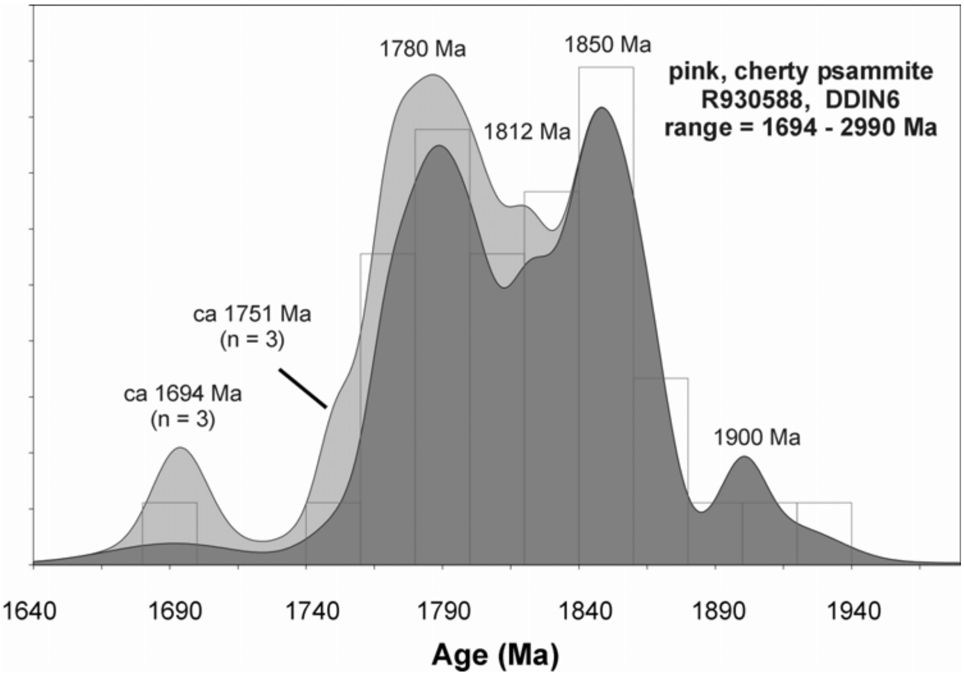

Figure 3. Probability density distribution for the pink, cherty psammite at Polygonum. Shading of curves as for Fig. 1. Total number of analyses = 61. Twenty reconnaissance analyses of a second sample yielded an age range of ca 1787-3600 Ma. NB: to highlight Dmax age, the figure illustrates the 1640-1900 Ma interval rather than the full range of data.

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BHEI 2006: What's Hot

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The state of exploration

Record high prices for most commodities have stimulated mineral exploration world-wide. Australian Bureau of Statistics (ABS) surveys indicate that Australian mineral exploration rose 24% in 2005 (calendar year) to $1136 million, the highest amount since 1998. Most commodities showed strong increases in exploration spending, especially base metals which increased by 55% to $320 million (copper up 90%) and iron ore by 55% to $152 million. Uranium exploration spending more than doubled, but gold exploration was down 7% on the previous year. Year-to-date information suggests that spending on mineral exploration will reach $1250 million in 2005-06.

Exploration activity has increased significantly in both South Australia and New South Wales (up 79% and 53% respectively in 2005 over 2004) with base metal exploration spending up 72% and 43% respectively in each state. This increase has helped reinvigorate exploration across the Curnamona Province. The entire province is covered by exploration tenements and exploration expenditure in the Province has doubled over the past 5 years.

Exploration in and around Broken Hill has spread from new operators on the 'Line of Lode' to a raft of new exploration companies and major multinational miners exploring the Curnamona Province for copper, lead, zinc, gold, nickel, Platinum Group Elements (PGEs), and uranium in a wide range of target types, reflecting both the proven high mineral endowment and the unexplored potential of the Curnamona Province. Uranium is clearly a 'hot' commodity with exploration levels not seen since the early 1970s. The wealth of pre-competitive geoscience information and new knowledge generated by the BHEI partners, industry, and university researchers provides a sound basis for an exciting new period of discovery.

Line of Lode Advances

The giant Broken Hill 'Line of Lode' has produced more than 200 million tonnes of ore since mining commenced in 1885. As in the past, the lode and nature of Broken Hill Type (BHT) Pb-Zn-Ag mineralisation continue to foster the growth of new generations of miners such as Perilya Ltd and CBH Resources Ltd.

- Within the southern and northern operations, Perilya has delineated new mineral resources and ore reserves. At the North Mine, a recent study resulted in an inferred resource of 4.2 million tonnes (Mt) at 11.2% Zn, 13.7% Pb and 214g/t Ag with options for accessing and mining this resource currently under consideration. The Perilya Board has approved ‘in principle’ the staged development of an exploration decline to achieve the necessary confidence prior to considering full development of the Potosi orebody (Potosi North inferred resource 0.23 Mt @ 12.9% Zn, 7.2% Pb; Potosi inferred resource of 1.6 Mt @ 12.7% Zn, 2.8% Pb).

- CBH Limited’s Western Mineralisation (10.1 Mt @ 4.9% Zn, 3.5% Pb and 43g/t Ag) is offset by a fault and repeated as the Centenary Mineralisation. Drilling by CRA in the 1980s outlined 6.7Mt @ 6% Zn, 2.3% Pb and 32g/t Ag using a 5% (Pb+Zn) cut-off.

Curnamona Province Developments

The Curnamona Province is prospective for a wide range of mineral commodities and deposit types in addition to the BHT Pb-Zn-Ag mineralisation. Exploration is currently being conducted for copper, gold, uranium, nickel and PGEs by a range of junior explorers and major multinational mining companies. Some of the more interesting intersections and outcomes reported in the past year are listed below.

Zn-Pb-Ag

Broken Hill Type mineralisation occurs regionally throughout the outcropping block and covered areas of the Mundi Mundi Plain, extending north and south of Broken Hill.

- Perilya Ltd reported that drilling of geochemical anomalies in the Sterling Vale area, 12 km southwest of Broken Hill, intersected high-grade zinc mineralisation at several prospects including: 5 m @ 24.9% Zn, 0.2% Pb and 6g/t Ag at the 1130 anomaly; 6 m @ 9.9% Zn and 6 m @ 9.5% Zn at Smith’s prospect; and 2 m @ 17.8% Zn, 1.3% Pb and 60g/t Ag and 5 m @ 6.4% Zn and 13g/t Ag at Henry George.

- Stellar Resources Ltd intersected low grade mineralisation over a broad area in drilling at its Goldfinger gravity anomaly 20 km south of Broken Hill which was identified in the regional Falcon™ airborne gravity gradiometer survey.

- PlatSearch NL has signed with Teck Cominco Australia Pty Ltd on the Stephens-Centennial Pb-Zn-Ag prospect at Broken Hill. Teck can earn a 75% interest in the Stephens-Centennial tenement by completing expenditure of $3 million within 3.5 years and will undertake hyperspectral and geochemical surveys and interpret hyperspectral data.

- Minotaur Exploration, in JV with the Japan Oil, Gas and Metals National Corporation (JOGMEC), is exploring a region straddling the SA-NSW border for Broken Hill Type mineralisation using gravity data.

Copper-Gold

The potential of the Curnamona Province to host copper and gold deposits, especially of the IOCG type has been highlighted since the early days of the BHEI by advances in geological knowledge that showed the geological similarities to the major IOCG deposit-bearing Gawler Province and the Cloncurry District of the Mt Isa Inlier, notably the presence of early Mesoproterozoic magmatic rocks, the thermal history, widespread alteration, and association of Cu-Au mineralisation with iron oxides. This potential is borne out in the widespread known mineralisation and continuing encouragement from drilling at a number of prospects. Most lie in the central Curnamona Province beneath sedimentary cover over the Benagerie Ridge where a mineralised copper-gold horizon wrapping around a series of structural domes extends over 400 km.

- Havilah Resources NL have undertaken substantial drilling programs at the Kalkaroo Cu-Au-Mo, Benagerie (Portia Au, North Portia Cu-Au), and Mutooroo Cu-Co prospects and reconnaissance drilling at the Eurinilla Dome Cu-Au-Mo prospect. Havilah has updated its mining scoping study and financial model for the Kalkaroo Cu-Au-Mo deposit, 90 kilometres WNW of Broken Hill in South Australia. An optimized open pit to an average depth of 230 m incorporates 70 Mt of ore at a grade of 0.47% Cu, 0.46g/t Au and 124ppm Mo, equivalent to 11 years production at 31,000 t Cu, 95,000 oz Au and 820,000 kg Mo pa. Mutooroo has an 'in-pit' resource of 11.5 Mt @ 1.1% Cu and 0.1% Co. Mineralisation at these localities is hosted by Willyama Supergroup metasedimentary rocks typically stratabound near the interface between the lower magnetite bearing and upper, more reduced, less magnetic parts of the succession.

- Havilah also reported breccia-vein hosted mineralisation (oxide copper ore associated with native copper) at their West Kalkaroo prospect where drill intersections included 78 m of 0.5% Cu and 0.75g/t Au from 75 m depth. This follows the discovery of mineralisation in a dioritic intrusion at Kalkaroo South last year.

- At their North Portia project, Havilah reported oxide copper and gold intersections including 38 m @ 3% Cu, 0.66g/t Au and 36m @ 1.6% Cu, 1g/t Au, with appreciable associated Mo. Resource drilling is in progress.

- Exco Resources NL reported significant progress with the development of its White Dam heap leach gold mine (total resource of 257,000 oz) in the Olary region following the successful negotiation of a Native Title agreement and the purchase of a 2 Mta heap leach process plant. Plant construction should be completed late in 2006 with gold production expected to commence in early 2007. White Dam, a greenfields discovery by MIM utilising surface geochemistry in the 1990s, has indicated and inferred resources of 7.32 Mt @ 1.09g/t Au for 257,000 oz. Mineralisation is in vein-like leucosomes in Willyama Supergroup quartz-feldspar-biotite gneiss.

- Western Plains Gold Ltd reported intersections of anomalous gold values within the upper portions of an ironstone body at the K1 prospect at their Mulyungarie project, 50 km northwest of Broken Hill on the Mundi Mundi plain.

Nickel-PGE

- Golden Cross Resources Ltd has entered into an agreement with Inco Australia Limited for a farm-in under which Inco will explore nickel-platinum-copper-bearing ultramafics extending for over 20 km to the south from Mt Gipps, through Little Darling Creek, Red Hill, Rockwell and the Little Broken Hill Gabbro. At Little Darling Creek, old workings contain high grade Ni-Cu-PGE lodes, and at Red Hill there are old Ni-Cu-PGE(Pt) workings and a 40m mining shaft, reported to have been in Ni-Cu-Pt mineralisation for its full extent.

- Golden Cross also reached agreement with JOGMEC to farm-in to its exploration properties in the Moorakie-Mulga Springs area northwest of Broken Hill which contain ultramafic rocks prospective for Ni and PGE.

Uranium

Tertiary sediments and palaeochannels in the Frome Embayment overlying the basement rocks of the Curnamona Province host a number of uranium deposits and prospects including Heathgate Resources' Beverley in situ leach (ISL) uranium mine – the largest of its type in the world – which produced 977 tonnes of U_3O_8 in 2005. Further south in the Province, SXR Uranium One Inc is at an advanced stage with planning for the development of the Honeymoon Tertiary palaeochannel sediment-hosted deposit as an ISL operation. Honeymoon contains an indicated resource of 2900 tonnes U_3O_8 @ 0.24%. The region is a prime area for uranium exploration for both sediment and basement-hosted uranium mineralisation styles. Exploration is currently focussed around a number of known deposits and occurrences (e.g. Gould's Dam, Radium Hill, Mt Gee).

- The most significant new discovery is the Beverley 4 deposit (8 km northwest of Beverley) discovered in 2005 where Quasar Resources Pty Ltd recently announced new high grade uranium intersections including 9.0 m @ 1.66% pU_3O_8, 9.5 m @ 0.97% pU_3O_8, and 11.0 m @ 0.80% pU_3O_8 (pU_3O_8 refers to the U_3O_8 grade as determined from PFN logging). Work is continuing to drill out the high-grade part of the Western Zone to enable a JORC-compliant mineral resource estimate later this year.

- At the Mt Painter iron oxide breccia-hosted deposits (late Ordovician age?), Marathon Resources Ltd has recalculated uranium resources from previous exploration (Mt Gee deposit, inferred resource 25,323 tonnes U_3O_8 @ 0.0847%) and has undertaken further drilling to confirm the grade of mineralisation.

- Other companies exploring for sediment hosted uranium in palaeochannels in the Curnamona region include Afmeco, Curnamona Energy Ltd, Scimitar Resources Ltd and Red Metal Ltd. Past exploration in the Crockers Well-Mt Victoria area has located extensive areas of uranium mineralisation in Mesoproterozoic granites and Willyama Supergroup metasedimentary rocks. PepinNini Minerals Ltd has released an inferred resource for prospects in the area (6,740 tonnes U_3O_8 @ 0.053%) and has identified numerous prospective areas using radiometrics.

Geothermal Energy

An interesting recent addition to the Curnamona Province exploration scene is geothermal exploration. Although conducted separately from mineral exploration, the search for heat producing rocks, particularly radiogenic granites, beneath thick insulating sedimentary cover overlaps with concepts driving uranium and IOCG exploration in the Curnamona region.

- Petratherm Ltd has completed geothermal exploration holes at Callabonna and Paralana. Both holes produced encouraging temperature gradients.

- Havilah Resources' spin-off company Geothermal Resources Ltd plans to explore for geothermal energy in the west of the Curnamona Province where large granite bodies overlain by Neoproterozoic and Cambrian sedimentary cover are interpreted from gravity data and from the 2003-2004 PIRSA-*pmd*CRC*-GA deep crustal seismic survey data. The granite is interpreted to be similar to the uranium-bearing granites cropping out in the Crockers Well area.

Margins of the Curnamona Province

The Koonenberry Belt wraps around and defines the eastern margin of the Curnamona Province in NSW. The exposed late Proterozoic to late Cambrian sediments and volcanic rocks form a segment of the late Cambrian Delamerian Orogen and are prospective for gold, copper, nickel and PGEs.

- Black Range Minerals Ltd has been actively exploring the Grasmere deposit 140 km northeast of Broken Hill and its exploration licences cover more than 600 km^2 of the Koonenberry Belt. The Grasmere copper deposit has an inferred resource of 5.75 Mt @ 1.03% Cu, 0.35% Zn, 2.3g/t Ag and 0.05g/t Au. Recent results confirm that high-grade copper mineralisation at the newly discovered Peveril prospect (located 2 km along strike from the Grasmere copper deposit) extends over more than 1,100 m of strike. Recent intersections include 11 m at 2.04% Cu and 6.30g/t Ag from 52 m, 5 m at 2.28% Cu and 5.28g/t Ag from 225 m, and 5 m at 2.02% Cu and 5.94g/t Ag from 66 m.

- Inco Australia Limited has taken a large ground holding in the Koonenberry Belt and other companies, including Mithril Resources Ltd (nickel) and Graynic Minerals Ltd (tungsten), have also taken interest in the area.

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A deep seismic reflection transect across the Curnamona Province from the Darling Basin to the Flinders Ranges

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Introduction

In 1996-97 a consortium consisting of the New South Wales Department of Primary Industries – Mineral Resources, Geoscience Australia and the Australian Geodynamics Cooperative Research Centre acquired 294.6 km of explosive (dynamite) source deep seismic reflection data in the Curnamona Province in New South Wales from the South Australian border eastwards to the Darling Basin (Gibson et al., 1998). In 2003-04, another consortium consisting of Primary Industries and Resources South Australia (PIRSA), the Predictive Mineral Discovery Cooperative Research Centre (***pmd****CRC*) and Geoscience Australia acquired 198 km of vibroseis source deep seismic reflection data in the Curnamona province in South Australia from the New South Wales border to the Flinders Ranges (Goleby et al., 2006).

The data from the original 1996-97 seismic survey have been reprocessed using current seismic processing techniques so that we can combine the results of the two surveys into a single 400 km long transect across the entire Curnamona Province from the Darling Basin in the east to the Flinders Ranges in the west. This consists of combining several seismic lines (96AGS-BH1B, 96AGS-BH1A and 03GA-CU1, Figure 1) into a single transect.

Seismic Acquisition and Processing

The ~ 400-km long seismic reflection transect that crosses the entire Curnamona Province consists of two deep seismic reflection projects: the 1996-97 Broken Hill Seismic Survey as a part of the Broken Hill Exploration Initiative (BHEI) and the 2003-04 Curnamona Seismic Survey. This transect presented here includes the 96AGS-BH1A and 96AGS-BH1B dynamite-source lines (~ 215 km) and the 03GA-CU1 vibroseis-source line (~198 km). The 96AGS-BH1 seismic line (Lines 1A and 1B) begins at the South Australia-New South Wales border and then continues in a southeasterly direction to the Darling River. The 03GA-CU1 line also started at the South Australia-New South Wales border and continued in a westerly direction towards the Flinders Ranges (Figure 1). In this paper, we present results of combined vibroseis and re-processed dynamite seismic data that includes Line 03GA-CU1 and 96AGS-BH1A-1B.

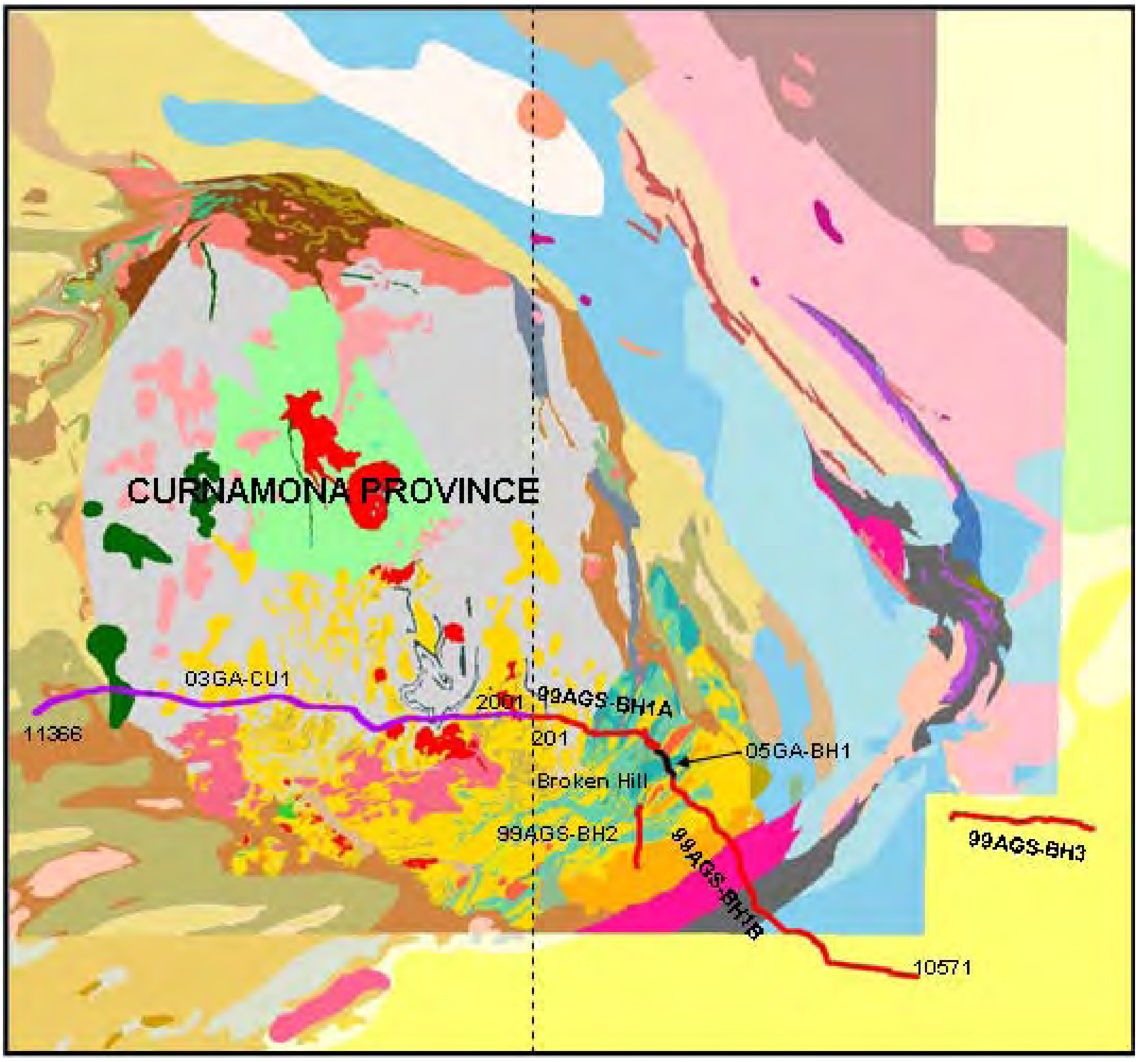

Figure 1. Map showing the solid geology of the Curnamona province, the locations of the deep seismic lines in SA and NSW, and the location of the 2005 high resolution line to the east of Broken Hill.

1996-97 Broken Hill Dynamite Seismic Reflection Survey

The Broken Hill Seismic Project was carried out during April-August 1996 but was not finished until a follow-up survey in June 1997 due to weather conditions. The survey consisted of four seismic lines 96AGS-BH1A (52.92 km), 96AGS-BH1B (191.92 km), 96AGS-BH2 (24.24 km) and 96AGS-BH3 (55.52 km) with a total length of 294.6 km, including overlaps. The lines 96AGS-BH1A and 96AGS-BH1B overlap north of Broken Hill in a ‘bow-tie’ for ~10 km. The low fold seismic reflection data were collected with an explosive source. A summary of acquisition parameters is given in Table 1.

These dynamite deep reflection data were reprocessed using new processing techniques to be able to match seismic images obtained from low (6-12) fold explosive data with high (60) fold Curnamona vibroseis data. The seismic data were re-processed using the Disco/Focus seismic processing package. The processing steps, such as an application of refraction and residual statics, velocity analysis, vertical stacking techniques and spatial migration in the time domain, improved the resolution of seismic data. The major improvement in resolution of the dynamite

Table 1. Summary of acquisition parameters for Broken Hill Seismic Survey, 1996-1997, Lines 96AGS-BH1A and 96AGS-BH1B.

LINE	96AGS-BH1A	96AGS-BH1B
AREA	Broken Hill Block	Broken Hill Block - Murray Basin - Darling Basin
DIRECTION	W to E	NW to SE
LENGTH	52.96 km	162.0 km
STATIONS	100 – 1423	1498 – 5442
CDP RANGE	201 – 2842	2996 – 10571
GROUP INTERVAL	40 m	40 m
GROUP PATTERN	16 in-line @ 2.6 m	16 in-line @ 2.6 m
GEOPHONES TYPE	GSC20D 8 Hz	GSC20D 8 Hz
SOURCE TYPE	Explosive (powergel 3000), 10 kg avg.	Explosive(powergel 3000), 10 kg avg.
SHOT INTERVAL	240 m (nominal)	240 m (nominal)
SHOT HOLE DEPTH	40 m depth avg.	40 m depth avg.
ACQUISITION SYSTEM	Sercel SN368, 120 channels	Sercel SN368, 120 channels
FOLD (NOMINAL)	10	10
RECORD LENGTH	20 sec (approx. 50-km depth)	20 sec (approx. 50-km depth)
SAMPLE RATE	2 msec	2 msec
RECORDING FORMAT	SEGD	SEGD

Table 2. Final processing stream for Broken Hill seismic Lines 96AGS-BH1A and 96AGS-BH1B.

1. Field SEGD data to Disco/Focus format
2. Quality control of the data and trace editing
3. Line geometry and crooked line definition
4. Resample to 4 msec
5. Notch filter (50 Hz)
6. Spectral equalisation
7. Common midpoint (CMP) sort
8. Gain balance (spherical divergence corrections based on velocity function)
9. Refraction statics (datum 100 m) and automatic residual statics corrections
10. Band pass filter
11. Velocity analysis
12. Normal moveout correction (15 % stretch mute)
13. Signal enhancement (digistack)
14. Stack of the data with a range of different velocity functions
15. Vertical sum of selected stacked sections
16. Migration of the data (finite-difference algorithm in time domain)
17. Merging two lines at cross section point
18. Band pass filter
19. Signal enhancement (digistack)
20. Linear gain and amplitude balancing
21. Display data

seismic data appears after a detailed stacking velocity analysis, with an average spacing of 2 to 5 km between picked velocity functions. In real geological environments, not only horizontal layers but also dipping structures are present. To properly stack the conflicting events, higher velocities need to be applied for dipping events and lower velocity for horizontal events. The dip move out (DMO) corrections in the common-offset domain need to be applied for data to achieve this result. An application of normal move out (NMO) corrections attempts to enhance horizontal reflections. The offset distribution of dynamite data is irregular; this makes it very difficult to apply DMO corrections for this data set. To simulate DMO corrections, data were stacked with a range of different velocity functions and were then vertically summed. This alternative technique has improved the resolution of the dynamite seismic data. For the final migration, variable velocity models of 50 to 75% of the stacking velocity values were chosen. The final processing flow for seismic Lines 96AGS-BH1A and 96AGS-BH1B is summarised in Table 2.

2003-2004 Curnamona Vibroseis Seismic Reflection Survey

A deep seismic reflection survey was carried out in the Curnamona Province of South Australia. It passed through the Honeymoon Mine site and close to Kalkaroo, Strathearn and Curnamona stations. The seismic line 03GA-CU1 started at the NSW-SA border, at a point coincident with the 96AGS-BH1A dynamite seismic transect, and continued west towards the Flinders Ranges (Figure 1).

A total of 197.6 km (line 03GA-CU1) of 60-fold seismic reflection data were acquired to 18 s two-way time, using three HEMI-60 (60,000 lb) peak force vibrators. An ARAM 24-bit 240 channel recording system was used to record and correlate the seismic data. Three sweeps 7-56, 12-80, & 8-72 Hz each 12 s long with an 80 m vibration point interval were selected as source acquisition parameters for this survey. Data were processed in the DISCO/FOCUS seismic processing package. A detailed description of the acquisition parameters and details of the data processing were given in Goleby et al. (2006).

The new 400 km long transect combines 6-12 fold explosive and 60 fold vibroseis data, proving that it is possible to reuse old, low fold seismic data by utilising new processing techniques. We demonstrate comparability in the resolution of reprocessed dynamite and new vibroseis data. Reprocessing of the dynamite data using a vertical stacking technique that simulates DMO corrections and a detailed velocity analysis have resulted in an improved seismic section that images dipping structures not detected in the original processing. The combined deep seismic transect images the entire crust of the Curnamona Province from the Darling Basin to the Flinders Ranges.

The Curnamona seismic transect

The combination of several deep seismic profiles into a single transect across the Curnamona Province has provided the first seismic transect across an entire mineralised province in Australia, and has provided insights into the crustal architecture and geological evolution of the province.

The Curnamona Province consists of the Palaeoproterozoic (~1720-1640 Ma) Willyama Supergroup and coeval magmatic rocks. These rocks were deformed and metamorphosed during the ~1600 Ma Olarian Orogeny, which was followed by an early Mesoproterozoic magmatic event. In New South Wales, the transect crosses outcrops of the rocks in the Redan and Broken Hill domains, but in South Australia the Curnamona province is mostly under cover of Neoproterozoic to Cenozoic sedimentary rocks.

Seismic Transect in New South Wales

The original interpretation of the seismic transect in New South Wales by Gibson et al. (1998) indicated that the dominant features seen in the seismic data were a series of reflections that had an apparent dip to the southeast. These reflections were interpreted to represent shear zones, some of which were inferred to cut deep into the crust (e.g. Mundi Mundi Fault and King Gunnia Shear Zone). Upper crustal shear zones to the east of Broken Hill, such as Globe-Vauxhall and Stephens Creek shear zones also dip to the southeast, but were considered to be listric and sole into major subhorizontal detachment surfaces at depths of about 10 km. The direction of tectonic transport was mainly to the northwest, indicating that these shear zones were predominantly thrust faults.

Gibson et al. (1998) considered the Mundi Mundi Fault was an important structure that possibly marked the boundary between the Broken Hill and Olary blocks. It separated a zone of subhorizontal to shallow-dipping reflections to the west from the southeast dipping shear zones to the east. The Moho is relatively flat at about 13 s TWT (~40 km depth).

One key aspect of the interpretation by Gibson et al. (1998, figure 28) was the inference that a rift geometry was preserved to the east of the Stephens Creek Shear Zone at a depth of ~3-6 km. The inferred rift has a width of at least 30 km. At the surface, however, granulite grade rocks with a steeply dipping metamorphic to migmatitic fabric crop out, and this raises the question of how a rift geometry might be preserved beneath these granulite grade rocks?

A recent short high resolution seismic line to the east of Broken Hill (05GA-BH1) has provided a much improved image of the upper 1 s TWT (~3 km) of the crust, including the region between the Stephens Creek and Globe-Vauxhall shear zones (Korsch et al., 2006). This confirmed the apparent southeast dip and thrust geometry of the shear zones.

Reprocessing of the 1996-97 seismic data has resulted in an improved seismic section that images dipping structures not detected in the original processing (Figure 2). For example, the reprocessing has shown the presence of a series of dipping reflections to the west of, but parallel to the reflections defining the Mundi Mundi Fault. These reflections are interpreted to be a shear zone, and it extends the limit of the zone of major southeast dipping shear zones further to the west.

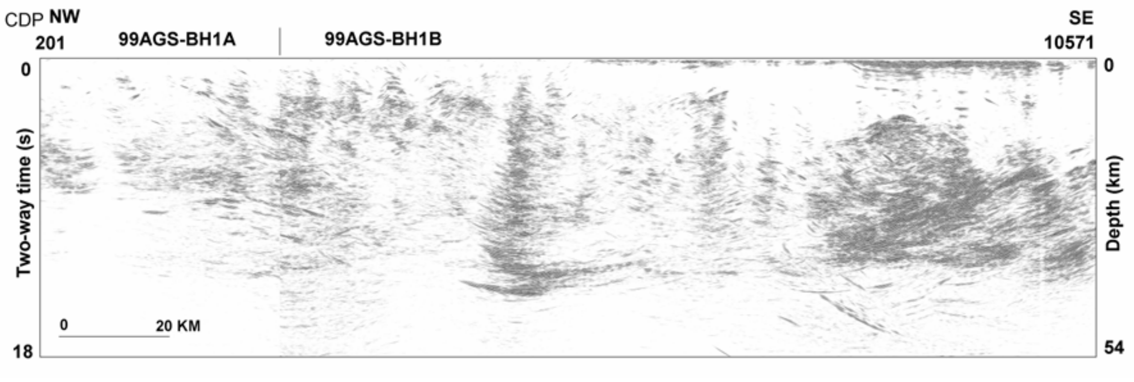

Figure 2. Merged migrated section of seismic lines 96AGS-BH1A and 96AGS-BH1B in New South Wales. Display shows the vertical scale equal to the horizontal scale, at a crustal velocity of 6000 km s-1. Horizontal scale is based on 1 CDP equal 20 m. Semblance filtering has been applied to the section.

Towards the southeast, the southeast-dipping shear zones extend at least to the Rockwell Shear Zone, but the Redan Fault, which marks the southeastern limit of the Curnamona Province, appears to dip to the northwest.

At the surface, the boundary between the Curnamona Province and the Neoproterozoic-Phanerozoic rocks of the Koonenberry Belt and Darling Basin is the northwest-dipping Redan Fault. Crust of very different reflectivity occurs beneath the Koonenberry Belt and Darling Basin compared with that under the Curnamona Province, with the crust to the east being much more reflective (Figure 3). The reflective packages representing the Curnamona Province and the Koonenberry Belt appear to be separated by a major structure that has an apparent dip to the southeast. This possibly represents a crustal suture, with the Koonenberry Belt thrust over the Curnamona Province. The Redan Fault appears to be a high level east-directed thrust above this suture, truncating the suture about 5 km below the surface.

At the eastern end of seismic line 96AGS-BH1B, the Darling Basin is imaged as a series of subhorizontal reflections up to 2 s TWT (~6 km thick).

Seismic Transect in South Australia

The eastern part of the seismic transect in South Australia has a well defined Moho at ~13 s TWT (~40 km depth) with a strongly reflective crust above a non-reflective upper mantle. In the western half of the seismic section, the Moho is not as well defined, but appears to be undulating and slightly deeper than the eastern half (Figure 3).

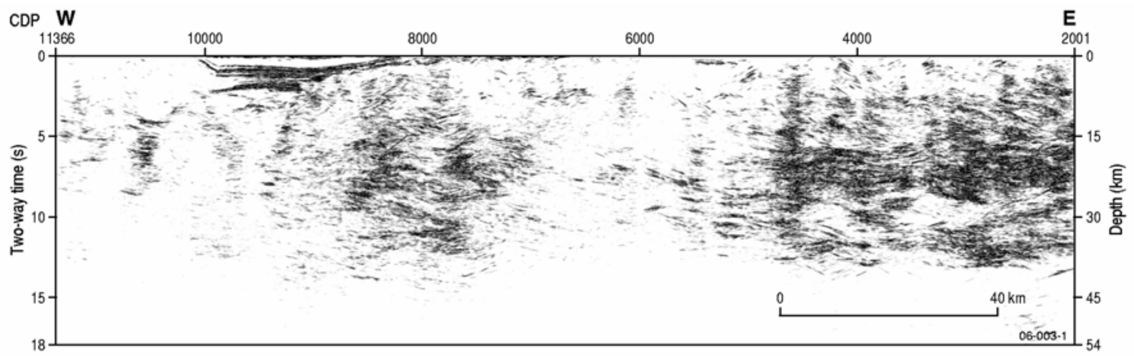

Figure 3. Migrated section of seismic lines 03GA-CU1 in South Australia. Display shows the vertical scale equal to the horizontal scale, at a crustal velocity of 6000 km s-1. Horizontal scale is based on 1 CDP equal 20 m. Semblance filtering has been applied to the section.

In the eastern part of seismic transect 03GA-CU1, near the New South Wales border, there is an upper crustal thrust belt, with east-dipping thrusts cutting the Willyama Supergroup. This thrust belt sits on a “decollement” defined by strong reflectivity at 2-3 sec TWT (~6-9 km depth). This decollement can be tracked westwards across the seismic section almost to a Neoproterozoic-Cambrian basin (~CDP 7500 on Figure 3). The high level thrust belt propagated westwards, with the amount of displacement dying out to the west, and the shortening being accommodated into broad wavelength folds in the near surface. This is consistent with observed fold trends, as the northwest-verging F3 folds in outcrops of the Willyama Supergroup are consistent with apparent west-directed thrusting observed in the seismic transect.

The Kalkaroo prospect, located about 4 km to the north of the seismic line, appears to be associated with second order synthetic faults associated with hanging wall anticlines above a bounding east-dipping fault at depth. The fault beneath the anticline could have been the conduit for fluids moving from the deep crust to upper crustal levels where they could have migrated into favourable depositional sites associated with second order structures.

In the central part of the seismic traverse 03GA-CU1, there is a distinctive bland zone in the middle to lower crust. Its significance is unknown but in terms of its origin it could result from reduced acoustic impedance contrasts due to partial melting, metasomatism, or be a zone of high fluid flow which has homogeneously altered a large part of the crust. It is interesting to note that similar bland zones have been observed on seismic sections in the Olympic Dam and Kalgoorlie regions.

In the central-western part of the seismic traverse, a westward-thickening wedge of Neoproterozoic-Cambrian sediments up to 9 km thick overlies basement. Much of the crust beneath this basin is highly reflective, but it is not as obviously partitioned into subhorizontal layers as the eastern part of the traverse. At the western end of the seismic transect the crust is weakly to moderately reflective beneath a near surface triangle zone consisting of a west-directed thrust duplex. This has affected Neoproterozoic rocks and hence is inferred to have involved Delamerian age deformation.

Superimposed on the crustal reflectivity patterns described above, are a series of crustal-scale narrow zones that we interpret as faults with apparent dips to the east. The western one continues to the west beyond the limits of the seismic section. Two others appear to cut almost the entire crust, from just below the Neoproterozoic basins to the Moho. The eastern two faults represent a zone that partitions the crust into two types with very distinctive seismic properties, one underlying the Willyama Supergroup to the east and the other at great depth below the Flinders Ranges in the west. It is uncertain whether these represent different crustal blocks, or simply different styles or degrees of metamorphic or metasomatic alteration in the same crust, similar to the bland zone further east. If the faults represent a real crustal boundary, it raises the possibility of early amalgamation of terranes to form the deep crust beneath eastern South Australia.

Tectonic Implications

The combined seismic profiles from New South Wales and South Australia provide a holistic view of the crust across the entire Curnamona Province, thus allowing the linking of structures across the state border. Nevertheless, it is difficult to image steeply dipping structures, and also those that are highly deformed. Because the seismic image is one of the present day architecture of the crust, the later structures tend to be the best imaged because they overprint and deform earlier structures, but are not deformed by later events.

The key interpretation is the presence of a linked westward-propagating thrust belt. The thrusts are thick skinned and cut deep into the crust in the core of the orogen in the vicinity of Broken Hill, whereas to the west, principally in South Australia, the thrust belt is thin skinned and consists of a series of thrusts that link onto a shallow detachment at a depth of ~6-9 km. Further west, the thrusts die out and the deformation is expressed as a series of folds above a subhorizontal decollement. This geometry is very similar to that predicted by Davies and Anderson (2000) in their schematic cross section across the Olary Block.

Because the thrust belt includes individual folds and thrusts that are interpreted as F3, it is inferred to have formed late during the Olarian Orogeny. Nevertheless, the structures may have been reactivated during Neoproterozoic and/or Palaeozoic (Delamerian) deformational events. Shear zones exhibiting this timing are well documented at the surface in the southern Curnamona province. Also, Delamerian deformation is seen at the western end of the transect, where Neoproterozoic rocks are intensely deformed.

Conclusions

Key conclusions include:

- The Moho under the Curnamona province is at ~40 km depth, and is slightly undulating in the west.
- In the east, the Willyama Supergroup is cut by a series of southeast dipping shear zones that penetrate deep into the crust.
- No basis was found to interpret an undeformed rift below the highly deformed Willyama Supergroup of the Broken Hill Block.
- In the South Australian segment, the crust is partitioned into several subhorizontal layers. The Willyama Supergroup is possibly confined to being above a decollement at ~ 6-9 km, with thin-skinned deformation in the upper crust. This deformation is part of a thin skinned, westward propagating fold-thrust belt.
- A Neoproterozoic-Cambrian basin up to 9 km thick occurs in the western part of the seismic transect, and intense Delamerian deformation has affected the region at the western end of the transect. East-dipping shears under this basin pre-date the Neoproterozoic, confirming that at least some thrusts are of Olarian age.
- The western limit of the Curnamona Province is defined by a possible suture zone between two different types of lower crust, with the crust in the west below the Flinders Ranges being overthrust by sub-Curnamona crust in the east.

- The eastern limit of the Curnamona province is defined by a crustal scale east-dipping structure that thrusts the Neoproterozoic-Phanerozoic Koonenberry Belt over rocks of the Curnamona province.

We have interpreted major crustal scale structures that cut to the Moho on the deep seismic transect across the Curnamona Province. Age and history of some of the structures are uncertain but they may be important conduits for transporting fluids from the deep crust and/or mantle to the upper crust. If so, do favourable depositional sites exist in the hanging wall in the upper crust above these structures?

Acknowledgements

We thank ANSIR (Australian National Research Facility for Earth Sounding) for acquiring the seismic data in the South Australian portion of the Curnamona province in 2003 and 2004. We especially thank PIRSA and the ***pmd****CRC* for providing additional funds in 2004 to complete the survey because the 2003 phase was washed out after 40 km of data acquisition due to heavy rains. We thank Richard Blewett and David Maidment for their comments on the manuscript. RJK, TF and BRG publish with permission of the Chief Executive Officer, Geoscience Australia; CHHC, RSR and WVP publish with permission of the Executive Director PIRSA Minerals & Energy Resources; BPJS publishes with permission of the Deputy Director General, NSW Department of Primary Industries – Mineral Resources.

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Preliminary results of a high resolution seismic reflection survey at Broken Hill

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Introduction

In 2005, the New South Wales Department of Primary Industries – Mineral Resources and Geoscience Australia combined to acquire a high resolution deep seismic reflection profile approximately 12 km in length immediately to the east of Broken Hill (Figure 1). The energy source was vibroseis, and the new seismic profile followed the route taken by the 1996-97 Broken Hill deep seismic reflection profile 96AGS-BH1B, which was acquired using a dynamite source. The current survey was designed to provide a high resolution seismic image of the uppermost part of the crust across an economically important area along strike from the world class Broken Hill Ag-Pb-Zn deposits using modern acquisition equipment and processing techniques.

Data Acquisition and Seismic Processing

A high resolution 120 fold seismic reflection survey was carried out in August 2005 along a 12 km portion of the seismic line 96AGS-BH1B in the Broken Hill region that was recorded by the Australian Geological Survey Organisation (AGSO) in 1996-97 (Figure 1). The purpose of the new survey was to compare high resolution seismic data with low (6-12) fold explosive seismic data along the same line and to image geological structures at shallow crustal levels (down to ~ 2 s TWT, i.e. ~6 km depth). Two HEMI-60 Vibroseis trucks were used as the energy source. An experimental program to test parameters was implemented prior to seismic acquisition.

A total of 12.2 km of seismic reflection data recorded to 16 s TWT were acquired with 120 fold, except for the last 2 km of the profile where the fold was decreased to 60. A summary of acquisition parameters is given in Table 1.

The seismic data were processed using the Disco/Focus seismic processing package. The application of several major processing steps improved the resolution of seismic data, mainly for the upper two seconds, such as velocity analysis, dip move out corrections in common-offset domain and post-stack migration.

The application of refraction statics for this data set did not improve the seismic data significantly, possibly because the thickness of the weathering layer does not vary much along the line, being only from a few metres to 50 metres with an average thickness about 20 metres. Horizontal ‘layers’ in the very shallow 100-150 ms (eg ~ CDP 2960-3480, Figure 2) correspond to thickening of the refractor model up to 45-50 m in some areas (Figure 2a). The velocity for the refractor underneath the weathering layer (top of bedrock) is very high, varying from 5000 m s^{-1} to 5500 m s^{-1}.

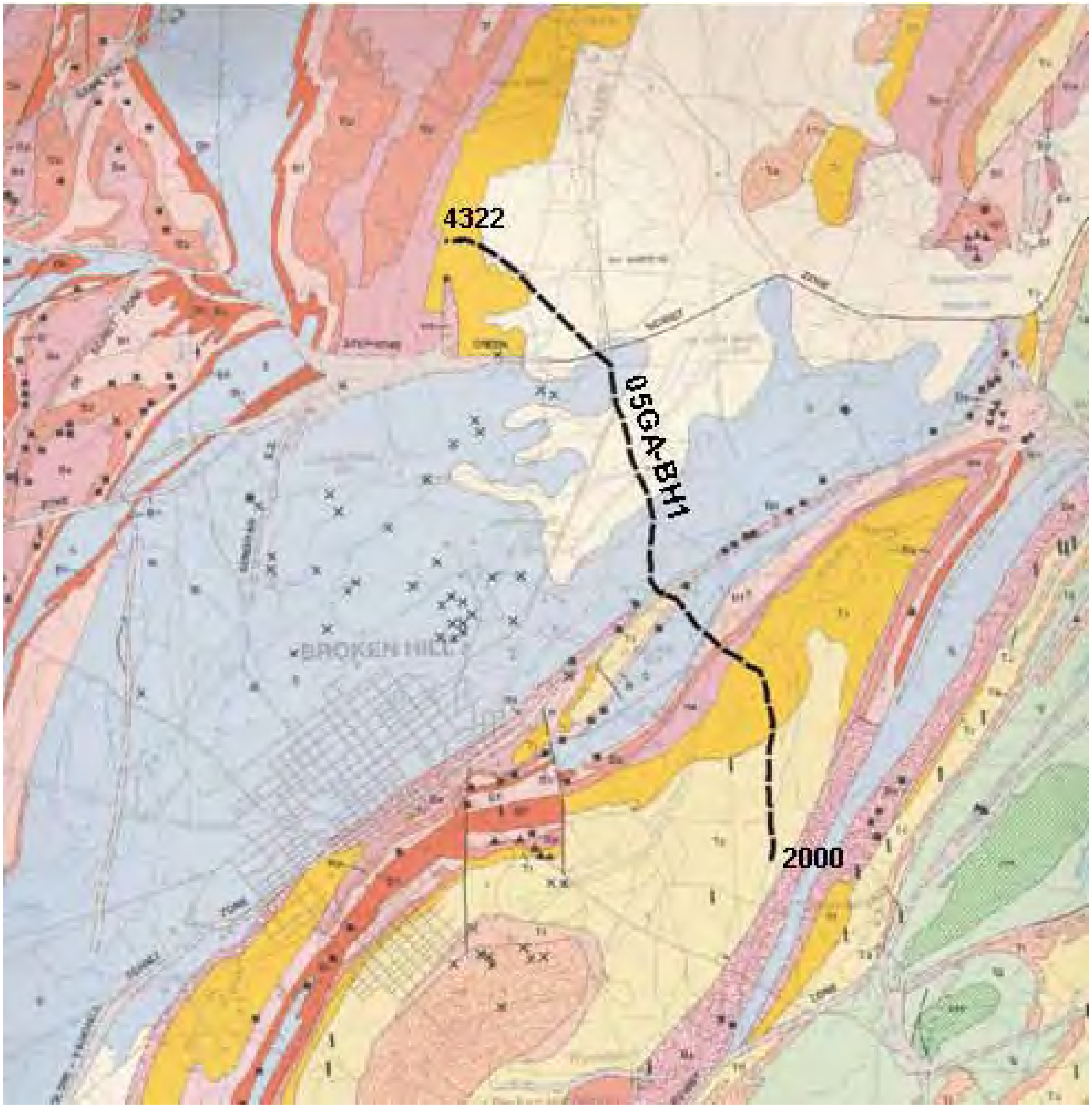

Figure 1. Geological map of the area around Broken Hill showing the location of the high resolution seismic line 05GA-BH1.

Stacking velocity analysis was carried out at two stages during the processing of the seismic data, on average at ~500 m interval along the line, after statics corrections and then after dip move out (DMO) corrections. The major improvement in resolution of the seismic data appears after DMO corrections. The steeper reflections at least of up to 45° at different depth levels were imaged after the stacking of the seismic data with the velocity model obtained after DMO corrections (Figure 2a). Migration utilising stacking velocities estimated after DMO has significantly improved resolution of the imaged structures, due to re-positioning of originally overlapping and intersecting events to their correct spatial positions. Because of the limited length of the line, sensible migration of the data was possible only for the first 2 s.

The final processing stream for the high resolution seismic Line 05GA-BH1 is summarised in Table 2. The new high resolution data has resulted in much better resolution of the geological structures in the shallow part of the section, compared to the regional scale low-fold data recorded using a dynamite source.

Table 1. Summary of acquisition parameters for seismic line 05GA-BH1.

LINE	05GA-BH1
AREA	Broken Hill, NSW
DIRECTION	SE to NW
LENGTH	12.2 km
STATIONS	1000 – 2220
CDP RANGE	2000 – 4322
GROUP INTERVAL	10 m
GROUP PATTERN	12 in-line @ 0.83 m
SOURCE TYPE	2 x IVI Hemi-60
VP INTERVAL	10 m
SWEEP TYPE	Varisweep:12-100 & 20-120 Hz
NUMBER OF SWEEPS	2 x 15 sec
SOURCE MOVE-UP	5 m, 15 m pad-to-pad
CHANNELS	240
FOLD (NOMINAL)	120 (60 for Western end)
RECORD LENGTH	16 sec (approx. 50-km depth)
SAMPLE RATE	1 msec
RECORDING FORMAT	SEGY

Table 2. Final processing stream for Broken Hill high resolution seismic line 05GA-BH1

22. Field SEGY data to Disco/Focus format
23. Quality control of the data and trace editing
24. Line geometry and crooked line definition
25. Resample to 2 msec
26. Spectral equalisation
27. Common midpoint (CMP) sort
28. Gain balance (spherical divergence corrections based on velocity function)
29. Refraction statics (datum 250 m) and automatic residual statics corrections
30. Band pass filter
31. Velocity analysis (1st pass after statics application, 2nd pass after dip move out (DMO) correction)
32. Normal moveout correction (15 % stretch mute)
33. Dip moveout correction
34. Stack of the data
35. Migration of the data (time-space Kirchhoff algorithm)
36. Signal enhancement (digistack)
37. Linear gain and amplitude balancing
38. Display data

Local Geology

This short seismic profile crosses parts of the Broken Hill and Sundown Groups, as well the Rasp Ridge granitic gneiss in the southeast and quartzo-feldspathic granitic gneiss at the northwest end of the line. The rocks are predominantly upper amphibolite to granulite metamorphic grade, with the dips of the predominant metamorphic fabric being from gentle to very steep. The profile crossed several mapped retrograde shear zones including the Globe-Vauxhall Shear Zone, Western Shear Zone, Morgan Street Shear Zone (projected) and the Stephens Creek Shear Zone.

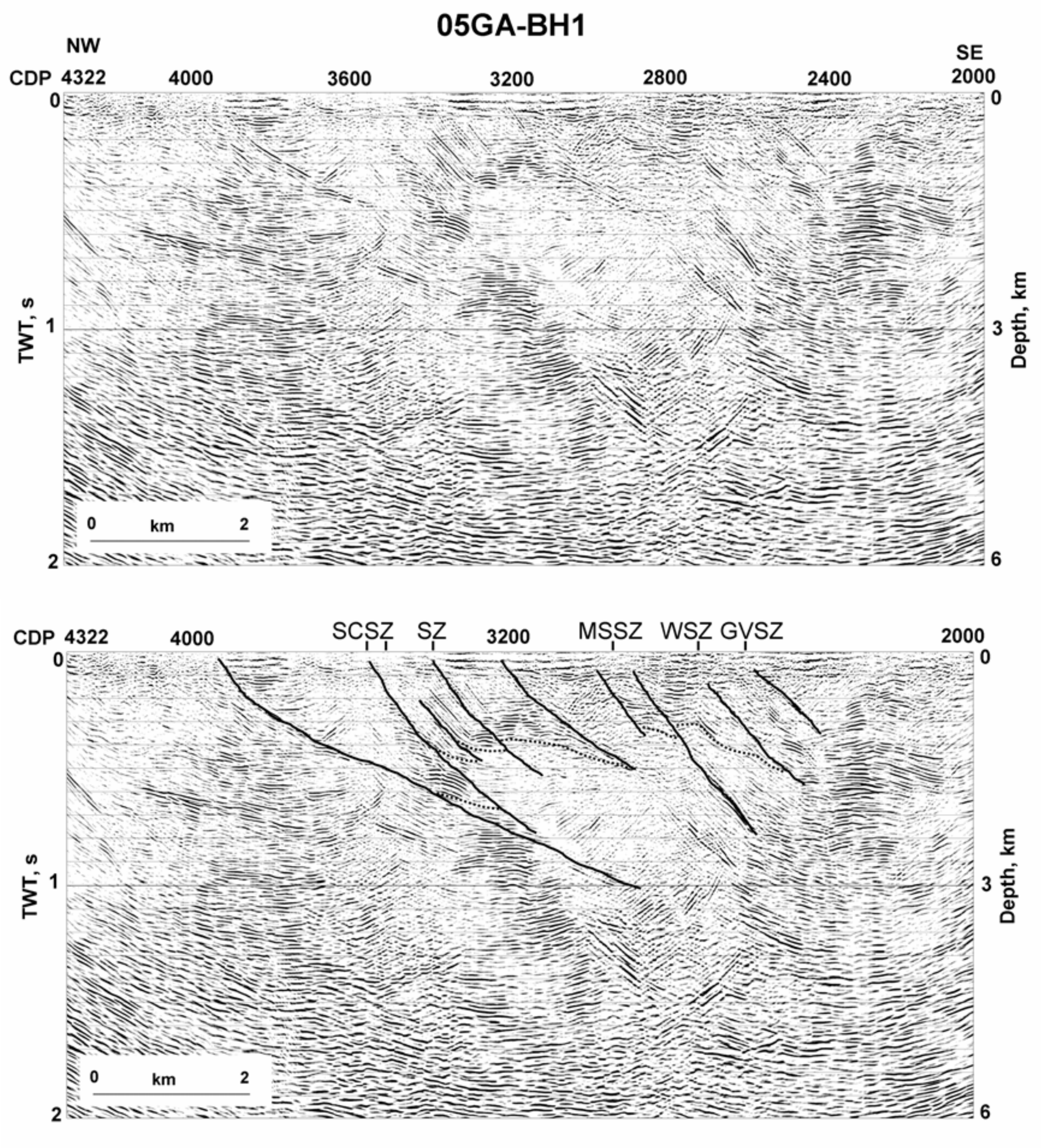

Figure 2. a. Uninterpreted migrated high resolution seismic profile from immediately east of Broken Hill. Display shows the vertical scale equal to the horizontal scale, at a crustal velocity of 6000 km s-^{1}. Horizontal scale is based on 1 CDP equal 5 m. **b**. Preliminary geological interpretation of the high resolution seismic profile from immediately east of Broken Hill showing a series of shear zones with an apparent dip to the southeast. The dotted line is a form surface that marks the base of a series of strong reflections. SCSZ = Stephens Creek Shear Zone, MSSZ = Morgan Street Shear Zone, WSZ = Western Shear Zone, GVSZ = Globe-Vauxhall Shear Zone

Burton (1994) has constructed a series of geological cross sections to the northeast of Broken Hill which are constrained by detailed surface mapping (e.g. Bradley, 1984; Stevens & Bradley, 1993) and by drilling to depths of about 1 km. One of Burton's sections is located near the southeast part of the seismic line and shows the Western and Globe-Vauxhall shear zones dipping steeply to the southeast, with dips of 75° and 50-70° respectively.

The interpretation of the 1996-97 deep seismic line by Gibson et al. (1998, figure 28) also shows the Globe-Vauxhall and Stephens Creek shear zones dipping to the southeast, with dips of 35-60° and 40° respectively. In a composite cross section drawn about 20 km to the southwest of the seismic line, Stevens (2004) shows the Globe-Vauxhall Shear Zone dipping to the southeast at approximately 65°.

Preliminary Interpretation

The preliminary interpretation presented here focuses on the upper one second two-way travel time (~3 km). The most apparent features in the upper 1 s of the section (Figure 2a) are a series of reflections that have an apparent dip to the southeast. When compared to the mapped geology (Bradley, 1984; Stevens & Bradley, 1993), these can be interpreted as a series of retrograde shear zones (Figure 2b). They are well imaged because they are relatively planar and developed late in the geological history and have not been subjected to the polyphase deformation during the prograde metamorphic events.

Using the apparent dip of the shear zone and the trend of the seismic line, coupled with the mapped strike direction of the shear zones, true dips can be calculated (on the understanding that the seismic section is displayed at V:H = 1, assuming an average crustal velocity of 6000 m s^{-1}). For the Globe-Vauxhall Shear Zone the dip is about 45°, the Western Shear Zone is 50°, the Morgan Street Shear Zone is about 55° and the Stephens Creek Shear Zone is 50°. These dips are slightly lower than the dips observed in drilling in the uppermost kilometre.

Besides the mapped shear zones, at least two other sets of reflections are interpreted as shear zones; these occur at about CDPs 3200 and 4000 (Figure 2b). At CDP 3200, the Proterozoic geology is covered by alluvium, but a shear zone has been interpreted in this position on the solid geology map interpretation by Maidment and Gibson (2000). The reflections at about CDP 4000 are shallower dipping and more listric in form than the shear zones further to the southeast and it can be traced to at least 1 s TWT (~3 km depth). The mapped geology does not favour a substantial shear in this position, so further investigation is required.

In terms of the geology between the shear zones, the packets of rock are mostly steeply dipping and hence are not conducive to being imaged by the seismic technique. Nevertheless, there is a general correspondence between the mapped geology and the seismic reflections between the retrograde shear zones. For example, between the Western and Morgan Street shear zones, the mapped dips of the fabric, particularly bedding, is generally shallow, but ranges up to 50°. Gently dipping reflections occur on the seismic section (Figure 2a) between these two shear zones. In another example, the rocks to the southeast of the Globe-Vauxhall Shear Zone, dip predominantly to the northwest, and weak to moderate reflections in the seismic data are consistent with this observation.

Between the Globe-Vauxhall and Stephens Creek shear zones, the uppermost part of the crust is seismically reflective. Beneath these reflections, however, there is a zone of low reflectivity, which starts at a depth of about 400 ms (~1-1.2 km). This is not an artefact of acquisition or processing because strong reflections are imaged below it. There are several possible interpretations, including granite gneiss, albite rocks of the Thackaringa Group or a zone of alteration or migmatisation. The upper surface of this zone appears to be displaced by the retrograde shear zones (Figure 2b), suggesting that the zone of low reflectivity formed earlier than the shear zones. This area corresponds with a gravity low, unexpected from the Sundown Group metasediments found at the surface.

The seismic line crosses the northeastern extension of the line of lode between the Globe-Vauxhall and Western shear zones. The line of lode is not obvious in the seismic section, possibly because it is less than the minimum horizontal size imaged by the seismic method here, which is approximately 100 m.

In conclusion, the new high resolution seismic data to the northeast of Broken Hill has resulted in much better resolution of the geological structures in the shallow part of the section, compared to the old low-fold data recorded using a dynamite source. It has provided a good correlation with some aspects of the mapped geology and, in particular, has allowed the recognition of several retrograde shear zones down to depths of as much as three kilometres.

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Investigations stemming from the 2003 Broken Hill airborne gravity gradiometer survey

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Introduction

An airborne gravity gradiometer (AGG) survey was flown over the Broken Hill region in early 2003 using the Falcon® AGG system (Lane et al., 2003). The survey generated several new mineral exploration targets which are discussed in Anderson et al. (2006). Furthermore, the survey was the first of its type to be carried out for Australian government organisations, and the first time that AGG data had been acquired specifically for release to the public. This provided a unique opportunity for a range of investigations to be carried out, and the results from a number of these projects are presented in this paper.

AGG methods and pre-competitive data acquisition

Geoscience Australia (GA) has an ongoing interest in new technologies that could be used by government geoscience agencies to provide publicly available pre-competitive geoscience information. The Broken Hill Survey was studied in detail to analyse the strengths and weaknesses of the Falcon® AGG system from a regional mapping perspective. The criteria that GA used to characterise the system were likely to be very different to those that would be used by explorers, reflecting the value judgements for pre-competitive information. In this instance, the criteria included the capacity of the technology to be used at a range of line spacings, an assessment of the data "shelf life" before they would need to be replaced or discarded, and establishing whether there was a suitable quantitative approach that could be used to integrate data from different methods and surveys into regional compilations. The Falcon® assessment was a snapshot of a system's characteristics at a specific moment in time, and if subsequent developments were to significantly alter the system, the data characteristics would need to be re-evaluated.

Data characteristics

The processed AGG data relate to a smooth drape surface approximately 80 m above the ground surface. Filtering is applied to the observed AGG data to suppress high amplitude short wavelength noise in data. The filtering applied to the Broken Hill Falcon® data was shown to be consistent with a 6th order Butterworth filter with a central wavelength of 400 m (Lane, 2004). The accuracy of the long wavelength information is known to diminish at wavelengths exceeding the smallest dimension of the survey area (Boggs and Dransfield, 2004), which is approximately 20 km in this instance. The standard deviation of the noise in the Falcon® vertical gravity gradient (GDD) data appeared to be in the 5 to 8 Eo range, consistent with estimates derived by Hinks et al. (2004) for the Falcon® system at another location around this time. Based on estimates provided by Boggs and Dransfield (2004), the standard deviation of the noise in the Falcon® vertical gravity (gD) data was thought to be around 4 $\mu m/s^2$ with a bandwidth of 0.4 to 20 km (Lane, 2004). These performance figures for the Falcon® system are essentially the same as those used by Dransfield (1994) to simulate the response over a synthetic density model of the Broken Hill region (i.e., 12 $Eo/\sqrt{Hz}$ noise with a low pass filter with a cut-off wavelength of 500 m). These results are reproduced in Van Kann (2004) along with a simulation using far more desirable AGG system characteristics of 1 Eo/√Hz and a 100 m low pass filter.

Combining ground and airborne gravity data

The Australian National Gravity Database contains a large number of ground vertical gravity observations both within and surrounding the survey area. In places, these pre-existing ground data have better resolution than the airborne data, but in most parts of the survey area, the airborne data improved the resolution. It is desirable to be able to integrate the ground and airborne data into a single regional dataset and a procedure to combine the datasets was described by Lane (2004). The procedure is unfortunately complicated because the two sets of observations relate to different irregular drape surfaces, both datasets contain noise, the airborne data are band-limited by low-pass filtering of the short wavelengths and limitations of the acquisition technique at long wavelengths, and there are few commercial software options for estimating a best-fitting surface to overlapping noisy measurements.

It is impractical because of noise levels to downward continue the airborne data to ground level without additional low-pass filtering. This would compromise the spatial resolution of these data and negate the purpose of the data integration. The procedure was thus to upward continue the ground data to match the location of the airborne data on a drape surface at the mean terrain clearance of the survey. The long wavelengths were removed from both datasets and uncertainty values assigned to each observation. A smooth surface was then derived that would best fit the combined dataset. Finally, the long wavelengths from the ground data were restored. The outcome for a portion of the airborne survey area is shown in Figure 1. A seamless result is obtained, but this requires compromises to be made to accommodate the characteristics of both datasets.

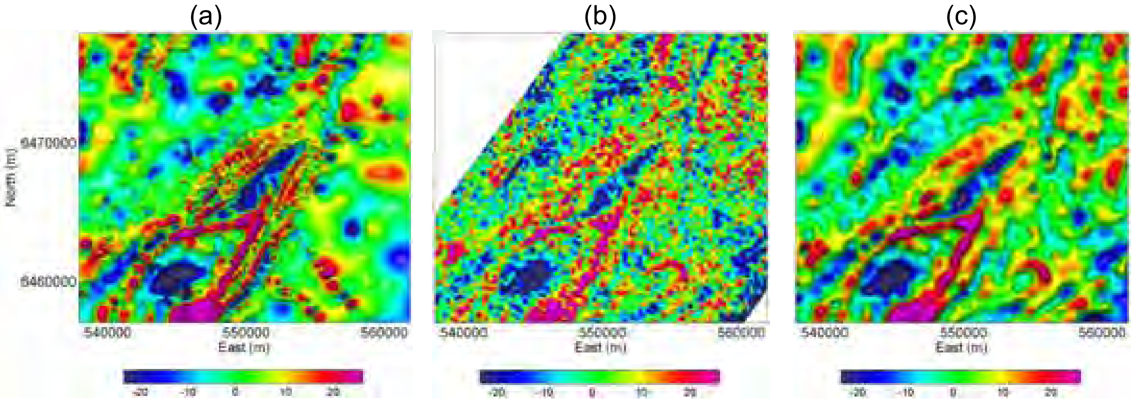


Figure 1. Results of integration of ground and airborne data for a portion of the airborne survey area, presented as vertical gravity gradient data (Eo) on a drape surface at 80 m terrain clearance. (a) Ground G_{DD} data. (b) Airborne G_{DD} data. (c) Combined G_{DD} data.

Modelling and interpretation

BHP Billiton and Stellar Resources have performed 3D inversions of both the gravity and magnetic data from the Broken Hill survey (e.g., Anderson et al., 2006). BHP Billiton have also applied their SolidEarth™ modelling technology to combine the density and magnetic susceptibility inversion results (Tom Whiting, pers. comm.). SolidEarth™ modelling is a form of neural network or self-organising map (SOM) processing that is used to analyse multiple property models (AIM Resources, 2006). The output is a distillation of the information into a series of map categories. This can highlight regions that have a prospective signature, some of which may have been overlooked during manual inspection of the individual inversion results.

Effects of data filtering on inversion of gravity gradient data

The low pass filtering that is applied to AGG data reduces the amplitude of anomalies and makes them broader. Programs that simulate the gravity response from these systems need to reproduce this filtering if they are to be used to directly compare a calculated response with survey data. Using the Broken Hill data as an example, this issue has been investigated for 3D voxel-type inversions such as those used by Stellar Resources and BHP Billiton (Lee, 2006; Lee et al., 2005).

It was shown that inversions that ignore the filtering will have significant artefacts for source bodies that are narrow and at shallow depth relative to the wavelength of the low pass filter. Since the filtering in the case of the data from the 2003 Broken Hill AGG Survey is equivalent to a 6th order Butterworth filter with a 400 m filter length, this will impact most of the mineral exploration targets at depths of less than a few hundred metres.

Results of an inversion of vertical gravity gradient data over the Goldfinger Prospect in the southern part of the survey area are shown in Figure 2. When the effects of filtering are included in the inversion calculations, the anomalous bodies are more clearly resolved and have a larger density contrast.

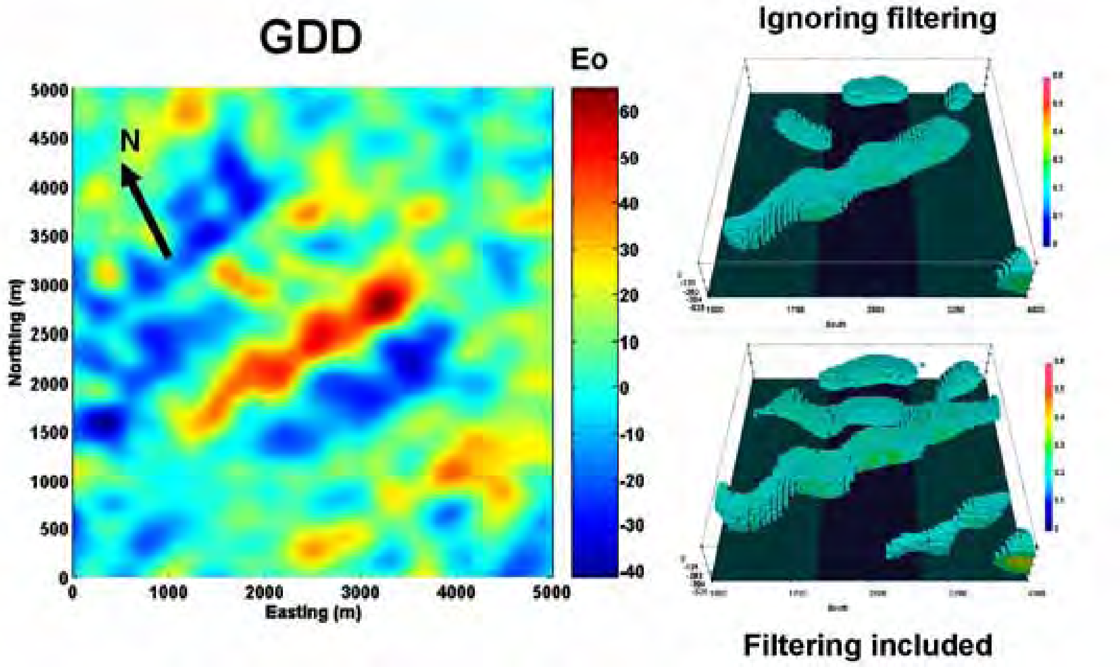


Figure 2. Inversion results for a portion of the AGG dataset over the Goldfinger Prospect. The G_{DD} data on the left have been rotated counter clockwise by 36° such that the flight lines were oriented parallel to the left edge of the image. Density iso-surfaces enclosing material with +0.2 t/m^3 contrast are shown on the right. The result which allowed for filtering of the observed data had bodies which were more compact, with larger density contrasts and with larger depth to top. Reproduced from Lee (2006).

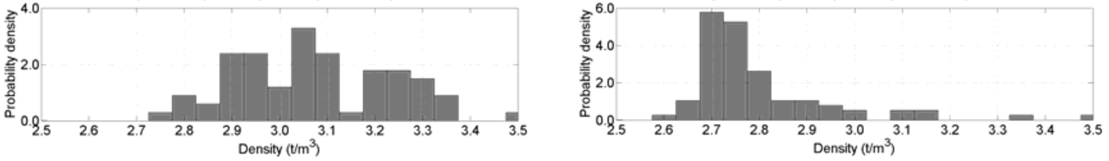
Mass density properties

Mass density properties are the link between gravity response and geological features. Previous work has indicated that the relationship between the two is complex in the Broken Hill region. The mapped units at the Group level can be thought of as a mixture of end members, typically a host lithology (e.g., metasedimentary rock) plus variable proportions of amphibolite, pegmatite and granite gneiss. To deal with this complexity, we need to know the properties of the end members and their proportions in each of the map units. The statistical analysis of mass density properties in Lane et al. (2003), based on approximately 750 density measurements from Maidment et al. (1999), is extended here by considering around 1800 measurements recorded by Pecanek (1975) for samples of drill core from the Line-of-lode. This has enabled better estimates of the properties of the end members to be derived. The Pecanek data also allowed an investigation of the density of the Broken Hill Group metasedimentary rocks to be carried out in the immediate vicinity of the lodes. These results were compared to properties for samples of the same map unit taken at greater distance from the deposit to see if any differences could be discerned.

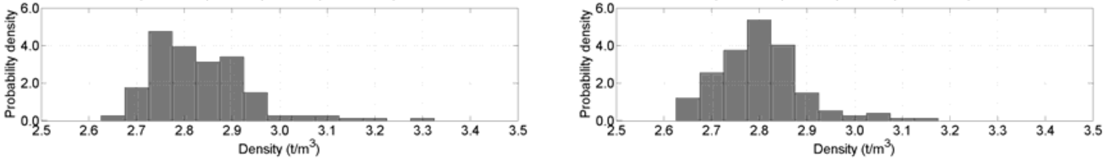
Both sets of samples show an approximately normal distribution for Broken Hill Group metasedimentary rocks of 2.82 ± 0.12 t/m^3. A secondary peak around 3.2 t/m^3 in Figure 3(c) might indicate mis-classification of amphibolite samples. The histograms for samples classified as amphibolite have been interpreted as representing a normal distribution of 3.2 ± 0.1 t/m^3 for pure amphibolite. Lower density values reflect mis-classified samples and samples that are a mixture of metasedimentary rock and amphibolite, known as 'potobolite' in the vicinity of the Broken Hill lodes. The granite gneiss samples show a normal distribution of 2.71 ± 0.1 t/m^3 contaminated by samples with varying proportions of metasedimentary rock with a density around 2.8 t/m^3.

The metasedimentary rocks in the immediate vicinity of the lodes ('Lode zone gneiss' in Figure 4(d) and Table 2) and the samples of the lodes themselves ('Zinc and Lead Lodes' in Figure 4(e) and Table 2) are interpreted as mixtures from normal distributions 2.88 ± 0.15 t/m^3 and 3.2 ± 0.15 t/m^3. The former value indicates that there is a detectable increase of approximately 0.05 t/m^3 in the density of the metasedimentary rocks in the immediate vicinity of the lodes. The value of 3.2 ± 0.15 t/m^3 for the lode mineralisation is consistent with the estimates in Kelly and Bell (1992) for the Broken Hill ores.

(a) Amphibolite (d) Granite gneiss



(b) Sundown Group metasedimentary rock (e) Thackaringa Group metasedimentary rock



(c) Broken Hill Group metasedimentary rock (f) Clevedale Migmatite

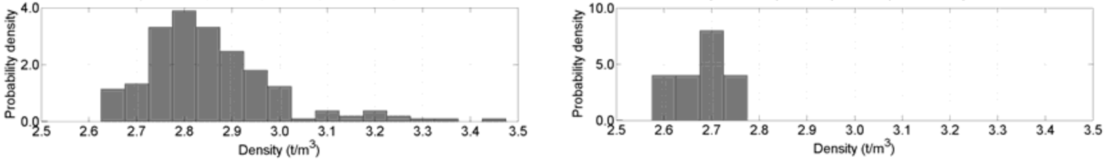
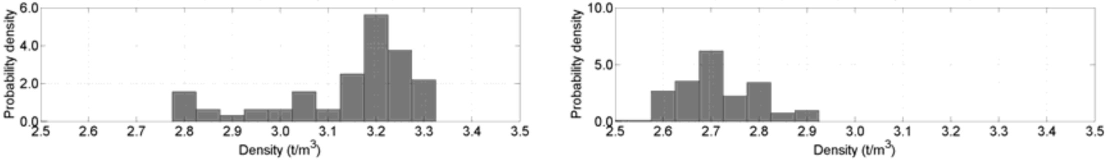
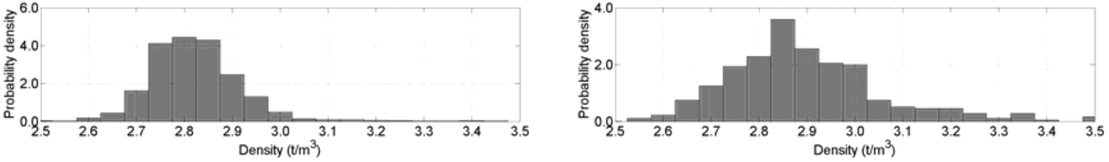


Figure 3. Histograms for density measurements in Maidment et al. (1999).

(a) Amphibolite (c) Granite gneiss



(b) Broken Hill Group metasedimentary rock (d) Lode zone gneiss



(e) Zinc and Lead Lodes

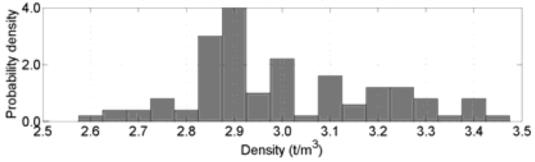


Figure 4. Histograms for density measurements in Pecanek (1975). The 'Amphibolite' grouping contains samples from the Unit 3 (Lower Amphibolite) and Unit 11 (Upper Amphibolite). The 'Broken Hill Group metasedimentary rock' grouping contains samples from Unit 2 (Sillimanite Gneiss), Unit 4 (Sillimanite Gneiss), Unit 5 (Potosi Gneiss), Unit 10 (Undifferentiated Gneiss) and Unit 12 (Undifferentiated Gneiss). The 'Granite Gneiss' grouping contains samples from Unit 1 (Footwall Gneiss) and Unit 13 (Hanging Wall Granite Gneiss). The 'Lode zone gneiss' grouping contains samples from Unit 6 (Enveloping Gneiss) and Unit 9 (Zinc Lode Horizon). The 'Zinc and Lead Lodes' grouping contains samples from Unit 7 (Zinc Lode) and Unit 8 (Lead Lode).

Table 1. Statistics for density measurements in Maidment et al. (1999). 'N' is the number of samples in each grouping.

Grouping	**Median** (t/m^3)	**N**	**Mean** (t/m^3)	**Standard deviation** (t/m^3)	**Minimum** (t/m^3)	**Maximum** (t/m^3)
Amphibolite	3.05	67	3.071	0.164	2.76	3.50
Sundown Group	2.81	147	2.833	0.104	2.63	3.30
Broken Hill Group	2.83	211	2.853	0.135	2.63	3.44
Granite gneiss	2.75	76	2.800	0.155	2.59	3.50
Thackaringa Group	2.80	149	2.812	0.165	2.64	4.51
Clevedale Migmatite	2.69	5	2.686	0.047	2.62	2.75

Table 2. Statistics for density measurements in Pecanek (1975). 'N' is the number of samples in each grouping.

Grouping	**Median** (t/m^3)	**N**	**Mean** (t/m^3)	**Standard deviation** (t/m^3)	**Minimum** (t/m^3)	**Maximum** (t/m^3)
Amphibolite	3.20	64	3.140	0.148	2.79	3.32
Broken Hill Group	2.82	1096	2.824	0.105	2.43	3.66
Granite gneiss	2.70	187	2.711	0.081	2.52	2.92
Lode zone gneiss	2.87	351	2.896	0.176	2.16	3.82
Zinc and Lead Lodes	2.96	100	3.043	0.282	2.62	4.42

The variations in density for drill core samples at 10 ft intervals (~3 m) from DD130 (Figure 5) are typical of the measurements provided by Pecanek (1975). Geostatistical methods can be applied to these measurements to characterise the spatial variability approximately perpendicular to the lithological layering. In turn, this information can be used to predict the variability to be expected for samples with larger volume, such as those used when modelling gravity data. The semi-variograms in Figure 6 show that almost the entire variability occurs at very short separations between sample locations. The implication is that very little variability in density would be expected within a single lithological unit for volumes that span at least 10 m perpendicular to the layering. The variability in density would instead result from changes in the proportions of the lithologies (e.g., metasedimentary rock mixed with amphibolite) over distances of tens, hundreds or thousands of metres. An example of this type of variability can be seen in the interval 700 to 800 m in DD130 (Figure 5). The average density of this interval is raised relative to other Broken Hill Group intervals by the presence of one mapped and several unmapped bands of amphibolite.

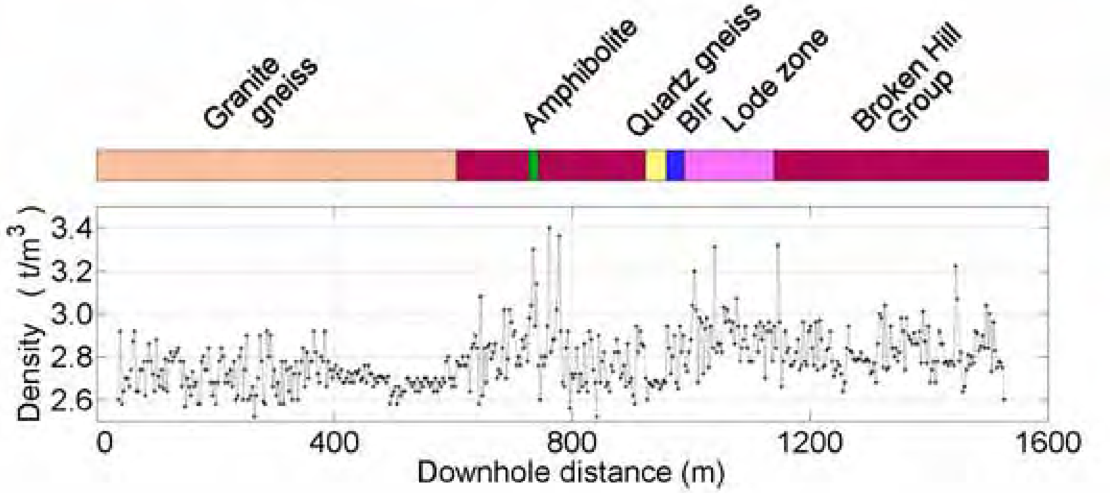
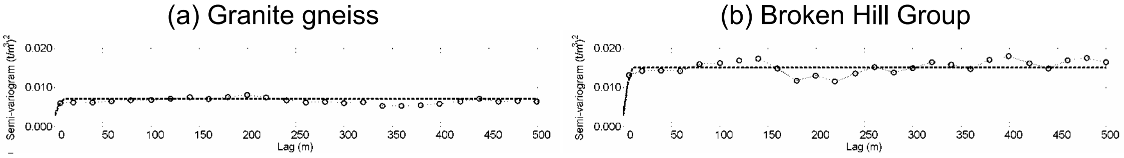


Figure 5. Lithological log and density measurements for DD130, based on information in Pecanek (1975).

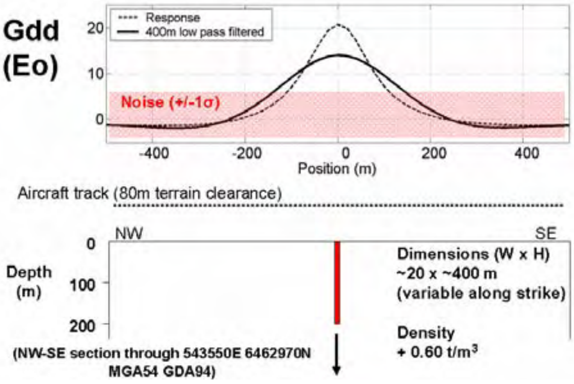

(a) Granite gneiss

(b) Broken Hill Group

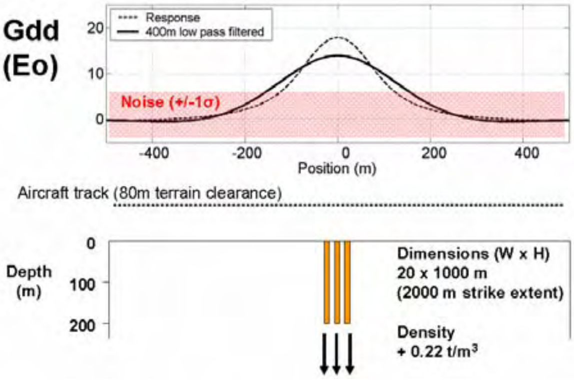
Figure 6. Semi-variograms for density measurements in DD130. Observed values are showed as circles. Results for a spherical model with range of 10 m, sill of 0.0045 (t/m^3)^2 and nugget of 0.0025 (t/m^3)^2 are plotted as a heavy line in (a). Results for a spherical model with range of 10 m, sill of 0.0125 (t/m^3)^2 and nugget of 0.0025 (t/m^3)^2 are plotted as a heavy line in (b).

Simulated response of the Broken Hill orebody and correction for mining

(a) Broken Hill orebody model



(b) Stacked amphibolite model



(c) Low contrast metasedimentary rock model

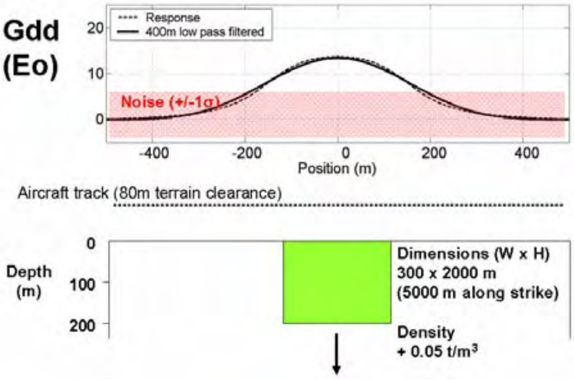


Figure 7. Response for simple models.

The most common question arising from the AGG survey has been "what would another Broken Hill orebody look like in the data?" We cannot use observed response from the 2003 survey over the deposit because mining has substantially modified the mass distribution and hence the gravity response. A simple 3D model of the orebody was used to simulate 2 different scenarios; the gravity response of the deposit, and the correction to be added to the response observed in 2003 to restore the response to the pre-mining state (Lane and Peljo, 2004).

The orebody response was calculated assuming a density contrast of +0.6 t/m^3, a total mass of 300 Mt and a volume of 88 Mm^3. The response was clearly visible against the background noise of the measurements. The correction for mining was calculated assuming that 200 Mt of ore with a density contrast of +0.6 t/m^3 and a volume of 59 Mm^3 had been removed and replaced with backfill with a density contrast of -0.7 t/m^3. When this response was added to the observed data, a positive anomaly was evident over the main concentrations of mass in the northern and southern limbs of the deposit. However, it was also clear that there were a large number of anomalies with similar character and amplitude. It was thus concluded that the response of a similar deposit would be detectable in the data but that the principal difficulty would be to discriminate the response of this target from other geological features in the region. The results presented in Figure 7 illustrate this ambiguity by demonstrating the similarity in response for the orebody model, a series of stacked amphibolite horizons, and a metasedimentary rock interval with weakly elevated density.

GeoModeller 3D mapping and inversion

The Broken Hill region was used to demonstrate the 3D mapping functionality of the GeoModeller software (McInerney and Lees, 2004; McInerney et al., 2005). It became clear when a preliminary gravity inversion was carried out (Guillen et al., 2004) that additional inversion module functionality would need to be developed to deal with complex geological situations such as those at Broken Hill. The input data type options were subsequently extended from vertical gravity and total magnetic intensity to include gravity gradient tensor quantities, magnetic vector components and magnetic gradient tensor quantities. An option to specify the mass density and magnetic susceptibility properties for each unit as a mixture of end member properties was also introduced.

Stochastic gravity and magnetic inversion for a geological section

To prototype some of the new elements identified during the initial GeoModeller gravity inversion work, a 2D inversion of gravity and magnetic data was carried out along the traverse shown in Figure 8 (Lane and Guillen, 2005). The modelled section has a horizontal extent of approximately 33 km and a depth extent of 7 km. The map units and proportions of each of the component end members are given in Table 3. The groupings for the lowermost units were based on an analysis of the property measurements and a qualitative comparison of the gravity and magnetic images with the outcrop geology map.

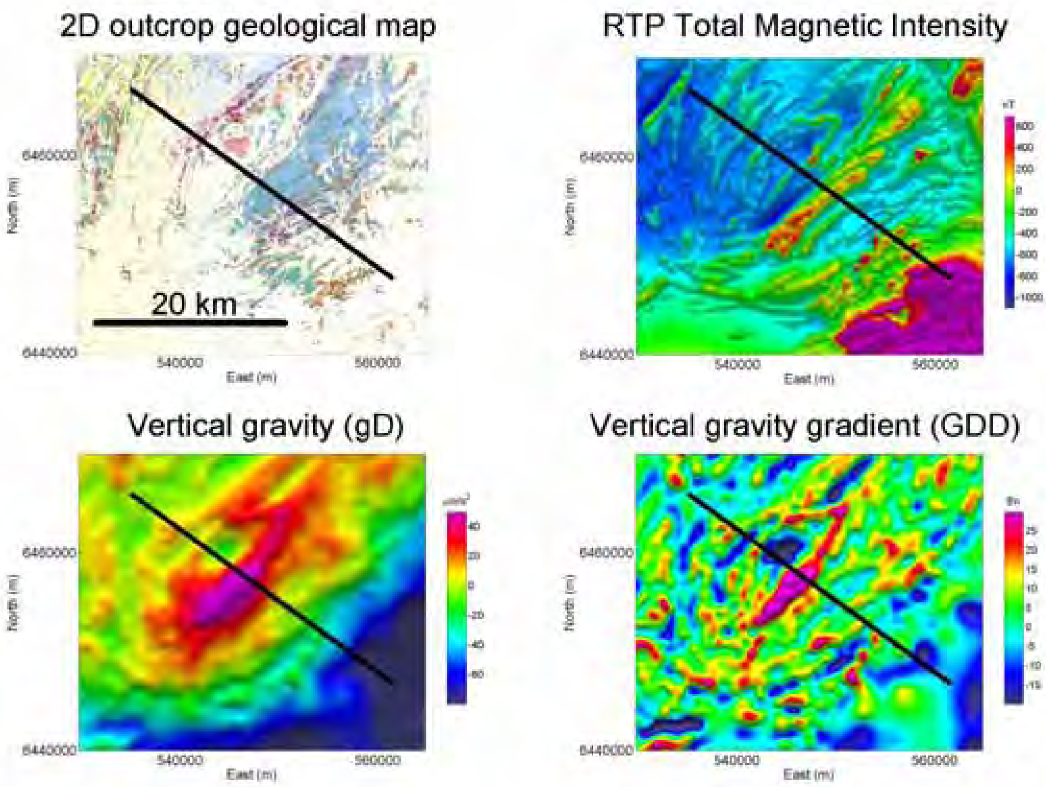


Figure 8. Location of the section. The end points are at 535000 mE 6466658 mN and 561400 mE 6447260 mN (MGA54 projection, GDA94 horizontal datum).

After converting the geological section derived from the 3D map of McInerney and Lees (2004) into a 2D lithological mesh, a stochastic inversion method was used to iteratively propose modifications to the litho-model. The modification involved either selecting a cell at random and re-sampling the properties from the statistical distributions supplied for the geological unit at that location, or changing the geological unit for a cell at the boundary of 2 or more units. The proposals were accepted or rejected according to the effect the proposed changes had on the gravity and magnetic data. Using this procedure, a large number of models having reasonable likelihood with respect to the gravity and magnetic data were generated. A typical example showing the state of the models midway through a sequence of proposals is shown in Figure 9. Cross-plots of magnetic susceptibility and density for these models are shown in Figure 10 to illustrate the multi-modal nature of the specified properties.

Table 3. Map units and sub-divisions used in the 2D litho-model.

Map unit		Map unit sub-divisions		
Colour	**Label**	**Number**	**Label**	**Proportion**
				%
6	Sundown Group	6.2	Magnetic metasedimentary rock	30
		6.1	Metasedimentary rock	70
5	Broken Hill Group	5.4	Magnetic metasedimentary rock	20
		5.3	Magnetic amphibolite	10
		5.2	Amphibolite	25
		5.1	Metasedimentary rock	45
4	Alma Gneiss and Rasp Ridge Gneiss	4	Granite gneiss	100
3	Thackaringa Group	3.4	Magnetic metasedimentary rock	20
		3.3	Magnetic amphibolite	10
		3.2	Amphibolite	15
		3.1	Metasedimentary rock	55
2	Clevedale Migmatite and Thorndale Composite Gneiss	2.2	Magnetic metasedimentary rock	50
		2.1	Metasedimentary rock	50
1	Middle & Lower Redan Units	1.2	Magnetic metasedimentary rock	50
		1.1	Metasedimentary rock	50

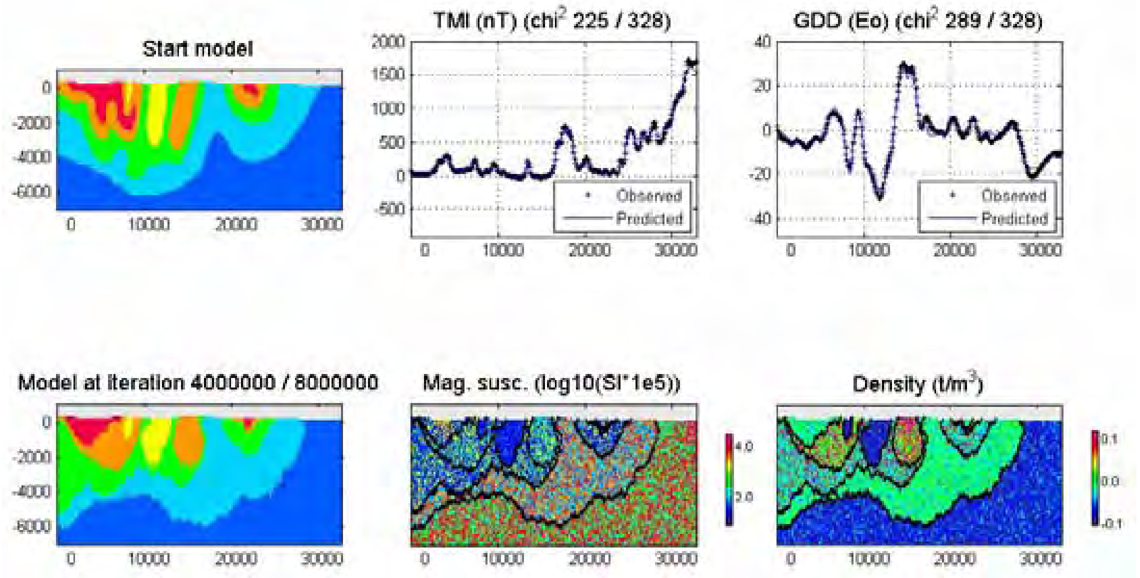


Figure 9. Snapshot of the model sections and data profiles at the midpoint (iteration 4 million) of a run of 8 million iterations. The sections are shown with 2:1 vertical exaggeration.

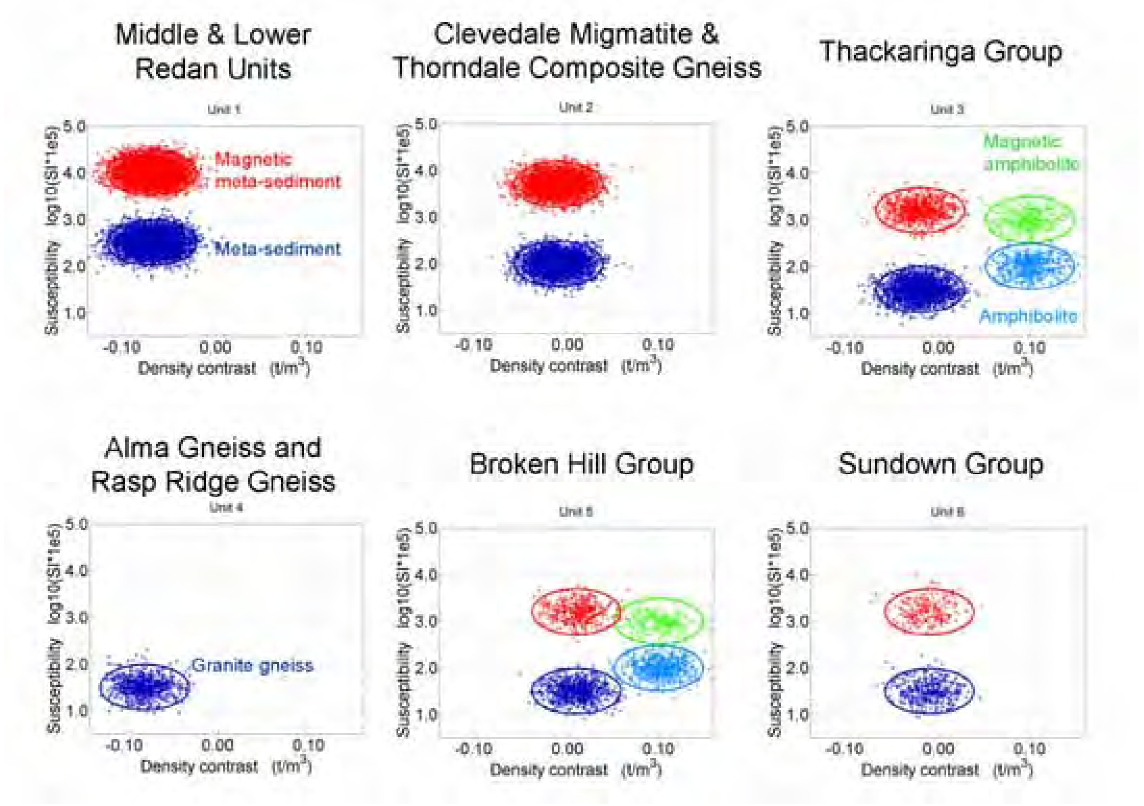


Figure 10. Typical magnetic susceptibility against density cross-plots from the models present at iteration 4 million out of a sequence of 8 million. All models beyond 1 million iterations in this run reproduced the gravity and magnetic data to an acceptable tolerance. The ellipses represent the 95% confidence level for the supplied property distributions. All units except the granite gneiss were a mixture of multiple end member components.

The accepted models were analysed statistically to identify features that were common to many of the solutions and to assign relative uncertainty levels to different parts of the section (Figure 11). The limited amount of direct observational input into the initial geological model is shown by the extent of surface outcrop and the location of the underground workings in the top right section. The geological assignments for these cells were held fixed during the procedure. We can see to a high level of probability that the position of the sub-cropping contact between low density - high susceptibility Middle and Lower Redan Units and the denser - less magnetic Clevedale Migmatite and Thorndale Composite Gneiss is around 28 km along this profile. The geometry of these lower-most units is quite different in the ensemble of inversion models to that shown in the initial litho-model, with a “basement high” predicted between 4 and 12 km along the profile. An expanded region of highly prospective Broken Hill Group rocks was predicted at shallow depth below Sundown Group rocks, to the northwest of the mine area at a distance of about 5 km along the profile. An anomalous region of elevated density was required within the Broken Hill Group in the Thorndale region around 15 km along the profile. This was satisfied by a local increase in the proportion of cells assigned to the amphibolite sub-division. The Broken Hill Group did not include an “ore” end-member which would have had similar density and magnetic susceptibility properties to the non-magnetic amphibolite end member. Had this subdivision been included, the procedure would not have been able to differentiate on the basis of gravity and magnetic data alone between the ore and non-magnetic amphibolite solutions for the Thorndale gravity high.

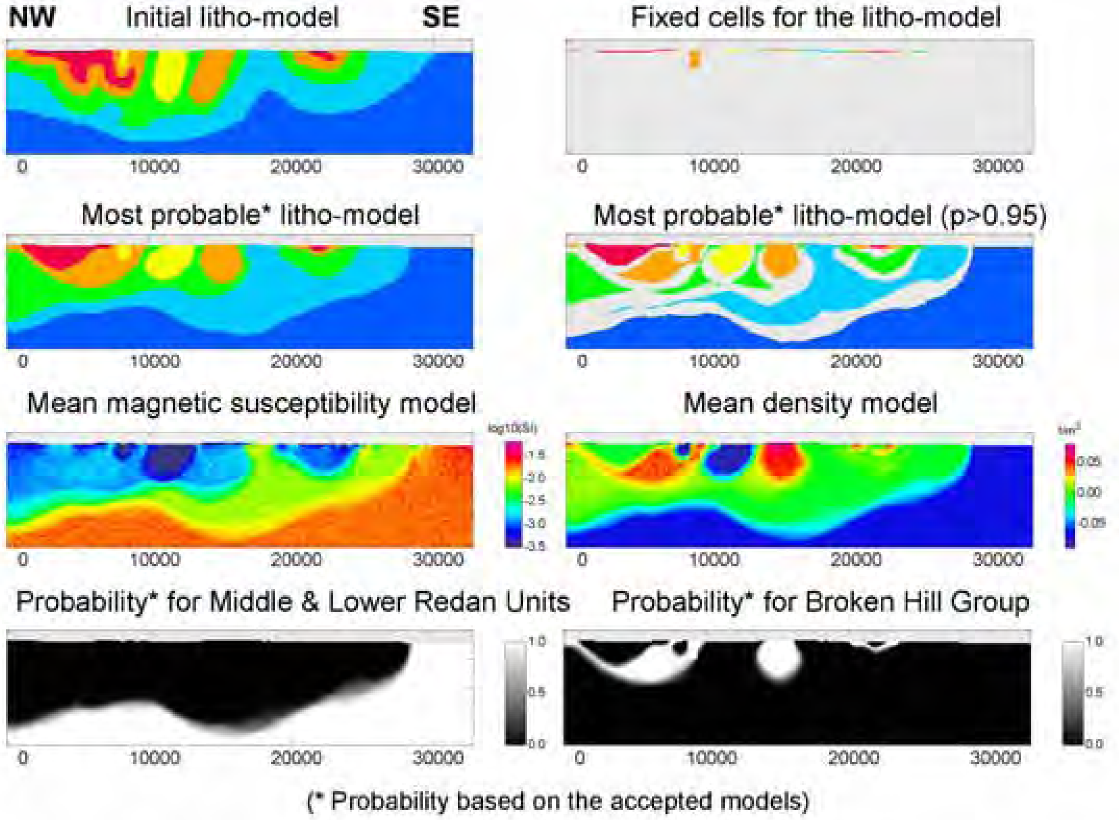


Figure 11. Summary sections derived from statistical analysis of all of the models with acceptable misfit for the gravity and magnetic data. The sections are shown with 1:1 vertical exaggeration and have a vertical extent from +1000 m to -7000 m AHD.

The AGG survey re-ignited the debate on the value of gravity data for mapping and direct targeting in the Broken Hill region. A general decrease in magnetic susceptibility upwards through the sequence and an increase in density from the lower units to a peak in the Broken Hill and Thackaringa Groups were recognised in the early geophysical work (Isles, 1983; Tucker, 1983), together with the association of low density and magnetic susceptibility properties for granite gneiss bodies. The above procedure demonstrates that a combination of gravity and magnetic data can be used at the Group level to quantitatively exploit these systematic variations in density and magnetic properties. Mineral explorers have demonstrated that valid new targets can be generated using more detailed gravity data than was previously available.

Acknowledgements

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HyLogging the Mt Gee Alteration system

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HyLogging the Mt Gee Alteration System.

The HyLogger TM developed by the CSIRO is designed to rapidly scan drill core continuously with a hyperspectral radiometer at ~ 10mm intervals. The system comprises of a robotic tray table designed to accommodate varying sizes of core tray; a profilometer used to measure the height of the drill core; a high resolution digital linescan camera used to compile virtual core trays (imaging at ~0.1mm); and three spectrometers. The spectrometers measure the visible to short-wave, infrared wavelengths (400 to 2500nm), which are, for example, suitable for measuring iron oxides, aluminium hydroxide minerals, chlorites and in some instances chemical variations within mineral species can also be determined. The system can be used to log approximately 700m of core per day and several thousand metres of drill chips, and produces approximately 3GB of data daily. Software tools also developed by the CSIRO synchronises the raw data and can be used to interpret the mineralogy, to which ancillary data such as assays may be added to enhance interpretations.

Approximately 13,500 m of drill core from the Curnamona Province have already been scanned and analysed. These analyses can be easily viewed on SARIG database on the PIRSA website (https://info.pir.sa.gov.au/geoserver/sarig/frameSet.jsp). Presented here are the interpretations of the HyLogger results of three select cores in the Mount Painter Inlier of the Curnamona Province.

Geology of the Mt Gee proximity

Mount Gee is located in the southern Mount Painter Inlier (MPI), which is located in the northwest Curnamona Craton. The MPI is comprised predominantly of the arenaceous Radium Creek Metamorphics intruded by various granites of the 'Older Granite Suite' (Coats and Blissett, 1971); and granites, granodiorites, leucogranites and pegmatites of the 'Younger Granite Suite', for example the British Empire Granite which is dated at 444Ma (Elburg et al., 2003).

In the southern MPI, including Mt Gee, areas of the granitic crystalline basement have been brecciated (termed the Radium Creek Breccias by Drexel and Major, 1987), with potash metasomatism affecting the basement prior to and during this brecciation (Drexel and Major 1986). This brecciation took place after the 490Ma to 516Ma Delamerian Orogeny. Subsequent to brecciation chloritic, hematitic and primary uranium mineralising fluids intruded these breccias followed by a later, multi-episode epithermal system.

These two phases of intruding fluids altered the host rock to produce a range of minerals, which include kaolinite, illite and montmorillonite.

HyLogging Results

The three diamond drill holes selected for this study were Mount Gee CRA DD91GE33, MGD 151 and Bonanza Gold Pty Ltd DD02 MTG-01. Typical semi-quantitative mineral assemblages extracted included kaolin, white mica, carbonate and iron oxides. Fig 1 shows an example of mineral distribution with depth for DD91GE33. When compared to the distribution of U_3O_8, hematite, montmorillonite, kaolinite and siderite exhibit distinctive spatial associations with mineralisation.

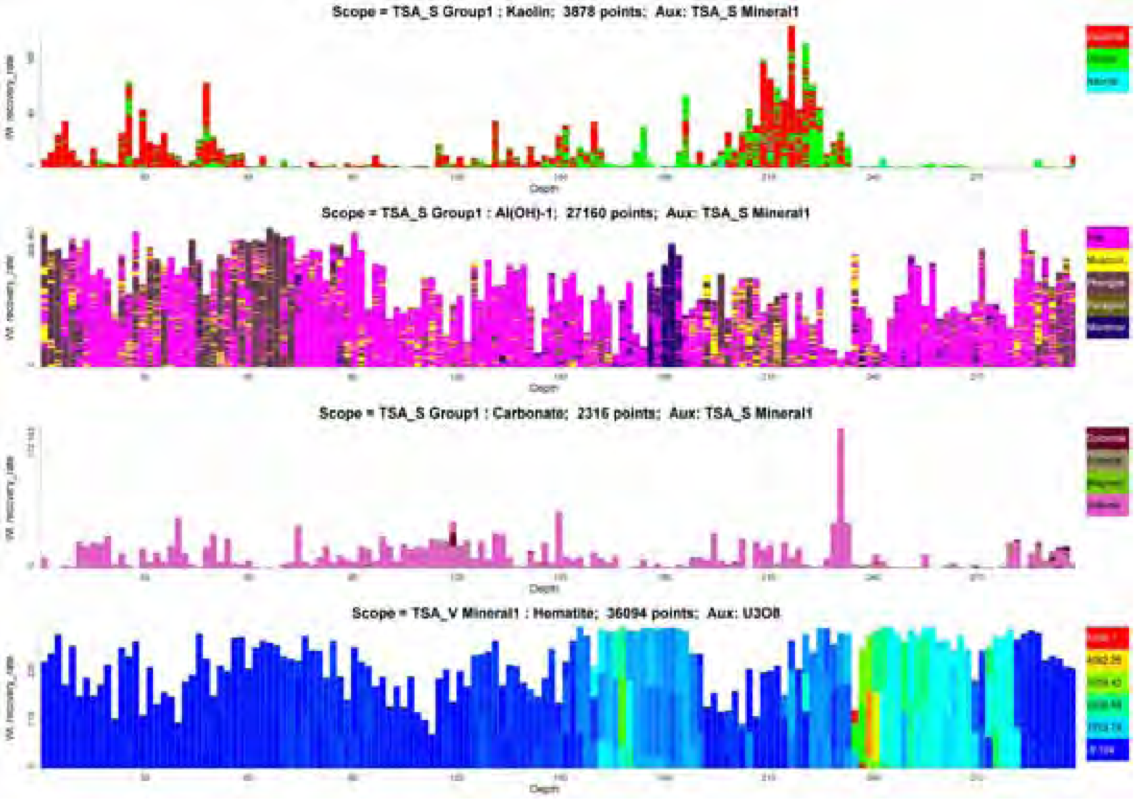

Figure 1. Automated semi-quantitative mineralogy derived from HyLogger for hole CRA DD91GE33.

It is anticipated that further HyLogging campaigns will allow for the refinement of alteration models associating key mineral assemblages with mineralisation thus developing new vectors to ore.

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New Discoveries – Cu-Au & U Mineralisation, Mount Painter Province, South Australia

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Introduction

Quasar Resources, an affiliated company of Heathgate Resources, manages an exploration programme in the northern Curnamona Craton. Recent discoveries include the 4 Mile uranium prospect and the M1 and M2 iron oxide associated copper gold prospects. These discoveries highlight the Palaeozoic and Cainozoic prospectivity of the Northern Flinders Ranges.

Copper–Gold Targets

Quasar farmed in to the Alliance Resources held EL2874 in 2002. Following reviews of historic work (Teale, 2002), the assessment and ranking of anomalies defined by the potential field data (Anderson, 2003) and follow-up geological assessments (McConachy, 2003), two priority magnetite/haematite associated Cu-Au targets were selected for drill testing.

These Fe-oxide Cu-Au targets (M1 and M2) located within the Mt Painter Inlier represent high amplitude magnetic anomalies associated with anomalous Cu and Au geochemistry at surface. The prospectivity of the M2 prospect is enhanced by the close proximity of the historic Yudnamutana Cu workings located only 800m to the east.

Field associations of copper and gold anomalism with magnetite rich sulphide rocks at both prospects supports the concept that the high amplitude magnetic anomalies provide an even larger target for sulphide associated Cu-Au mineralisation.

The M2 prospect is represented by a series of magnetic highs hosted within Adelaidean sediments. Parabolic bulges associated with northwest trending fold noses coincide with zones of increased magnetic intensity. Recent diamond drilling at M2 confirmed the association of the magnetic anomalies with extensively altered Adelaidean host lithologies. The main prograde assemblages are biotite ± quartz ± microcline, microcline-biotite ± albite and biotite ± scapolite ± actinolite ± quartz. Prograde metasomatic magnetite is also abundant and widespread. Retrogression commonly involves sericite replacing scapolite and/or plagioclase as well as chlorite, carbonate and clays, with hematite as well as or instead of magnetite in altered samples, commonly together with sulphides. The sulphides typically post date magnetite (Pontifex, 2006). Best copper results include:

- 12m @ 0.56% Cu (QM2003, from 74m)
- 2m @ 2.5% Cu (QM2005, from 386m)

and the best gold result was 6m @ 0.31g/t Au (QM2003, 80-86m).

The M1 prospect, the highest amplitude magnetic anomaly in the north Flinders Ranges, is located on the northern margin of the Terrapinna granite. The prospect is defined by an iron oxide breccia complex returning rock chip samples of 1%Cu and 1g/t Au at the western end of the anomaly and sheeted magnetite vein system on the eastern margin. Recent drilling intersected a magnetite/hematite breccia complex hosted within adjacent quartzites. A close association between sulphide mineralisation and the hematite/magnetite breccia complex was observed in the drill core with the best result being 10m @ 0.3% Cu (QM1003, from 264m).

Uranium

The 4 Mile uranium prospect covers an area in excess of 10 km^2 and remains to be closed off by +150 hole drilling programme. The uranium mineralisation is hosted by reduced Eocene sands and sandy siltstones located at varying depths, from 140m to 200m below surface, and in lateral zones of variable grade. The best drill intercepts include:

- 9.5m @ 0.97% pU_3O_8 (AK086, from 151.5m)
- 11m @ 0.80% pU_3O_8 (AK101, from 145.5m)
- 9m @ 1.66% pU_3O_8 (AK103, from 150.5m)

These intercepts help define a portion of a linear high-grade zone adjacent to the southern termination of the western limb of the prospect. The geological setting is significantly different to the Miocene hosted channel systems of the nearby Beverley uranium orebody.

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Progress and problems in unravelling the evolution of the Koonenberry Belt

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The Koonenberry Belt, named after Koonenberry Mountain, is a term referring to an area of deformed rocks that is exposed between Menindee and Tibooburra, east of the Bancannia Plain in western New South Wales. The framework for this belt was consolidated during the Cambrian Delamerian Orogeny and the fold trends are seen to wrap around the eastern margin of the Palaeoproterozoic Curnamona Province. This deformed region has been regarded as a northern correlative or an extension of the Kanmantoo Fold Belt (Scheibner & Basden, 1996).

With the break-up of Rodinia late in the Proterozoic the early Pacific Ocean opened and a portion of the eastern continental margin of Gondwanaland formed to the east of Broken Hill. This segment of continental margin became the site of the development of the Koonenberry Belt through the Cambrian. A succession of orogenic extensions and compressions through the Palaeozoic left their marks on the Koonenberry region, as crustal shells were progressively added to the eastern margin of Gondwanaland with the development of the Lachlan, Thomson and New England Orogens. The Koonenberry Belt has preserved a long and complex history that includes the manifestations of a number of orogenic events that affected eastern Australia since Late Proterozoic time. New SHRIMP U-Pb zircon geochronology reported here provides critical information on the timing of the two major crustal events (the Delamerian Orogeny and the Benambran Orogeny) that developed the framework and consolidated the Koonenberry Belt. Of the 15 igneous ages achieved so far, nine fall between 512 and 496 Ma (individual error bars are about 3 Ma) reflecting the Middle to Late Cambrian Delamerian Orogeny. The remaining six ages range between 427 and 414 Ma, and reflect the Silurian Benambran Orogeny

Delamerian Cycle

The sedimentary history of the Koonenberry region extends back to at least the Neoproterozoic with the Adelaidean Kara beds that make up the western side of the fold belt. This siliciclastic succession of mudstones, dolomites and minor laminated traction-current arenites was formed on a wide, and at times shallow-water, marine continental shelf and intra-continental rift basin environment that developed as Rodinia underwent a slow stretching, eventually leading to a new continental margin on the eastern side of Gondwanaland. In spite of generally poor exposure and more intense deformation of the Kara beds there are strong lithological similarities with the upper part of the Adelaidean succession (the Farnell Group) on the western side of the Bancannia Plain. A distinctive feature of the Kara beds is the presence of a local rift-related suite of transitional alkaline basalts, pyroclastics and felsic differentiates (the Mount Arrowsmith Volcanics) that have yielded an age of 586 ± 7 Ma (Crawford et al., 1997).

A stratigraphic contact between the Kara beds and overlying Teltawongee beds can be seen immediately south of Teltawongee Tank on the western side of the Koonenberry Belt.

Elsewhere, the Teltawongee beds are fault-bounded against the other rock units. The Teltawongee beds are characterised by turbidity current sandstones that formed as continental slope deposits on the eastern margin of Gondwanaland, and are in marked environmental contrast to the laminated traction current sandstones of the underlying Kara beds. Distinctive features of the Teltawongee beds are the rarity of sandstones coarser than medium sand size, the dominance of graded bedding and Bouma sequence sedimentary features, and the common presence of detrital mica flakes and other metamorphic mineral clasts. Some red and grey slates are found in the succession. Sparse fossils and trace fossils in parts of the sequence suggest a Cambrian age (Webby, 1984). Most of the Teltawongee beds occur east of the Koonenberry Fault, a regional structure that trends almost parallel to the strike and divides the fold belt into eastern and western sections. Two smaller regions of Teltawongee beds are located west of the Koonenberry Fault, one near the central part of the Koonenberry Belt and one on the western margin between Packsaddle and Nundora.

A linear fault-bounded belt of apparently unfossiliferous phyllite and fine-grained turbiditic sandstones with minor quartz-magnetite rocks, thin fine-grained felsic tuffs, tholeiitic pillow lavas and pyroclastic units is exposed on the western edge of the Koonenberry Fault. This unit, the Ponto Group, was deposited in a foot of slope or basin plain environment and is regarded as a distal equivalent of the Teltawongee beds. The ages determined on three Ponto Group air fall tuffs are tightly constrained between 508 and 512 Ma. A similar tuff from the Canella beds of the Gorge Inlier west of Milparinka yields 508.3 ± 2.2 Ma.

During the Early and Middle Cambrian, as the Teltawongee beds accumulated on the continental margin, the ocean east of Gondwanaland began to contract leading to a westerly dipping subduction zone that generated calc-alkaline volcanism (the Mount Wright Volcanic Arc) at Mutawintji and beneath the axis of the Bancannia Trough. A determined age of 510.3 ± 3.2 Ma for an ignimbrite from the upper part of the Cymbric Vale Formation (Gnalta Group) indicates a close tie between igneous activity in the Mount Wright Volcanic Arc and tuffaceous rocks in the Ponto Group. Early and Middle Cambrian fauna thrived in shallow seas on the seaward edge of the arc at Mutawintji and are preserved in the limestones, shales and volcanic rocks of the Gnalta Group. A Middle Cambrian section exposed west of Mount Arrowsmith was deposited on the landward side of the arc.

Near the end of the Middle Cambrian a crustal collision at the eastern margin of Gondwanaland led to the culmination of the Delamerian Orogeny (D1). A folded felsic tuff in the Mt Poole Inlier dated at 504.5 ± 2.6 Ma provides an upper limit to sedimentation before onset of Delamerian deformation. A felsic body intruding into the Ponto Group, and apparently unaffected by the Delamerian deformation, yields an age of 496.3 ± 3.1 Ma suggesting that the ~500 Ma Delamerian deformation was active for only a few million years. Strong vertical cleavage, thrust faults and tight to isoclinal folds were developed through much of the succession. Fine-grained units, such as the Ponto Group and the Kara beds, developed intense isoclinal folding and boudinage, but the metamorphic grade of the fold belt remained low. To the west of the Bancannia Trough, large regional folds with axial plane slaty cleavage were formed in the Adelaidean succession and this deformation extended some hundreds of kilometres to the west into the Flinders Ranges.

Benambran Cycle

Following the Delamerian Orogeny a seaway opened to the east, and through the Late Cambrian (Furongian) the sea transgressed across the Koonenberry Belt, leaving in its wake unconformable Late Cambrian sedimentary units that began the next orogenic cycle. The sedimentary units show features indicative of increasing depth and more marine character eastwards. In the west, the Scopes Range beds, the Mutawintji (formerly Mootwingee) Group and, by interpretation, a well-defined easterly thickening wedge at the base of the Bancannia Trough, are red bed quartzose sandstone successions with fluvial to marginal marine characteristics. Well-rounded and polished quartzite pebbles and cobbles in the Nuchea Conglomerate at the base of these units appear to have been transported from far to the west by fluvial activity. Prior to the deposition of the Nuchea Conglomerate, a large channel now exposed on Bilpa station was filled with polymictic conglomerate derived from erosion of the early Delamerian Mountains. Similar detritus is found at the base of the Cupala Creek Formation and the Kayrunnera Group in the northeast; the latter contains Late Cambrian to Early Ordovician sandstones, limestones and thick shales deposited on a marine shelf. Further northeast, the Yancannia beds are predominantly very low grade, tightly-folded and cleaved clayey siltstones of turbiditic aspect; only minor fine to medium-grained sandstones are present. Although no fossils have yet been found, this succession is thought to be part of a Late Cambrian-Ordovician sedimentary cycle.

In the northern Koonenberry Belt, a tightly folded syncline west of Mount Arrowsmith contains a quartzose and red-bed succession with some highly fossiliferous Early Ordovician limestones and shales. To the northeast of Mount Arrowsmith, the apparently unfossiliferous Warratta and Tibooburra Inliers of deformed basement poking through the Mesozoic cover contain Late Cambrian to Ordovician sedimentary rocks and minor volcanic tuffs. A tuff unit within the Tibooburra Inlier with an age of 497.2 ± 2.6 Ma may indicate that igneous activity associated with the Delamerian event continued into the next sedimentary cycle. Some diamictitic lenses with pebbles and cobbles derived from the Delamerian Koonenberry Belt occur in these inliers. A deformed rounded cobble of felsic tuff from the Warratta Inlier yields 510.4 ± 3.0 Ma, and suggests derivation of these clasts from the older Delamerian terrain.

In the Silurian, the Benambran Orogeny (D2) resulted from a second major crustal collision that affected the Koonenberry region, as the newly deposited Late Cambrian to Ordovician sediments in the northeast were deformed into tight low-plunging folds with steep dipping to vertical axial-plane slaty cleavage. A weak slaty cleavage was formed in shales of the Kayrunnera Group, and open folds formed in quartzose sandstones of the Cupala Creek Formation and in the Churinga area to the south. The Mutawintji Group and the Scopes Range beds in the west were very weakly deformed or only tilted by this event. Many areas of rock in the Koonenberry region previously deformed in the Delamerian Orogeny were strongly re-deformed in the Benambran Orogeny, with the steeply dipping limbs of earlier folds being folded about near vertical axes accompanied by steeply plunging pencil slate cleavage. Such Benambran folds are well displayed in the older rocks around Mount Arrowsmith, in large areas east of the Koonenberry Fault, and in some local belts around Packsaddle and Nundora. Easterly dipping Benambran thrusts may have pierced the older Delamerian structures in the Koonenberry Belt. There is evidence for Silurian Benambran igneous activity throughout the eastern side of the Koonenberry Belt.

Post-Benambran events

Following the Benambran Orogeny, the upper crust in the Koonenberry region became brittle, although local intramontane troughs filled with red and green nonmarine arenites and rudites (Mount Daubeny Formation) were developed in close association with Late Silurian to Early Devonian igneous activity. These rocks represent western outliers of a cycle of marine deposition that filled the Cobar Trough and spilled out over presumed Benambran basement beneath the Darling Basin.

Widespread easterly-directed fluvial activity in the Middle and Late Devonian resulted in the influx and deposition of a thick succession of mature quartz sandstones across the Koonenberry region and the Darling Basin. The Wana Karnu Sandstone (formerly Snake Cave Sandstone), containing some units with abundant well-rounded vein quartz and quartzite pebbles but very little heavy mineral, is thought to have once mantled much of the southern and central Koonenberry region. A period of intense crustal faulting in the Koonenberry region under horizontal compression during the Middle Devonian expresses the far field effects of the Tabberabberan Orogeny in the east that added another crustal shell to Gondwanaland. East and west-dipping crustal shears, well displayed in the Koonenberry deep seismic reflection section (Mills & David, 2003), resulted in the early stage of down-faulting of the Bancannia Trough, where the Wana Karnu Sandstone is fully preserved, and uplift of the central section of the Koonenberry Belt, where the Wana Karnu Sandstone was removed. Although little deformed in the Bancannia Trough, the Wana Karnu Sandstone is strongly tilted at the eastern margin (Mutawintji National Park) and even tightly folded adjacent to major faults in the east (Coturaundee Range and to the south).

In the Late Devonian to Early Carboniferous, another succession of mature quartz sandstones, that are rarely pebbly, blanketed the area (Ravendale Formation). This succession is well-preserved by down faulting in the Bancannia Trough. Deposition of the Ravendale Formation was terminated by the Carboniferous Kanimblan-Alice Springs Orogeny, an event that generated most of the more obvious mapped faults in the Koonenberry area under a north-south compressive strike-slip fault regime. The major oroclinal bend of the Grasmere Knee Zone is thought to have developed at this time. Since the Carboniferous, the Koonenberry region has been eroded to a low topographic profile. There is evidence of Permian continental glaciation in the southern part of the Koonenberry region, and most areas were inundated by rising Cretaceous seas as the Eromanga Basin developed in the north. Post-Cretaceous rejuvenation of movement on older faults, however, is evident in the north and east, and some recent earthquake epicentres have fallen on or near the Mount Browne Fault.

Conclusion

SHRIMP U-Pb zircon geochronology of carefully selected samples has provided key information for unravelling the timing of geological events in the Koonenberry region. Igneous activity was associated with both the Delamerian Orogeny and Benambran Orogeny. The sequence of orogenic events that affected the Koonenberry Belt has introduced a structural complexity that becomes particularly apparent when attempts are made to draw cross-sections across the region. Clearly, some major structures must overprint others, and realistic illustrative sections should show these sequential relationships. Poor exposure, extensive cover and a lack of third dimension in the topography make it imperative that geophysical responses, particularly aeromagnetic, are used to advantage in modelling proposed sections. Modelling of the geophysics along section lines (Musgrave & Mills, 2006), has been valuable in solving a number of geological problems relating to body shapes, stratigraphic dips and overthrusting in this region.

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Hydrothermal alteration at Broken Hill

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Introduction

Manganoan garnet-bearing rocks are considered an indicator to Broken Hill-type Pb-Zn-Ag ore deposits at Broken Hill. Many other metamorphosed massive sulphide deposits are associated with manganese garnet-bearing rocks (Spry et al., 2000). At Broken Hill, there have been major element (Jones, 1968; Stanton, 1976; Spry, 1978; Spry and Wonder, 1989), trace element (Lottermoser, 1989) and rare earth element (Lottermoser, 1988, 1991; Parr, 1992; Schwandt et al., 1992) studies of samples of garnet-rich rocks. There have been various petrographic studies that have included garnet-rich rocks (Stillwell, 1959; Segnit, 1961; Matthias, 1974; Hodgson, 1975; Spry, 1978; Spry and Wonder, 1989). However, despite these petrographic and geochemical studies, there have been few field studies of garnet-rich rocks associated with the Broken Hill ore deposit (Jones, 1968; Billington, 1979) and in the Broken Hill district (Barnes et al., 1983; Leyh, 2000).

It is argued that garnet rocks at Broken Hill are a result of pre- and syn-metamorphic fluid rock interactions that took place during deposition of the Willyama Supergroup and during the Olarian and Delamerian Orogenies. Data in this presentation derives principally from recent work on CML7.

Garnet rocks of Broken Hill

Unit 4.5

Psammitic horizons of Unit 4.5 contain quartz-bearing garnetite laminae comprising very fine grained garnet and quartz. The lamination is coplanar with S$_0$ and S$_1$. These are associated with glassy blue quartz-gahnite±sulphides which, in places, contains disarticulated aggregates of quartz-bearing garnetite. It is interpreted that garnet, gahnite, blue quartz and sulphide occurrences in the psammites of Unit 4.5 result from Unit 4.6 providing an aquifer cap to pre-metamorphic fluids that replaced the porous permeable reactive feldspathic psammites of Unit 4.5.

Quartz-bearing garnetite of Unit 4.6

Up to three thin garnet-quartz horizons occur as thinly laminated beds at the base of Unit 4.6 on the western side of the Broken Hill orebody and at least two horizons on the eastern side. The horizons are finely-laminated and in drill core comprise a thinly-laminated quartz-manganoan almandine ± sphalerite-magnetite-gahnite horizon that has a stratigraphic continuity of at least 2 km and down dip continuity of at least 800 m. Lamination is coplanar with S$_o$, is remarkably consistent and no transgressive quartz-garnet layers were observed. Quartz-magnetite 3 x 1 cm-sized boudins with a garnet rim and transgressive quartz-magnetite veins are rare. Because

S_0 and S_1 are coplanar, lamination could have resulted from shearing coplanar with S_1. However, the stratigraphic position, the stratigraphic continuity, the sedimentary structures (bedding, bifurcation, cross bedding), the grading of quartz-bearing garnetite into garnet- and magnetite-bearing pelite, the lack of a mylonitic fabric, the stacking of at least three quartz-bearing garnetite horizons, the lack of garnet laminae in S_0, S_1 or S_2 and the lack of transgressive garnet-quartz masses strongly suggests that this laminated garnet-bearing rock was once a sediment.

Pre-metamorphic hydrothermal alteration garnet rocks

Metasediments stratigraphically beneath C Lode grade from pelite and feldspathic psammopelite into garnet rocks. C Lode and these associated garnet rocks were interpreted by Plimer (1979) as pre-metamorphic hydrothermal alteration. The gradation from pelite to garnet pelite is at the expense of sillimanite and biotite and the development of garnet in psammopelite is at the expense of feldspar. In pelites, as the sillimanite and biotite content decreases, the garnet content increases and the foliation disappears.

Garnet is characteristically equidimensional at 2-4 mm, imparts a spotted appearance to the rock (e.g. spotted psammopelite) and displays a similar texture to that of the garnet amphibolite and foliated garnet-plagioclase gneiss of Units 4.4 and 4.7. The thick feldspathic psammopelite beds at the footwall of C Lode (spotted psammopelite) suggest an addition of Fe and loss of Ca, Na and K.

Where neither sillimanite nor feldspar are present, the garnet is surrounded by late-stage blue quartz ± gahnite ± pyrrhotite, the rock retains a ghost-like lamination coplanar with S_0/S_1, stringers of pyrrhotite-chalcopyrite are common and the rock mass is veined and replaced by spongy pyrite. These areas are interpreted as a syn-metamorphic blue quartz-gahnite-sulphide overprint of a pre-metamorphic Fe-rich alteration zone.

Associated with C Lode is cm to dm thick horizons of sillimanite rock coplanar with S_0 and S_1. Furthermore, the sillimanite masses transgressive to S_0 and S_1 in Unit 3.10 suggest that some highly aluminous rocks at Broken Hill result from alkali loss during pre-metamorphic hydrothermal alteration.

Quartz-bearing garnetite of Unit 4.7

Quartz-bearing garnetite is commonly associated with all sulphide rocks at Broken Hill and occurs throughout Unit 4.7 stratigraphically below, between and above all sulphide masses. Quartz-bearing garnetite is most commonly associated with A Lode which is enveloped by masses of quartz-bearing garnetite and has strike equivalent quartz-bearing garnetites. In the pelitic parts of the metasediments within Unit 4.7 are zones where pelite grades into garnet-bearing pelite which, in turn, grades into quartz-bearing garnetite and garnetite. This is the most common form of garnet rocks on CML7. These gradations from pelite to quartz-bearing garnetite are both along and across layering, occur in proximity to sulphide rocks and commonly the core of a quartz-bearing garnetite comprises a massive garnetite. The gradational changes from pelite to quartz-bearing garnetite and the pseudomorphing of crenulated sillimanite by garnet suggest that extensive pelite garnetisation took place late or post D_2 and D_3. Elsewhere, D_2 quartz-gahnite boudins in No 3 Lens have a garnet-quartz rim demonstrating garnetisation during D_2 and clasts of green plumbian orthoclase pegmatite have a garnet-quartz rim, possibly also of D_2 origin. Boudins and bedding parallel schlieren of quartz-bearing garnetite are especially common associated with the Lead Lodes and can occur many tens of metres stratigraphically above No 3 Lens. Quartz-bearing garnetite commonly contains layer parallel white and blue quartz veins. Quartz-bearing garnetite contains minor gahnite, plumbian orthoclase and sulphides (especially pyrrhotite, chalcopyrite and galena) and is commonly transgressed by veinlets of spongy late-stage pyrite. In many places, quartz-bearing garnetite has been replaced by blue quartz-gahnite rock. Quartz-bearing garnetite can be laminated, massive, veined by quartz-sulphides and transgressed by veins of quartz in zones of dilation. Fragments of quartz-bearing garnetite occur in blue quartz-gahnite veins and quartz veins are rarely cut by a network of quartz-bearing garnetite.

Quartz-bearing garnetite associated with the Western Mineralisation

In the stratigraphic footwall of both C Lode and the Western Mineralisation, there is a distinct gradation from pelite to garnet-bearing pelite where very fine grained garnet has replaced crenulated sillimanite. Associated with most sulphide rocks there is a gradation from pelite to garnet-bearing pelite which, in places, grades into quartz-bearing garnetite and garnetite. If S_2 sillimanite has been replaced, then this alteration is late- or post-D_2.

Quartz-bearing garnetite associated with the Eastern Mineralisation

The Eastern Mineralisation comprising quartz-garnet-hedenbergite-sulphides, interpreted as A Lode equivalent, is characterised by massive orange garnet-quartz rocks, faintly laminated red brown garnet-quartz rocks, white and blue quartz-rich rocks with rotated clasts of quartz-bearing garnetite and massive red garnet-quartz rocks. All garnet rocks are veined by quartz ± sulphides, cataclastic massive sulphide veins with bleached clasts of pelite and sulphide veinlets. The garnet-rich rocks associated with the Eastern Mineralisation are along the axis of a S-plunging ?F_2 antiform and it appears that Mn^{2+}- and sulphide-bearing fluids and cataclastic sulphides have moved up and along the axis of a F_2 antiform.

Garnetite of Unit 4.7

Garnetite is a friable high metamorphic grade rock composed of >90% orange-brown to pink garnet. It is finely laminated and lamination defined by changes in garnet grain size and garnet:quartz ratios. Some garnetite has lamination coplanar with S_0/S_1 and other garnetite contains folds, chaotic lamination, transgressive garnet-quartz masses and quartz veins unrelated to S_1/S_0 in the enclosing metasediments. On CML7, garnetite occurs as discontinuous masses at the boundary of No 2 and No 3 Lenses, intercalated with No 2 Lens sulphide rocks and on the underwall of No 3 Lens on the 200' level of Block 14 Open Pit as a discontinuous boudinaged layer 200 m in strike, 50 m in width and 1-2 m thick. The garnetite stratigraphically overlies No 3 Lens and at the garnetite-No 3 Lens contact, the sulphide rock comprises a breccia with clasts of green plumbian orthoclase crystals and garnetite. In Block 14 Open Pit, the garnetite is laminated with laminae defined by changes in garnet grain size and rare quartz and quartz-garnet laminae. Garnet grain size is 0.5–1 mm. Lamination in the garnetite is coplanar with S_0/S_1 lamination in the underlying high metamorphic grade pelites which have green plumbian orthoclase pegmatite veinlets 1-3 cm in size along S_0/S_1 and minor bedding-parallel garnet laminae 0.1–1 cm thick. The garnetite-pelite boundary is sharp. Laminae in garnetite are 0.5–10 mm thick and are cut by blue quartz-gahnite veinlets and the garnetite is overlain by a more massive blue quartz-gahnite unit coplanar with S_0/S_1. Within the blue quartz-gahnite unit are fragments and schlieren of garnetite. Boudins of garnetite in Block 14 Open Pit are coplanar with S_0/S_1 and layering in boudins is commonly transverse to layering in the enclosing pelite. In places, the underlying pelite contains ptygmatically-folded veinlets of blue quartz-gahnite. Garnetite associated with No 3 Lens on CML7 contains 0.2–1.7 g/t Au. Transgressive blue quartz-gahnite veinlets and masses of blue quartz-gahnite contain minor chalcopyrite, zoned löllingite-arsenopyrite, galena and tetrahedrite.

Garnetite occurs stratigraphically equivalent to sulphide rocks, at the edge of sulphide rocks, overlying Lead Lodes, interlaminated masses and pods in sulphide rocks and as clasts within sulphide rocks. In the Kintore Open Pit on the western limb of the Broken Hill Antiform, a remnant outcrop of No 2 Lens contains a friable faintly-laminated garnetite layer 15 cm thick. Lamination is coplanar with S_0/S_1 in the enclosing high metamorphic grade psammopelites which contain minor laminae and pods of garnetite. No 2 Lens contains clasts and pods of garnetite with lamination coplanar with S_0/S_1. Both the garnetite and No 2 Lens are enriched in löllingite-arsenopyrite.

Garnetite hosted by unretrogressed high metamorphic grade metasediments where garnetite layering is coplanar with S_0 (and S_1) in the enclosing metasediments is regarded as a metasediment. Another type of garnetite wherein layering is either coplanar with a retrograde schistosity or unrelated to measurable bedding or schistosity is also very common, especially associated with the Lead Lodes. Prograde pelitic rocks are those where there is primary sillimanite (commonly crenulated) which defines S_1 and S_2, biotite, garnet, pinitised cordierite and feldspar. Retrograde rocks contain no sillimanite and abundant sericite which defines the schistosity. Layering in garnetite is defined by changes in grainsize of garnet, changes in colour of garnet and changes in the garnet: quartz content. Garnet layering is commonly folded, these folds bear no relationship to the regional structure of Laing et al. (1978) and garnetite is commonly transgressed by blue quartz-gahnite ± chalcopyrite, galena, tetrahedrite and sphalerite. Garnetite contains interstitial quartz, biotite, galena, tetrahedrite, chalcopyrite and scheelite, contains rare löllingite-arsenopyrite porphyroblasts and even rarer transgressive quartz-molybdenite veinlets. Garnetite and sericite schist commonly interdigitate and the sericite schist is slightly altered to a garnet rock. Garnetite has high Hg, As, Ag and Au contents.

Garnetites associated with F_2 and F_3 axial plane sulphide projections (locally known as droppers) have been described by Jones (1968) and Maiden (1972). These are up to 10 m thick. Garnetite is commonly developed at the retrograde schist-sulphide rock boundary, the garnetite and droppers are discordant to the high metamorphic grade fabric and S_0. Projections of sulphide rocks along the axes F_2 and F_3 folds (Maiden, 1976) and projections of sulphides unrelated to regional tectonic structures suggest plastic flow of rheologically incompetent sulphides during deformation. These are locally known as droppers, are up to 12 m wide, have a strike of up to 120 m and project up to 60 m. They rarely project upwards. Sulphide projections commonly have a garnetite and/or quartz-bearing garnetite envelope (Jones, 1968), contain coarse-grained sulphides, display a cataclastic texture and are enveloped by schistose retrogressed pelite. Clasts comprise bleached metasedimentary wall rocks. On 21 Level, NBHC (Maiden, 1972), the No 1 Lens has intruded silicate rocks and the No 2 Lens and contains clasts of No 1 Lens, No 2 Lens, and silicified and garnetised wallrocks. On 20 Level, NBHC, a 50 m tongue of sulphides projects 50 m upwards from No 2 Lens and transgresses No 1 Lens (Maiden, 1972). This mass is highly brecciated, contains quartz veins emanating from the dropper into the wall rocks, contains clasts *inter alia* of garnetite up to 1 m across and is bounded by retrograde schist and garnetite. The timing of the sulphide projections is unknown and they probably occurred during D_1, D_2, D_3, D_4 and in the Delamerian Orogeny because one dropper contains a rounded clast of dolerite of the same composition as dolerite dykes emplaced between the Delamerian Orogeny and 820 Ma (G. Scott, pers. comm.). Although $S_{2/3}$ droppers derived from No 3 Lens have been identified in Block 14 Open Pit, the exposures are so limited that it is not possible to ascertain whether they have a garnetite rim as described by Jones (1968) and Maiden (1972) for similar features some 4 km south of the Block 14 Open Pit.

Garnet in sulphide rocks

Garnet occurs as a gangue mineral in all sulphide rocks as euhedral, rounded grains (? xenocrysts) and porphyroblasts. In the No 2 and No 3 Lenses, rare port-wine red garnet porphyroblasts can be up to 8 cm in size. Garnet occurs as isolated red to pink grains or in quartz-garnet laminae, commonly juxtaposed with blue quartz-gahnite laminae. Garnet is most commonly unzoned; fractures are filled with sulphides (especially galena and pyrrhotite) and commonly contain sulphide and quartz inclusions with spheroidal inclusions of quartz commonly in the garnet core and spheroidal inclusions of sulphides throughout the whole garnet grain. Rarely garnet forms a retrograde rim to gahnite.

In the Western Mineralisation, where garnet is in contact with quartz it is unretrogressed whereas where garnet is in contact with sphalerite, it has corroded grain boundaries and is retrogressed to biotite, pyrrhotite and sphalerite. In places, especially in C Lode and the Western Mineralisation, garnet has a manganese-rich rim and an iron-rich core.

Garnet envelope

An intermittent garnetite and quartz-bearing garnetite envelope invariably encloses both the Zinc and Lead Lodes. It is best developed in contact with retrograde rocks. Garnet contains inclusions of sulphides, quartz, biotite and rare sillimanite.

The margins of the sulphide rocks, especially the Lead Lodes, comprises garnetite and garnet quartzite suggestive of reaction between Mn^{2+}-rich sulphide rocks and the host aluminous metasediments to produce a quartz-spessartine and quartz-manganoan almandine rim to sulphide rocks (Jones, 1968). Field studies suggest that these garnet rims could have formed in D_1, D_2 and D_3. However, sulphide rocks hosted by retrograde shear zones of Delamerian Orogeny origin (e.g. Browne Shaft; Boots, 1972) and retrograde shear zones pseudomorphing $D_{2/3}$ high grade shear zones (e.g. Block 14 Open Pit, North No 1 Open Pit) and transgressing $D_{2/3}$ high grade shear zones (e.g. Block 14 Open Pit) have a garnetite or quartz-bearing garnetite envelope. In this setting, sulphide rocks invariably show a cataclastic texture and contain bleached clasts of metapelite, quartz-gahnite rocks and garnetite. There appears to be no textural, mineralogical or mineral chemistry differences between garnets formed during D_1, D_2, D_3, D_4 and those formed in retrograde shear zones as the garnet composition reflects the bulk rock composition of the sulphide rocks and the enclosing pelitic metasediments. The only way to ascertain whether garnet formed during D_1, D_2, D_3, D_4 etc is from mapping.

Garnetised dykes

Epidotised dolerite dykes have intruded the Willyama Supergroup, including the Broken Hill orebodies especially in the central part of the Broken Hill orebody (i.e. CML7) and including the Western Mineralisation at depth. Dolerite dykes have also been intersected in eastward drilling from the Broken Hill orebody. On the 25 and 26 levels, North Mine, Watson (1968) and Plimer (1968) observed that where dykes are hosted by the massive sulphide rocks of No 2 and No 3 Lenses, the dykes are fragmented and garnetised. Garnetisation post dates epidotisation of unknown age. Garnet has replaced the rim of the dykes and occurs as a network of veinlets in dolerite. The dykes are normally 40 cm in width, are altered to biotite at the margins of the sulphide masses, and within the enclosing silicate rocks are epidotised tholeiitic dolerite. In sulphide rocks, the concave parts of the dykes are wrapped around very coarse grained sulphides, there are injections of sulphide veinlets into the dykes and the dykes are also cut by quartz and actinolite veins.

If the dykes formed post-D_3 but pre-Delamerian, dyke fragmentation suggests that sulphide rocks must have moved during the Delamerian Orogeny and that garnetisation (i.e. addition of Mn from the intruded Mn-rich massive sulphide rocks) was associated with sulphide movement because the terminations of tabular masses of fragmented dykes are garnetised.

Where dolerite dykes have intruded the low grade Mn-poor Western Mineralisation on CML7, drill core intersections show that the dolerite has a 2 cm wide retrograde rim of biotite and no garnet is present. This is also the case where dolerite has intruded low grade SiO_2-rich Mn-poor Zinc Lodes hence, analogous to the garnet envelope, garnetisation of dolerite is related to the intruded sulphide rock composition.

Conclusions

On 1:10,000 scale, the Broken Hill orebody is stratiform within an identifiable stratigraphic horizon. The best indicator to sulphide rocks is a great diversity of manganoan almandine-bearing rocks. Garnet-rich exhalites are commonly associated with the sulphide rocks below, equivalent to and above the six main sulphide masses. On scales of 1:2,000 or less, the tonnage of the Broken Hill orebodies is controlled by stratigraphy, the grade is controlled by structure, the sulphides are cataclastic and the package of sulphide-silicate rocks has cooked in its own fluids producing a great diversity of garnet-rich rocks. Because of the massive rheological differences between galena-rich sulphide rocks and high metamorphic grade silicate rocks, thermal pulses and minor events of strain have probably moved sulphide rocks in the presence of fluids that have remobilised manganese to form quartz-bearing garnetite, garnetite and garnet envelopes to sulphide rocks. Garnet rocks formed by sulphide-silicate rock reaction during every identified deformation event; manganese was released during coeval deformation and metamorphism and replaced pelites to for garnet-bearing rocks.

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Tectonic Overview of the Curnamona Province

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Introduction

The Curnamona Province is a near-circular remnant of Palaeo- to Mesoproterozoic crust that is bounded by much younger structural boundaries (Robertson et al., 1998). At the surface, it records a history of sedimentation and syn-sedimentary magmatism from 1720 to 1640 Ma (Willyama Supergroup), deformation and metamorphism in the ~1600 Ma Olarian Orogeny, and early Mesoproterozoic magmatism coeval with magmatism in other provinces (e.g. the "Hiltaba event" on the Gawler Craton). The substrate of the supracrustal package is unknown, and inferences can be drawn only from analogy with other provinces (e.g. Mt Isa) and from a single deep seismic transect (Goleby et al., 2006). The shallow-water facies of some of the oldest exposed sediments suggests deposition upon continental crust.

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

Curnamona in relation to other late Palaeoproterozoic provinces in Australia

Northern Australia

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

Gawler Craton

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

Adelaide Geosyncline basement

Basement to the Neoproterozoic sediments includes the Mount Painter Inlier, which, by one interpretation (Teale, 1993), contains Willyama equivalents as well as a younger, early

Mesoproterozoic metasedimentary and metavolcanic package. In the basement inliers of the Mount Lofty Ranges, the Barossa Complex contains a granitic orthogneiss recently dated at 1718 Ma, similar in age though not chemistry to syn-Willyama magmatism of the Basso Suite (Belousova et al., in press; Szpunar et al., 2006).

Subdivision of the Curnamona Province

The Curnamona Province is divided into domains based on a complex of key differences of age, sedimentary facies and thickness, magmatism and metamorphism (Figure 1):

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

Tectonic evolution of the 1720-1640 Ma Willyama depositional basin

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

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

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

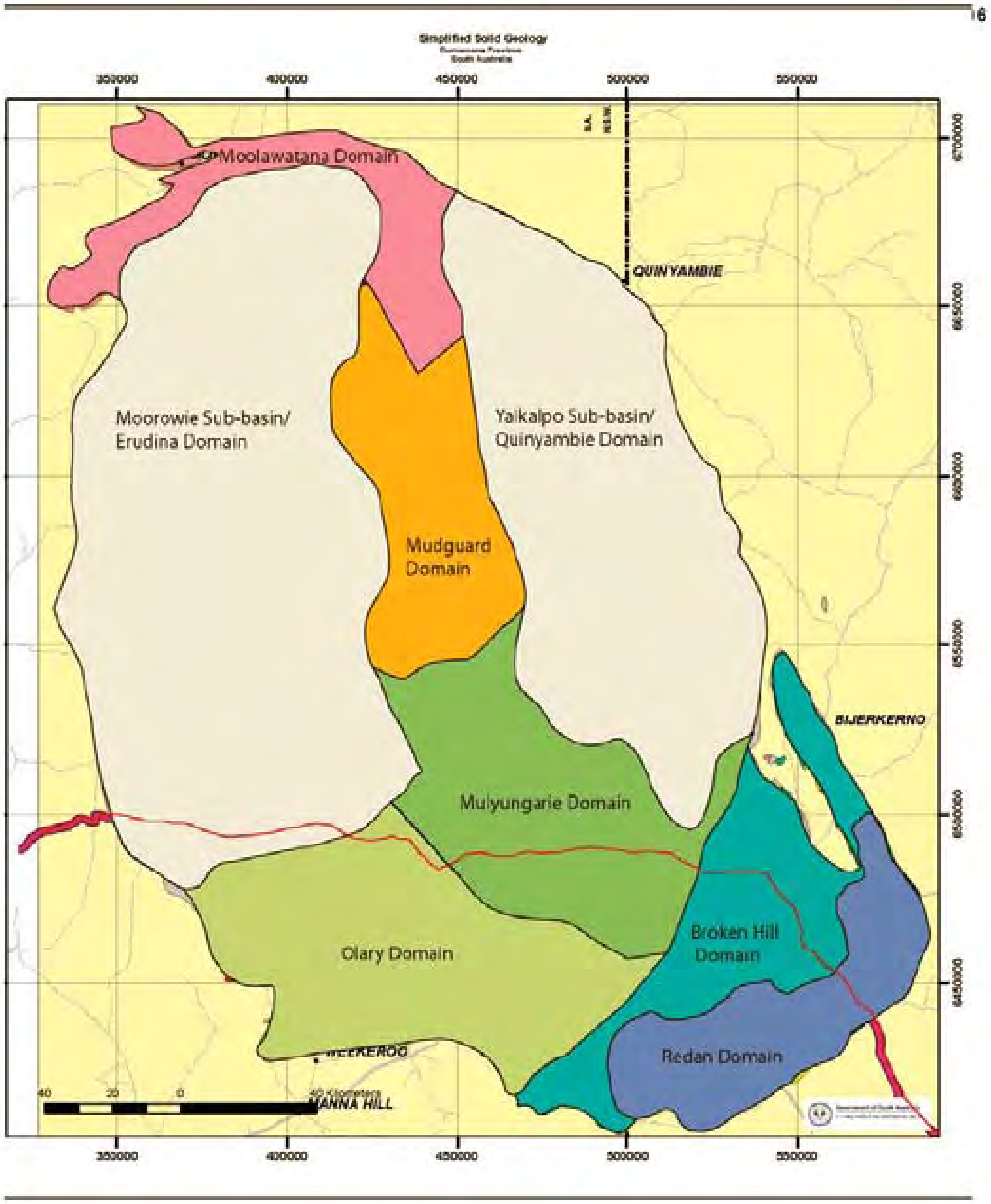

Figure 1. Domains of the Curnamona Province (after Conor et al., in preparation).

Upper rift packages and magmatism, ~1700-1670 Ma

In the upper (i.e. post-Thackaringa) Willyama Supergroup there are also important differences between the domains. The thin sulphidic carbonate, psammite and calc-silicate marker unit, the Bimba Formation, in the Olary Domain has long been correlated with the Ettlewood Calc-silicate Member of the Allendale Metasediments in the Broken Hill Domain, near the base of the Broken Hill Group. Correlation is strongly supported by the ~1693 Ma age obtained on the inferred volcaniclastic metasiltstone of the Plumbago Formation which directly overlies the Bimba Formation, and its equivalent in the Broken Hill Domain (Page et al., 2005). Thus the Bimba/Ettlewood – Plumbago couplet forms a through-going link between the two domains. However, the overlying stratigraphies differ markedly, reflecting the different tectonic settings of the Olary and Broken Hill Domains. Over most of the Olary Domain, pelite-dominated metasediments of the Saltbush Group overlie this couplet, and may be equivalent to either

Broken Hill Group or Sundown Group, or both, but mostly lack the distinctive lithologies, including “lode rocks” such as quartz garnetite, quartz-gahnite rocks and iron formations that occur in the Broken Hill Domain. The volcaniclastic “Potosi-type” gneisses such as the Hores Gneiss have no known equivalent in the Olary Domain. Mafic intrusives of the same age as those of the Broken Hill Domain do occur in the Olary Domain (Lady Louise Suite), but are mostly seen intruding the Curnamona Group (Conor and Fanning, 2001). Only in the Cathedral Rock-Blue Dam area are there thin intercalations of quartz-garnet rock and iron formation, and intrusive mafic sills in the Saltbush Group, which suggest correlation with the Broken Hill Group. These observations support earlier concepts that the Broken Hill Group was deposited in an active rift, and that its sediments lap out against an uplifted rift shoulder in the Olary Domain (Conor and Page, 2003), but the precise geometry of this rift and indeed the location of the bounding normal faults are yet to be elucidated.

Sag-phase sedimentation, ~1660-1640 Ma

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

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

Deformation and metamorphism

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

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

The implication is that the sedimentary pile was subjected to heating very early in its deformation history (W.P. Laing, 1995, pers. comm.; Stevens, this volume). Extensional tectonics have been invoked to explain this heating, but critical geochronological evidence does not support ideas of metamorphism coeval with sedimentation as proposed by Gibson and Nutman (2004), that is, prior to the Olarian Orogeny, which began at ~1600, possibly as early as 1620 Ma. Although the data permit extension immediately before the onset of contractional deformation to produce the early heating and layer-parallel foliation, the evidence for such extension is not strong. One possibility is that burial under a thick, largely pelitic (hence insulating) sedimentary blanket under conditions of high heat-flow, perhaps resulting from radioactive heating (Stevens, this volume) might produce an early, horizontal high-grade fabric. Another is that recumbent folding may have accompanied this heating, producing horizontal axial-plane fabrics, as suggested by Marjoribanks et al*.* (1980).

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

Repeated isoclinal folding greatly thickened the sedimentary pile and led to peak metamorphic conditions. Subsequently, the pile reacted to the deforming forces by more upright folding, traditionally termed “F2” in the Broken Hill Domain (Marjoribanks et al., 1980) and “F3” in the Olary Domain (Berry et al*.*, 1978). Such folds have more consistent orientations than the early isoclinal folds, forming a sweeping arc from ENE- (in the southern Olary Domain) through northeast- to north-south-trending axial traces (in the Broken Hill and Mulyungarie Domains). Plunge and plunge directions vary greatly and, though not sheath-like, the folds are clearly not all cylindrical. The vergence of the upright folds is not consistent, though northwest vergence is common in the Olary Domain. Upright folds in the Broken Hill area have been reconstructed with a slight easterly vergence (Stevens, 2004), and the tectonic relationships remain unclear. Metamorphic grade during upright folding also varies in different areas, but is still very high grade in the southern Broken Hill Domain, where a later phase of minor upright folding is considered retrograde (“F_3” of Marjoribanks et al., 1980).

Granites~1595-1580 Ma

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

Late Olarian deformation <~1580 Ma

Late Olarian deformation took the form of retrograde shearing in various orientations, but NNE-SSW and NNW-SSE trends are common. Some shear zones affect Ninnerie Supersuite intrusives and are therefore <1580 Ma. Associated east-west folds are locally quite intense. It is possible that exhumation of high-grade rocks in the southern part of the Curnamona Province took place at this time, since the overall trend of metamorphic isograds is east-west, consistent with uplift on a network of such retrograde shears. The Curnamona Province thus probably underwent overall northward tilting as a result, which allowed extrusion and subsequent preservation of ~1580 Ma volcanics over eroded folded, low-grade Willyama Supergroup in the Mudguard Domain, while the southern regions continued to be exhumed.

Neoproterozoic Tectonics, ~830-700 Ma

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

During the Sturtian glaciation (~720 Ma), the locus of rifting shifted eastward, resulting in normal faults that encircle and define the present boundaries of the Curnamona Province. Some may have used pre-existing structural discontinuities in the basement, but others were newly formed. Sturtian sedimentation records deposition in a number of eastward-tilting half-grabens on both sides of the province, with marked changes in thickness of stratigraphic units across normal faults. Proximal extremely coarse glacial debris (including megaclasts up to hundreds of metres) was dumped into a half-graben adjacent to the active MacDonald Fault (Preiss, 2006).

The remainder of Neoproterozoic and Early Cambrian sedimentation around the Curnamona Province records sag-phase deposition and deep burial of the marginal zones of the province, for example in the Moorowie Sub-basin as imaged at the western end of the seismic section (Goleby et al., 2006). In the central cratonic portion of the province, the cover is much thinner and flat-lying, being represented mainly by Marinoan and Cambrian deposits, apart from a small Torrensian to Sturtian-aged graben identified from the seismic section and very limited outcrop.

Delamerian Tectonics, ~515-490 Ma

Deformation

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

Metamorphism

Delamerian metamorphic grade in cover rocks ranged from essentially unmetamorphosed in the central, cratonic portion of Curnamona to lower amphibolite facies in the south, as recorded by calc-silicates in the basal Adelaidean. Geochronology has dated the growth of at least some garnet, kyanite and staurolite in basement rocks in the south as Delamerian (Dutch et al., 2006; Rutherford et al., in press).

Post-Delamerian events

Post-Delamerian events include intrusion of Early Ordovician felsic dykes in the Radium Hill area (Jagodzinski, 2006) and intrusion of granites and high-temperature veins in the Mount Painter Inlier at ~440 Ma (Elburg et al., 2003). The high-level hydrothermal system of the Radium Ridge Breccias and Mount Gee Sinter (Drexel and Major, 1987) are possibly of Permo-Carboniferous age (Idnurm et al., 1993).

Neotectonics

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

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The above summary is based on the work of many generations of geologists who have studied the Curnamona Province; only a small fraction of these could be referenced. Discussions over more than a decade with colleagues and collaborators, in particular Paul Ashley, Karin Barovich, Pete Betts, Andy Burtt, Chris Clark, Colin Conor, Wayne Cowley, Alistair Crooks, Mark Fanning, George Gibson, Martin Hand, Steve Hore, Liz Jagodzinski, Russell Korsch, Bill Laing, Mark McGeough, Rod Page, Ian Plimer, Stuart Robertson, Lachlan Rutherford, Barney Stevens, Mike Szpunar and Graham Teale, have helped to crystallise the ideas expressed about Curnamona tectonics, but in no way does the abstract purport to represent their very diverse views.

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The role of magmatic and exhalative rocks in the Broken Hill Systems: geochemical and isotopic evidence

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Summary

We present petrographic, geochemical (major, traces and REE) and isotopic (Sm-Nd, Rb-Sr, U-Pb) data from ca 1685 Ma high Fe-Ti mafic rocks (amphibolites), the Alma, Rasp Ridge and Hores-Potosi Gneisses, metasediments and "exhalites" from the Broken Hill Block. Our data confirms the ensialic rifting event in the Curnamona Province between ca 1710-1685 Ma, adding that rifting had reached thin lithosphere conditions by ca 1685 Ma and placing the Broken Hill Block in a central position of the developing basin. We infer a depleted mantle source (asthenosphere) for the mafic rocks and that Fe-Ti enrichment present in these lithologies is a result of fractional crystallisation. The Alma and Rasp Ridge felsic melts were generated by anatexis of crustal material from the Willyama sedimentary pile. The geochemistry of the Hores-Potosi Gneiss is best explained by mixing between these crustally derived melts and a juvenile mantle derived component, represented by the coeval mafic lithologies. The data on the exhalites is consistent with an origin via hydrothermal activity, with the fluids responsible for their deposition in equilibrium with the Willyama supracrustal sequence. We infer a crustal dominated source for the Pb of the Broken Hill orebody, with its metals provided by the Willyama Supergroup supracrustal pile. Exhalite deposition and Broken Hill orebody formation were coeval with the ca 1685 Ma magmatic activity.

Geochemistry of the amphibolites, granite gneisses and exhalites

Amphibolites and granite gneisses

The ca 1685 Ma (Raetz et al., 2002) high Fe-Ti mafic rocks occur throughout the lower Willyama Supergroup stratigraphy (Thackaringa and Broken Hill Groups) and are interpreted here as shallowly emplaced sills that were metamorphosed to upper amphibolite and granulite facies during the Olarian Orogeny (ca 1600-1580 Ma (Page et al., 2005b)). Our data indicate that the amphibolites originated by variable degrees of partial melting (15-20%) of a depleted mantle source at depths of approximately 35-40 km. This was followed by simple fractional crystallisation or by an AFC process involving only small degrees of crustal assimilation (r = 0.05-0.2). Fractionation occurred in high level magma chambers in a low fO_2 environment and involved manly olivine, clinopyroxene, with plagioclase fractionation occurring only during the final stages of the magmatic evolution. Fractionation proceeded along a tholeiitic trend of extreme Fe-Ti enrichment (up to 25 wt % of total iron as Fe_2O_3 and 4.2 wt % of TiO_2). We infer that low fO_2 retarded the saturation of magnetite until the final stages of fractionation. This process satisfactory explains the high content of Fe-Ti in the mafic rocks without the need to call for post-magmatic alteration (Phillips *et al.*, 1985).

The peraluminous characteristics and similar content of HFSE and REE of the Alma, Rasp Ridge and Hores-Potosi Gneisses (1704±3, 1683±3, 1685±3 Ma respectively, Page et al., 2005b), with respect to the sediments of the Willyama Supergroup, suggests that anatexis of the sedimentary pile was a significant petrogenetic process for the production of these felsic melts. This is consistent with the Nd isotopic composition of the Alma Gneiss ($\varepsilon Nd_{(i)}$: -4.6 to –5.35) and Rasp Ridge Gneiss ($\varepsilon Nd_{(i)}$: -3.35 to –3.89) which is essentially the same as the metasediments of the Willyama Supergroup ($\varepsilon Nd_{(i)}$: -4.44 to –5.76). The slightly less negative $\varepsilon Nd_{(i)}$ values for the Hores-Potosi Gneiss ($\varepsilon Nd_{(i)}$: -2.26 to -3.54) suggest mixing or contamination by a more juvenile, possibly mantle derived, isotopic component. Given the relatively high Fe-Ti content of the Hores-Potosi Gneiss this contaminant is likely to be coeval Fe-Ti enriched mafic magma, which often has close spatial relationship to the Potosi type gneiss in the field (eg. "potobolites"). Bulk mixing calculations using major element and the Nd isotopic composition of the mafic tholeiites and metasedimentary rocks as end members, shows that the overall geochemistry of the Hores-Potosi Gneiss requires about 20-30% of the mafic end member.

Pb isotopic composition of the amphibolites and granite gneisses

Pb isotopic ratios were measured on representative amphibolites, their plagioclase separates and the Rasp Ridge Gneiss, in order to compare with the Pb isotopic composition of the Broken Hill orebody (Parr et al., 2004). For the amphibolites and their plagioclase separates ^{206}Pb/^{204}Pb ranges from 16.034 to 21.524 whereas ^{207}Pb/^{204}Pb ranges from 15.364 to 16.103. The Rasp Ridge Gneiss values are more radiogenic with ^{206}Pb/^{204}Pb between 21.029 and 45.525 and ^{207}Pb/^{204}Pb ranging from 15.886 to 18.563. Despite some scatter all the data lie within error of a 1685 Ma isochron calculated using the Pb isotopic composition of the Broken Hill orebody as an anchor point. We interpret this data as evidence of a single, homogeneous Pb-isotopic reservoir at ca 1685 Ma. Since the overall geochemistry of the mafic and felsic gneisses suggests that the primary melts were derived from end-member sources (asthenosphere and crust respectively), it is unlikely that homogenisation of the Pb-isotopes was a magmatic or pre-magmatic process. Instead we infer that Pb-isotope homogenisation was a result of energetic and widespread supracrustal hydrothermal activity associated with formation of the Broken Hill orebody at ca 1685 Ma.

Exhalites

Unusual lithotypes commonly known as exhalites (Parr and Plimer, 1993) are relatively common in the Broken Hill Inlier. Interpretation of the origin of these rocks include: original exhalative sediments metamorphosed during the Olarian orogeny (Plimer, 1985; Parr et al., 2004); metasomatic rocks formed during or subsequent to metamorphism (Ehlers *et al.*, 1996) or; reaction products between partially melted ore bodies and surrounding pelitic rocks (Mavrogenes *et al.*, 2001). The lithologies sampled in this study can be broadly subdivided in two groups: group A are well banded rocks dominated by Qz-Mag-Gr-Ap whereas group B are more mineralogically diverse consisting of various combinations of Qz±Mag±Gr±Feld±Bi±Mu. Both groups have fractionated REE profiles commonly with negative Ce and positive Eu anomalies, consistent with an exhalative origin (Michard, 1989). Their Nd isotopic composition ($\varepsilon Nd_{(i)}$: -4.51 to –6.63) suggests that the hydrothermal fluids responsible for their deposition was in equilibrium with a crustal source, consistent with the Willyama Supergroup metasediments. In addition, despite an abundance of metamorphic zircon, we could not identify a single detrital zircon grain from samples of group A or group B exhalites. We infer a minimal clastic sedimentary component in the protolith – consistent with an exhalative origin.

Implications for the tectonic evolution of the Curnamona Province

Our results are consistent with a model of intra-cratonic rift for the Broken Hill Inlier as proposed by several workers (Willis et al., 1983; James et al., 1987; Stevens et al., 1988). In addition, comparison between the Broken Hill and Olary Inlier mafic lithologies provides further constraints to the tectonic evolution of the Curnamona Province.

The indication of a LREE and Nd isotope enriched source in the Lady Louise Suite of the Olary Inlier, lead Rutherford et al. (2006) to suggest a substantial input of the sub-continental lithospheric mantle in the petrogenesis of the Olary mafic lithologies. This is consistent with thicker lithosphere under Olary in comparison to the Broken Hill Block. We infer that the Broken Hill Block occupied an axial position in the developing rift whereas the Olary occupied a marginal position. This is consistent with the higher volumes of magmatic rocks in the Broken Hill Block and the inferred depocentre of the Broken Hill Group as discussed by Page et al. (2005a).

Implications for the genesis of the Broken Hill orebody

This study has shown that at ca. 1685 Ma the Broken Hill Inlier was site of bimodal magmatism and upwelling asthenosphere that lead to thinned lithosphere conditions, thus a tectonic environment with high geothermal gradient which is conceptually consistent with the formation of a large hydrothermal system capable of ore deposition. The hydrothermal system homogenized Pb-isotopic values and stripped metals from a large volume of the supracrustal pile. We interpret the ‘exhalites’ and the Broken Hill orebody as products of this supracrustal hydrothermal system, without the need to call on exotic sources of metals.

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Potential sources and relative timing of iron-oxide copper-gold mineralisation in the southern Curnamona Province

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Trace element and neodymium (Nd) isotopic analyses of sulphide and iron oxide mineral separates from iron oxide copper-gold (IOCG) prospects in the southern Curnamona Province (SCP) provide insights into the relative timing and potential sources of the IOCG mineralisation in this region.

Mineralisation is interpreted to have formed during two distinct hydrothermal events. The first of these events occurred during prograde metamorphism associated with the Olarian Orogeny (*ca* 1610 Ma). This event formed stratabound/stratiform mineralisation predominantly along the interface between the oxidised lower Willyama Supergroup and the reduced upper Willyama Supergroup. This type of mineralisation is observed at North Portia, Kalkaroo, Waukaloo and Polygonum prospects. $\varepsilon\mathrm{Nd}_{1610}$ values of the majority of sulphide separates from these prospects (-3.9 to -7.3) are comparable to whole-rock $\varepsilon\mathrm{Nd}_{i}$ values for the Willyama Supergroup metasedimentary sequence at *ca* 1610 Ma (Figure 1). However, some sulphides within the stratabound systems at North Portia, Kalkaroo and Waukaloo have $\varepsilon\mathrm{Nd}_{1610}$ values too evolved (-9.3 to -17.1) to be correlated with any known protolith in the SCP at *ca* 1610 Ma (Figure 1). Consequently, they were either derived from an as yet unidentified highly evolved source region (e.g. Archaean), or formed during a younger hydrothermal event. The majority of the sulphides in the stratabound prospects precipitated in equilibrium with a relatively light rare earth element (LREE) enriched fluid.

Mineral separates from IOCG mineralisation adjacent to shear zones reactivated during the Delamerian Orogeny (*ca* 500 Ma), at Copper Blow, Green & Gold and Lawsons prospects, have highly evolved $\varepsilon\mathrm{Nd}_{500}$ values (-13.5 to -18.6; Figure 1). The $\varepsilon\mathrm{Nd}_{500}$ values of these mineral separates are comparable to those of the highly evolved $\varepsilon\mathrm{Nd}_{i}$ values recorded in some of the stratabound prospects previously mentioned, and are comparable to εNd values for the Willyama Supergroup calculated at *ca* 500 Ma (Figure 1). Sulphide precipitation in the shear-related prospects likely occurred in equilibrium with a relatively less REE-enriched fluid.

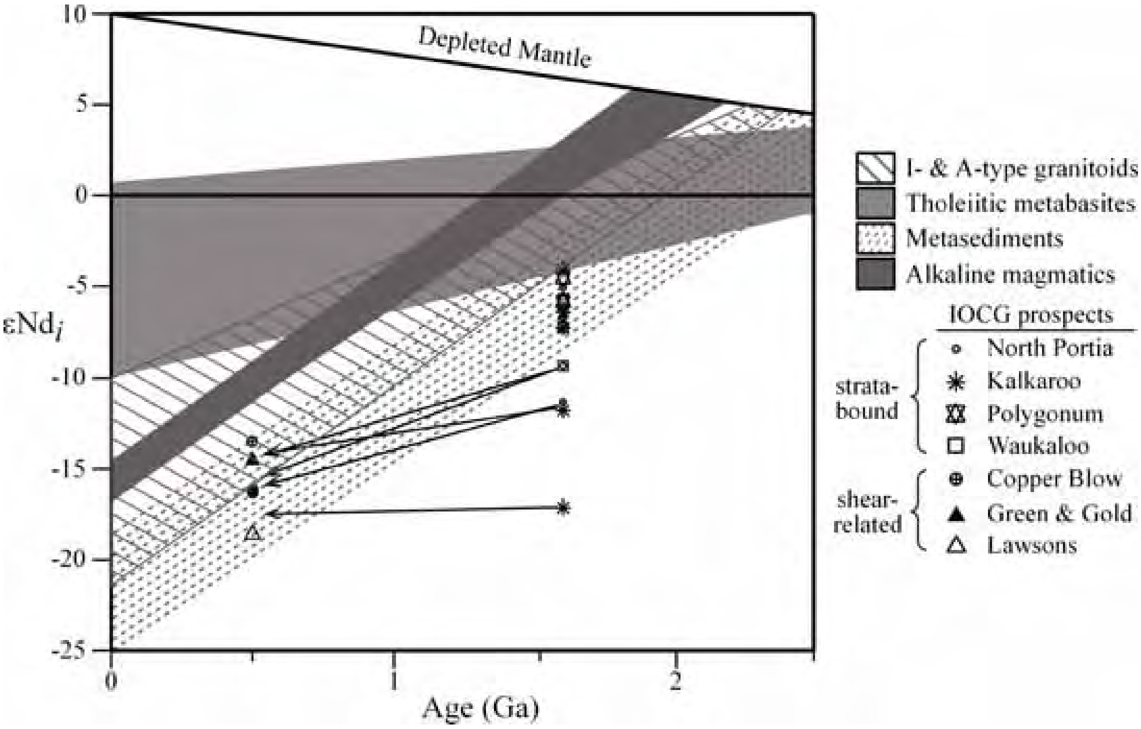

Figure 1. εNd$_i$ versus Age (Ga) of mineral separates and major lithological units that could potentially generate IOCG hydrothermal fluids. Initial Nd isotopic composition for stratabound mineralisation calculated at 1610 Ma. Shear-related Nd isotopic compositions calculated at 500 Ma.

The coincidence of the Nd isotopic signature of IOCG mineralisation and the surrounding Willyama metasedimentary units in the SCP (Figure 1), irrespective of the age of mineralisation, suggests that ore fluids were derived from metasedimentary units of the Willyama Supergroup. It is proposed that abundant carbonate, evaporitic and exhalative/inhalative horizons in the lower Willyama Supergroup produced highly saline, chlorine-rich fluids during dehydration as a response to prograde Olarian metamorphism (*ca* 1610 Ma). As fluids migrated through the lower Willyama Supergroup metasedimentary pile, metals were leached from the metasedimentary sequence. Sulphide precipitation took place predominantly along the redox boundary between the lower and upper Willyama Supergroup. Further upgrading of IOCG mineralisation may have occurred during hydrothermal activity associated with the intrusion of felsic magmatism between ~1590 – 1580 Ma.

A second mineralising event, commonly associated with shear zone reactivation, is interpreted to have occurred during the Delamerian Orogeny (*ca* 500 Ma). A similar process whereby the country rock was leached during hydrothermal fluid circulation is also interpreted to have occurred during this event. Minor remobilisation of IOCG mineralisation in the earlier formed stratabound/stratiform prospects may have also have occurred at this time.

The model proposed for the development of IOCG mineralisation in this study provides an alternative exploration model for this style of mineralisation in the SCP. The key ingredient for the formation of IOCG mineralisation is the circulation of fluid, whether of meteoric, magmatic or metamorphic origin, through the lower Willyama Supergroup metasedimentary sequence. Fluid circulation could be driven by any metamorphic or magmatic 'heat-engine'. Consequently, any number of tectonothermal events that occurred in the SCP could potentially mobilised metals, and precipitated them in favourable chemical or structural settings.

The Koonenberry Belt – Greenfield Ni Exploration

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Introduction

During 2004-2005 Inco Resources (Australia) Pty Ltd (Inco) acquired Exploration Licences 6343, 6344, 6397, 6398 and 6399 (approximately 2960 Km^2) within the Koonenberry Belt of northwestern NSW as a conceptual target for magmatic nickel deposits. The Koonenberry Belt is a Late Proterozoic to Palaeozoic fold belt that wraps around the eastern margin of the Palaeoproterozoic Broken Hill Block. It contains several ultramafic bodies (Macs Tank, Conns Creek, Mt Arrowsmith and Wyndonga near Packsaddle) that are possible hosts for nickel sulphide deposits, and regional geological interpretation indicates that there is potential to locate additional poorly-exposed or concealed mafic to ultramafic intrusive bodies within the belt.

Inco's initial exploration approach in the Koonenberry Belt involved assessment of regional magnetic and historical drainage geochemical data. The data clearly indicated that known exposed ultramafic intrusive bodies with anomalous Ni exhibit distinctive high amplitude magnetic features. A number of these magnetic anomalies were selected for evaluation through systematic detailed geological mapping, rock chip and soil sampling, ground magnetic traverses and ground TEM surveying.

Surface mapping and prospecting during this follow up program resulted in discovery of a previously unknown outcropping mineralised peridotite body at the Mt Arrowsmith East (MAE) prospect (EL 6399). The peridotite is a malachite-stained, weathered and elongate NNW striking body with exposed dimensions of approximately 210m x 30metres. Systematic rock chip sampling of MAE identified anomalous Ni, Cu, PGM and Ag with maximum values of 0.43% Ni and 1.47% Cu.

A recent drilling program at the MAE prospect confirmed the presence of up to 10% disseminated sulfides (pyrite, chalcopyrite and pyrrhotite) within the peridotite body. Preliminary assay results are in the order of 0.5% Ni and 0.45% Cu. Although the MAE prospect is clearly not of economic interest, the identification of an ultramafic body with disseminated sulfides and anomalous Ni is considered encouraging for the grassroots nickel prospectivity of the Koonenberry Belt.

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Partial melting of the Broken Hill lead-zinc-silver deposit: Fact or fiction?

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Introduction

Based in large part on the results of published experimental studies in the systems Fe-Pb-Zn-S and Pb-Fe-S, Lawrence (1967) suggested that the Broken Hill (BH) Zn-Pb-Ag ore deposit partially melted during peak high-grade metamorphism. Recently, this view was supported by Mavrogenes et al. (2001, 2004), Frost et al. (2002, 2005), Sparks and Mavrogenes (2005), and Wykes and Mavrogenes (2005). The aim of the present contribution is to evaluate the partial melt hypothesis as it pertains to sulphides in the Broken Hill deposit, Australia.

The effects of metamorphism on Broken Hill sulfides

Phillips (1980) showed that there was increase in regional metamorphic grade southward in the Broken Hill Domain with the BH deposit being subjected to peak metamorphic conditions of 780°C and 5.2 kb. Temperatures as high as 826° ± 29°C were obtained by Frost et al. (2005) from Black Bluff, 5 km SE of the deposit but no P-T studies have shown that the orebodies were ever metamorphosed to conditions higher than those originally suggested by Phillips (1980).

Experiments of Mavrogenes et al. (2001) in the system Pb-Zn-Fe-S show that the eutectic is 830°C at 5 kb and 850° to 870°C at 10 kb (average of 860°C). Based on these data, the first melt should form at ~838°C at 6 kb. This temperature is higher than the peak metamorphic temperature at BH. Mavrogenes et al. (2001) added 1 wt. % AgS to saturate their experiments and suggested that the eutectic will be lowered to <810°C, assuming a pressure of 5 kb. However, the amount of AgS added to their experiments was unrealistically high as it does not match the amount of Ag in the BH orebodies. In their experiments, they used a starting pyrrhotite composition of N_{FeS} = 0.960, which they based on the work of Bryndzia et al. (1990). Mavrogenes et al. pointed out that this S-rich pyrrhotite, rather than pure FeS (or troilite), will lower the solidus in the system Pb-Zn-Fe-Ag-S to 795°±5°C at 5 kb. This temperature will be about 803°C if a pressure of 6 kb is assumed. However, the average pyrrhotite composition of Bryndzia et al. (1990) was N_{FeS} = 0.953 not 0.960. This will raise the eutectic temperature even further. Monoclinic pyrrhotite compositions with N_{FeS} > 0.953 formed along with secondary pyrite upon retrograde cooling of the BH deposit. Mavrogenes et al. (2001) further suggested that impurities such as As, Sb, and Bi would have lowered the solidus temperature as peak metamorphic conditions were approached. Using the data of Johnson and Klingner (1975), the total range of trace element concentrations ranges from 2,473 to 3,391 ppm (or 0.25 to 0.34 wt %) ppm for four of the six orebodies (B and A lodes, 1 and 2 lenses), and 6,622 ppm (or 0.66 wt

%) for 3 lens. More than 60% of the trace element content of 3 lens is As (3,985 ppm). Despite the occurrence of a wide variety of rare sulphides and sulfosalts in pockets in the deposit, the concentration of these elements is small (0.25 to 0.66 wt %) by comparison with the two major ore elements and will lower the solidus by <20°C.

Mavrogenes et al. (2004) correctly argued that the ore system at BH was better represented by the system Pb-Zn-Fe-Mn-Ag-S than the Mn-free system. Experiments by them showed that when Mn-bearing sphalerite (in the presence of pyrrhotite and galena) was sandwiched between layers of pelite at 5 kb for one week at various temperatures, a Mn-silicate halo formed along the contact between the sulphides and melt and that experiments without a so-called "sulphide melt" did not form a Mn-silicate halo. Johnson and Klingner (1975) showed that ore concentrates analysed from 1961 to 1970 contained 3.8 wt. % MnO (or 2.9 wt % Mn) and 11.9 wt. % Zn. If it is assumed that all the Zn in the original ore-forming solution was in the form of sphalerite or wurtzite (ZnS) then approximately 24% of the tetrahedral site of the Zn sulphide was filled with Mn. Note that this figure is only a minimum value since the wall rocks, where most of the Mn-rich rocks occur, was not mined and not incorporated in the metal budget of Johnson and Klingner (1975). The Mn content of sphalerite at BH is also <1 wt. % Mn. It is likely that the protolith of the Mn-bearing rocks at BH was composed of Mn carbonates, oxides, and hydroxides rather than Mn-rich sphalerite/wurtzite.

Mavrogenes et al. (2001) also considered the effects of water on sulphide melting and cited the work of Naldrett and Richardson (1968) who concluded that "water does not have any influence on the melting temperatures of pyrrhotite-magnetite mixtures and would almost certainly be the same for oxide-free iron-bearing sulphide systems." Despite this conclusion, Wykes and Mavrogenes (2005) proposed that the addition of water depresses the solidus in the system FeS-PbS-ZnS by 35° ± 5°C relative to the dry eutectic of 900°C and 1.5 GPa. It is unlikely that the conclusions derived from these experiments are appropriate since the P-T conditions used in their experiments do not match those at BH. Furthermore, the aH_2O at BH was ~0.5 at peak metamorphic conditions (Phillips, 1980), which is lower than that used in the experiments of Wykes and Mavrogenes (2003).

Is there evidence for partial melting at Broken Hill? - A discussion

Frost et al. (2002) evaluated phase diagrams 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 and concluded there was a melt phase present in all of them for T between 280°C and 496 °C. Of these systems, only the system Fe-As-S has been investigated at P >1 bar. Despite the absence of experimental work in these systems at pressures of 5-6 kb, there is little doubt that partial melting would take place. However, the proportion of sulphides in these systems is *insignificant (i.e. < 0.0001 volume %)* when compared to the volume of sulphides in the system Pb-Zn-Fe-Mn-Ag-S,

If sulphides did melt, melt textures would not be preserved in sulphide masses because of subsequent deformation and recrystallisation during the protracted metamorphic history that affected the BH deposit. Sparks and Mavrogenes (2005) proposed that the only direct evidence of sulphide melt are SMINCs, within garnet in garnetite and in quartz veins as "planar features". They argued that SMINCs, which consist of galena, sphalerite, arsenopyrite, chalcopyrite, tetrahedrite-tennantite, argentite, dyscrasite, gudmundite, fluorite, calcite, chlorite, and quartz, formed directly from a homogeneous melt and crystallised upon cooling. Sparks and Mavrogenes (2005) recognized as many as eight phases in inclusions within garnet. However, an important feature of the sulphide inclusions at BH is that they formed in open systems since the inclusions commonly occur in fractures in quartz and garnet or along grain boundaries. Note that SMINCs also occur in contact with minerals, such as chlorite that formed during the retrograde event. Melt experiments by Sparks and Mavrogenes (2005) of SMINCs at temperatures and pressures as low as 720°C and 5 kb reinforced the concept to them that the orebody had melted. However, if SMINCs are evidence for sulphide melting, it is impossible to explain the presence of negative crystal-shaped monomineralic inclusions of sphalerite and galena adjacent to multi-phase low temperature SMINCs because the melting points of galena and sphalerite at 1 bar are 1115°C and 1850°C, respectively. Moreover, there is no textural evidence that proves SMINCs did not form during retrograde metamorphism and that the concentration of the SMINC assemblage is related to differential sulphide mobility rather than melting. The same minerals that occur in so-called SMINCs also occur in massive ore along the grain boundaries of the most common sulphides at BH, sphalerite, galena, and pyrrhotite, and in fractures. These minerals formed primarily by unmixing of a sulfosalt (possibly tennantite-tetrahedrite) in response to cooling.

Frost et al. (2002) used interfacial angles of galena against sphalerite-sphalerite pairs in the BH ore, which range from 5° to 115°, to argue that they reflect sulphide melting rather than solid-state equilibration. The likelihood that original melt textures have been retained throughout the complex deformation and metamorphic history is tenuous at best. Not only will the sulphides have recrystallised but they will also reflect directed stress associated with retrograde metamorphism. Based on the results of experiments carried out between 280° and 980°C, Lusk et al. (2002) derived a sulphide geothermometer based on the dihedral angle in sphalerite-galena-sphalerite triple junctions. They applied the results of these experiments to four massive sulphide deposits, including BH. Lusk et al (2002) obtained a peak metamorphic temperature of only ~700°C. Lusk et al. argued that the range of dihedral angles present in sulphides from BH was recording temperatures from 700°C down to 540°C. Their data reinforces the concept that the ore has continuously reequilibrated during a retrograde cooling path and that the interfacial angles cannot be used as evidence for melting as proposed by Frost et al. (2002).

Sulphide-filled projections into the country rocks occur at a range of scales from millimetre sized veinlets to sulphide dikes or so-called "droppers", which extend into the country rock for up to 160 m. Droppers project upward and downward from the main lodes and are enriched in silver and lead relative to them. Sparks and Mavrogenes (2005) proposed two different types of droppers, a tectonised variety (type D) and a partial melt variety (type P). They suggested that type P droppers were injected into the wall rocks during peak metamorphism when the orebody was molten. However, on a gross scale, droppers primarily cut the fabric in the wall rocks and have a retrograde schist zone and retrograde mineral assemblages along their margins. Furthermore, a dropper in the old Zinc Corporation mine contains clasts of uralised dolerite dyke that formed post-850 Ma, when temperatures were well below peak metamorphic conditions. We suggest that droppers are not products of partially molten melts but were derived by plastic injection of sulphides into the wall rocks.

Frost et al. (2002) and Mavrogenes et al. (2004) suggested that manganese-rich rocks formed as a result of a reaction between a sulphide melt and surrounding silicates. If this was the case, then these rocks should envelope each orebody. However, garnetite and quartz garnetite have a patchy distribution and there is no systematic zonation of these rocks with respect to each other and the orebodies. If the Mn-Ca rocks around the orebodies are reaction halos produced by melting, it is impossible for the melt model to explain the presence of: Mn-rich rocks with sulphides in the southern Curnamona Province (SCP) that were metamorphosed to temperatures and pressures well below the peak metamorphic conditions required to produce melting in the system Zn-Pb-Mn-Ag-Fe-S; several layers of garnet-rich rock in the central part of the mine that show no spatial relationship to sulfides; and thick intersections of garnet-quartz-hedenbergite and garnet-rich rocks in the Western and Eastern Mineralisation that were intruded by folded rhodonite veins. Although Frost et al. (2002) noted that Mn-rich rocks may form by exhalative processes and by melting, quartz-garnetite and garnetite in and adjacent to the Broken Hill deposit exhibit the same mineralogical, textural, and chemical characteristics as those metamorphosed to upper greenschist-lower amphibolite facies in several locations in the Olary Domain. Frost et al. (2002) suggested that Mn-rich rocks formed by melt processes will lack compositional layering, cut the regional fabric, and be markedly high in variance. However, there are manganiferous garnetites and quartz-garnetites that fulfil these criteria that occur throughout the SCP in the absence of sulphides. For these situations, the implication of the melt model is that wherever garnetite and quartz garnetite are present there should be massive sulphides that partially melted. Clearly, this is not the case as shown by the presence of lode rocks without sulphides throughout the SCP.

Laing et al. (1978) demonstrated that the mine sequence at BH, including the 6 major orebodies, occurs on a single inverted limb of an F_1 fold. This folding resulted in an inverted metal zoning pattern typical of syngenetic massive sulphide deposits. However, Mavrogenes et al. (2001) argued that the inverted metal zoning pattern could have resulted from partial melting with the Zn lodes being the residual of the Pb-rich melt. In such a scenario, one would expect to find altered rocks between orebodies and zoned stringers of sulphides between the orebodies, notwithstanding the complex folding that has affected the orebodies. Such features are not observed at Broken Hill. However, a bigger problem with the Mavrogenes et al. sulphide segregation model is that it cannot explain the orebody zonation at the Pinnacles deposit, which also occurs in the two pyroxene zone in the Willyama Domain. A Zn-rich "restite" occurs stratigraphically above *and* below the Pb-lode orebody at the Pinnacles deposit. Despite considerable drilling of the Pinnacles deposit, a Pb-rich orebody, which would be required by the segregation model of Mavrogenes et al., has not been found stratigraphically below the lowermost Zn-rich lode. Furthermore, there is a strong stratigraphic control on the orebodies and one of the zinc lodes (B lode) contains lode pegmatite which could not have formed as a restite.

Conclusions

Despite considerable attempts to mimic the ore system and the peak metamorphic conditions at Broken Hill, Mavrogenes and co-workers have been unable to conclusively demonstrate that the presence of water, Ag, Mn, and other trace elements in the ore prior to metamorphism were sufficient to lower the solidus in the system Pb-Zn-Fe-Mn-Ag-S to 780°C, the peak metamorphic temperature determined by Phillips (1980). However, there is evidence of partial melting of an insignificant amount of sulphides at Broken Hill. However, we contend that there is no evidence for melting in the system Pb-Zn-Fe-Mn-Ag-S, large scale movement of sphalerite-galena-rich ores, and the formation of the Mn-halo around the deposit as a result of reaction between partially molten Mn-bearing sulfides and aluminous country rocks.

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Advances in Understanding Broken Hill Geology

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In recent years there have been significant advances in understanding various aspects of Broken Hill geology, especially geochronology, stratigraphy, sedimentology, igneous petrology and mineral deposit geology. Structural geology is still a major area of uncertainty: the deformation history, the 3-D configurations, and the temperature-pressure history. Related to this is the tectonic history: how did Broken Hill rocks get to ~20 km depth and why did maximum metamorphic temperature reach ~900º C? How and when were the rocks exhumed? The fluid system that formed the Broken Hill orebody is another topic not well understood. A further area of uncertainty is the stratigraphy and structure of the Broken Hill mine area. Some of these topics are pursued in this abstract, others elsewhere in this volume.

Stratigraphy, Geochronology and the Origins of Rock Types

The stratigraphic interpretation of Willis et al. (1983) and Stevens et al. (1983) was established before the advent of modern zircon U-Pb geochronology. SHRIMP zircon geochronology by Page et al. (2005) and Stevens et al. (in press) validated the stratigraphic order and created a time framework of deposition from about 1720 Ma to 1640 Ma. This and other zircon geochronology have provided a basis for reinterpreting the origins of certain rock types, which in turn requires a redefinition of some stratigraphic units.

A number of quartzo-feldspathic gneisses were considered by Brown et al. (1983) to be metavolcanic rocks, while others considered them to be later intrusions. Stevens and Barron (2002) confirmed the volcanic or volcaniclastic nature of the “Potosi-type” gneiss that comprises most of the Hores Gneiss. Vernon and Williams (1988) and Vassallo and Vernon (2000) considered the granite gneisses (Rasp Ridge Granite Gneiss and Alma Granite Gneiss) to be granites emplaced during high grade deformation(s). Page et al. (2005) determined the crystallisation age of the Rasp Ridge Granite Gneiss as 1683±3 Ma, too young for its stratigraphic position, and therefore not a metavolcanic rock. It was emplaced as a shallow, sill-like granite body at the base of the Broken Hill Group at the time of deposition of the Hores Gneiss or lowermost Sundown Group. Zircon U-Pb dating of several other granitic gneisses gave ages between 1704 Ma and 1685 Ma (Figure 1). These granite sills are grouped as the Silver City Suite of granites (Stevens et al., in press), and all intruded the Thackaringa Group and/or lower Broken Hill Group at very shallow depths. As intrusive rocks, they cannot remain part of the Thackaringa Group.

Similarly most or all of the basic gneisses (amphibolites and hornblende granulites) are now interpreted as sub sea-floor sills and dykes (Stevens, 1998), and therefore should not be used to define stratigraphic units. Crawford (abstract, this volume) showed igneous fractionation within some individual basic gneiss bodies, confirming that those bodies are sills. Zircon U-Pb dating of samples from several areas produced dates of ~1690 Ma, although precise dates are

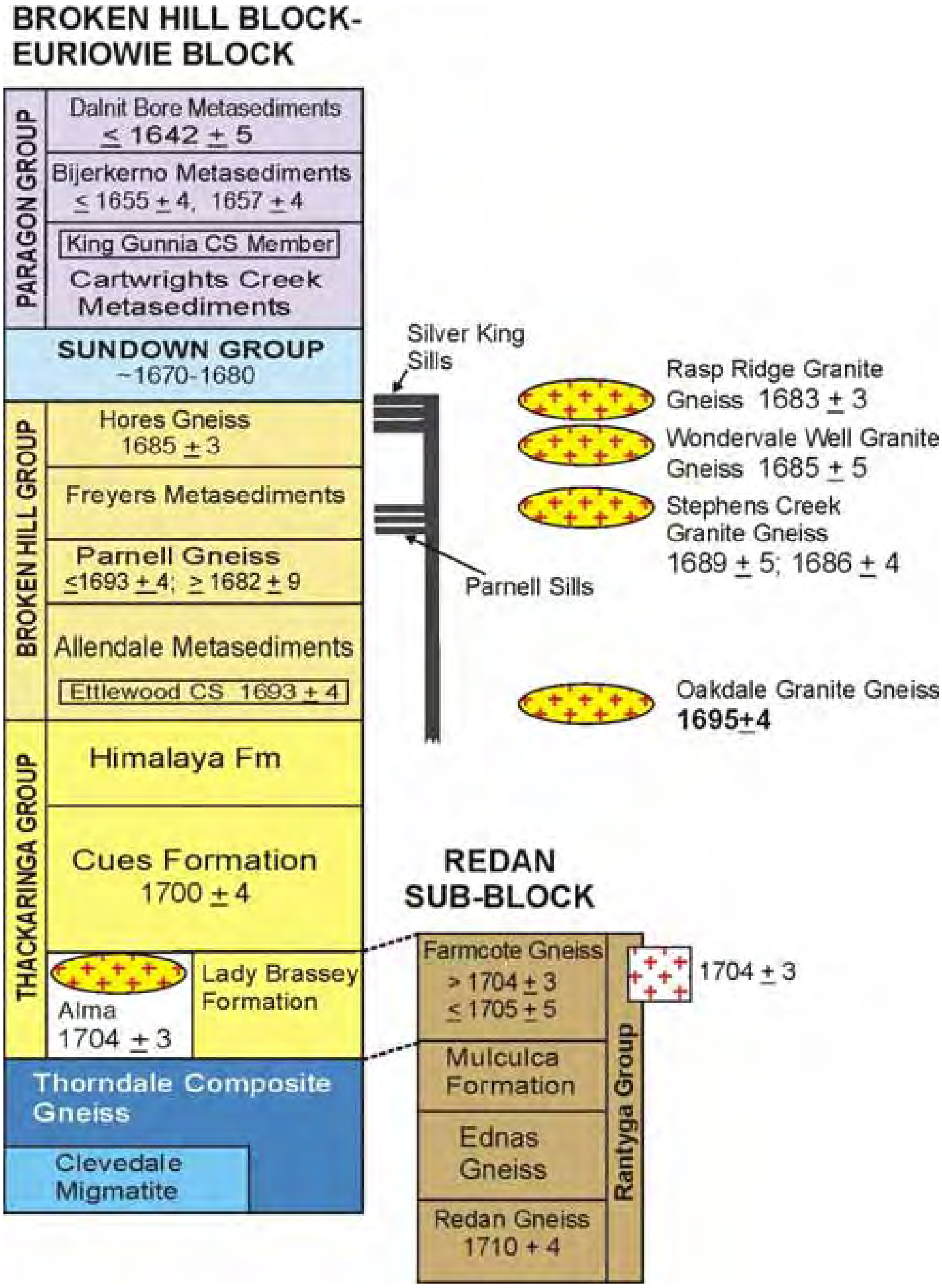

Figure 1. Stratigraphic column for the Willyama Supergroup, Broken Hill and Euriowie Blocks, showing new dates and revised nomenclature.

scarce. Most of the 1704-1683 Ma granite gneisses are intruded by basic gneiss bodies, but none intrude the Sundown or Paragon Groups. Basic gneisses previously included in the Parnell Formation, are now interpreted as the Parnell Sills, requiring redefinition of that formation. Conor et al. (in press) introduce the term Parnell Gneiss to apply only to the “Potosi-type” gneiss that was a component of the previous Parnell Formation. Where this gneiss is missing, its stratigraphic position may be inferred with less certainty, by sills of basic gneiss. The Silver King Formation was defined on the basis of abundant amphibolites. These preserve the textures and chemical fractionation of sills, and are renamed the Silver King Sills. It is likely that they were emplaced during early Sundown Group time. The name Silver King Formation is discontinued.

"Potosi-type" gneiss and leucogneiss in the Cues Formation, inferred to be volcanic or sedimentary/volcanic, are dated at 1700±3 Ma (Stevens et al., in press), but so far the ages of the underlying Himalaya Formation, Thorndale Composite Gneiss and Clevedale Migmatite have not been determined.

In the Redan geophysical zone on the southeast margin of the Broken Hill Block, a poorly-layered quartz-albite-K-feldspar-magnetite gneiss interpreted as a metavolcanic rock, from the Redan Gneiss, gave a SHRIMP zircon U-Pb age of 1710± 4 Ma (Stevens et al., in press). At the inferred stratigraphic top of this zone (Stevens and Corbett, 1993), an albitic metasediment from the Farmcote Gneiss gave a maximum (detrital) age of 1705±5 Ma (Stevens et al., in press), while an adjacent felsic leucogneiss (deformed granite) provides a minimum age of 1703±3 Ma and 1705±3 Ma (Page et al., 2005). Thus the Redan geophysical zone appears to consist of a thick pile deposited during a ~5 million year interval between~1710 and 1705 Ma. This zone is distinguished from the remainder of the Broken Hill Block by its highly magnetic character and mostly low gravity response. The name Rantyga Group is proposed to include the constituent formations: Redan Gneiss, Ednas Gneiss, Mulculca Formation and Farmcote Gneiss.

Sedimentology and Sequence Stratigraphy

Graded beds (Glen and Laing, 1975) in metasediments of the Willyama Supergroup have been used extensively to determine sedimentary younging. The presence of graded beds led to interpretations of the siliciclastic metasediments of the Broken Hill and Sundown Groups as deep water turbidites. Jon Wright, the first sedimentologist to study the Willyama Supergroup, reinterpreted the Broken Hill Group metasediments as shallow marine shelf sediments with occasional storm beds (Wright et al., 1987, 1993). Stevens et al. (1988) noted that most beds in the Broken Hill and Sundown Groups are not graded and interpreted these siliciclastic metasediments as shelf muds and silts, occasional storm-surge turbidite sands, and thick, shallow marine sheet sands.

Dyson (2005) also interpreted shallow shelf conditions for the Broken Hill, Sundown and lower Paragon Groups, identifying various transgressive systems tracts and highstand systems tracts. Dyson's sequence boundaries and sub-sets may be useful stratigraphic markers within the metasediments, permitting correlations where other markers are absent.

Sedimentology of high grade metamorphic rocks is daunting for most geologists who lack the appropriate training, and for sedimentologists who mostly avoid deformed rocks, but could be very rewarding. In many places the Willyama Supergroup retains bedding geometry and ratios of sand/silt to mud. Very delicate sedimentary structures retained in tourmaline-quartz rocks enabled Graham Bradley (pers. comm. 2005, 2006) to identify tidal couplets and micro-hummocky cross-stratification in Freyers Metasediments (4.6 pelite equivalent) not far below the Hores Gneiss. These structures indicate a relatively shallow marine setting with tidal influence.

Ore Deposit Studies

Reliable zircon geochronology combined with reinterpretation of rock origins has changed interpretation of the setting of the Broken Hill orebody. The interpretation of relatively shallow water depths just before deposition of the Broken Hill orebody, implies low confining pressure on the fluids that deposited the orebody. It is probable that the fluids boiled below the seafloor, depositing sulphides within the sub-seafloor sediments. Shallow level granite sills (granite gneisses) and sub seafloor ferrotholeiite sills (basic gneisses), emplaced during Broken Hill Group to very early Sundown Group time, may have supplied ore components and/or heat.

Isotope studies have placed constraints on the nature of the Broken Hill fluid system. Sulphur isotopes from the orebody (Spry, 1987) have a narrow range of values, appropriate for magmatic sulphur, but probably not for seawater. Cartwright (1999) related a systematic variation in oxygen isotopes across the Broken Hill Block, to pre-metamorphic alteration associated with mineralisation. High-precision double spike Pb isotope analyses suggest that Broken Hill type deposits formed over a time interval of about 16 million years (Parr et al., 2004). The lenses of the Broken Hill orebody were deposited over ~6 million years, not in stratigraphic order. The Pb isotope data support the conclusion from sedimentology that at least some lenses of the Broken Hill orebody formed beneath the seafloor, as did some of the smaller BHT deposits in the district.

Webster's (unpublished) series of mine level and sub-level maps are the basis for all future research on the Broken Hill orebody. Similarly Walters' (unpublished) study of wallrock alteration should set the stage for future research. The degree and implications of sulphide melting in the orebody is controversial (Sparks and Mavrogenes, 2005; Spry, this volume).

Advances in understanding Broken Hill's Pt-Ni-Co deposits were made in a recent exploration program by SIPA Resources Ltd. The mineralisation is associated with altered mafic-ultramafic intrusions probably related to Adelaidean tholeiitic flood basalts. The intrusions are emplaced along curved shear zones, possibly deformed in the Delamerian Orogeny.

Structural Geology

The first credible modern structural interpretations (Laing et al.,1978; Marjoribanks et al., 1980; refined by Laing, 1996) identified very large recumbent F_1 folds, large F_2 folds with steep- to fairly shallow-dipping axial planes, and some large F_3 folds with vertical axial planes. S_1 and S_2 are high grade schistosities, while S_3 is mostly muscovite grade.

White et al. (1995) emphasised the role of high temperature shears, interpreted the Broken Hill Block as a series of thrust sheets with individual deformation patterns and claimed that the stratigraphic sequence was deformed beyond recognition.

Gibson and Nutman (2004) and Gibson et al. (2004) claimed that D_1 extended from about 1700 Ma to 1640 Ma, produced no folds, but was characterised by an amphibolite-granulite grade schistosity. Their D_2 produced recumbent folds with large areas of downward-younging stratigraphy. These interpretations were refuted by Conor et al. (2005) and Stevens (2006).

It is probable that all of the researchers have discovered some of the answers, but not all of the answers. A few areas could provide vital keys. The Paps Synform area north of Yanco Glen is one which has been studied by several researchers over the last few decades.

The Paps Synform

The Paps Synform is a south-closing, north-plunging structure with a steep easterly-dipping axial plane. Metamorphic grade is andalusite-muscovite on the eastern limb and sillimanite in the hinge and western limb. Corbett (1979) interpreted this as essentially an F_2 fold.

Gibson et al. (2004) observed a relatively shallow-dipping S_2 schistosity cutting the eastern limb of the Paps Synform at a very high angle, and concluded that their S_2 must be axial plane to a major fold. But the eastern limb exhibits a uniformly steep easterly dip, with no sign of folding. Clearly, in that area S_2 is not associated with major folding.

Willis (1999) found a steeply east-dipping biotite grade axial plane schistosity (termed S_p) in the hinge of the Paps Synform. This overprints and deforms a relatively shallow-dipping high grade schistosity (S_2) that is axial planar to minor inclined to recumbent west-verging folds. S_2 is commonly oriented at a high angle to bedding and is probably the same feature identified as S_2 by Gibson et al. (2004). Willis (1999) also found hints of a high grade S_1 sub-parallel to bedding. A strongly-developed muscovite-dominant S_3 schistosity overprints S_1, S_2 and S_p. S_3 strikes NNE, nearly parallel to the strike of the axial plane of the Paps Synform.

Forbes et al. (2004) interpreted Willis' S_3 as the axial plane structure of the Paps Synform. However, both limbs and the axial plane of the Paps Synform dip steeply east, while S_3 is near-vertical, so overprints and post-dates the Paps Synform.

How Many Major Deformations

Marjoribanks et al. (1980) found three major deformation events, high grade D_1 and D_2 followed by lower grade D_3. S_3 was typically defined by muscovite, but areas of undeformed, near-vertical sillimanite-bearing schistosity resemble their S_3. S_2 of Gibson et al. (2004) and Willis (1999) is different in orientation from S_2 of Marjoribanks et al. (1980), which is more like Willis' S_p. Work under way by Bill Collins (JCU, pers. comm., 2006) in the Broken Hill-Southern Cross area, found a relatively shallow-dipping S_2, overprinted by an upright S_3 that was accompanied by melting. Stevens (2004, 2006) mapped zones of intense near-vertical schistosity (corresponding to Collins' S_3) in which numerous parallel high grade S_3 shears slice the metasediments into disconnected slivers. Collins interprets the Broken Hill Synform of Laing et al (1978) as an F_3 fold.

Evidence is accumulating for three high grade schistosities, followed by a sporadically-developed muscovite grade S_4. The S_4 schistosity may have developed at the same time as some of the retrograde shear zones.

Sheath Folds?

Hills et al. (2001) and Forbes et al. (2004) proposed large scale sheath folds, a concept dismissed for years due to lack of small-scale examples. Perhaps if the closures of large sheath folds are sufficiently open, small scale sheaths may not develop. The sheath fold concept was pursued by Stevens (2004), to explain phenomena observed in mapping and difficult to explain by other means. Stevens (2004) concluded that form surfaces mapped at 1:25 000 scale could be explained by early recumbent folds overprinted by later doubly-plunging to sheath-like folds, with minor modification by a further generation of folds.

Although Stevens (2004) favoured the existence of recumbent folds preceding the sheath folds, he recognised that shallowly-plunging sheath folds would produce large areas of downward-younging stratigraphy without any need for pre-existing recumbent folds.

Metamorphism, Melting, Deformation and the Heat Source

Despite previous confusion, recent reliable zircon U-Pb dating (Page et al., 2005; Stevens et al., in press) shows that high temperature metamorphism and accompanying deformation in the Broken Hill Block was confined to the period ~1600-1590 Ma. Support for this conclusion is given by the lack of high-angle unconformities in the Willyama Supergroup, implying no major deformation between about 1720 Ma and 1640 Ma.

The first two and possibly three deformations were coincident with high temperature metamorphism, as shown by the high grade mineralogy of the axial plane schistosities. This poses questions: 1. were there deformations at low metamorphic grade before the high grade metamorphism? 2. If not, were the rocks raised to high temperature before deformation occurred? 3. What was the source of heat?

There are no reports of folds either in bedding or in gross stratigraphy, pre-dating high grade S_1, so it is likely that the recognised D_1 was the first deformation. Bruce Hobbs (BHEI 2000 Conference, pers. comm.) suggested that relatively cold crust, thickened to 55 km by nappe-style folding would take 50-100 million years to reach granulite temperatures. The presence of minerals such as sillimanite defining the high grade schistosities demonstrates that the rocks were hot when they were deformed, and must have been hot before they were folded.

Folded sheets of pegmatite and pegmatitic leucogranite hundreds of metres thick (described by Stevens, 1978), in northern and central parts of the Broken Hill Block, exhibit a broad stratigraphic control, no thick sheets occurring above the top of the Broken Hill Group. The stratigraphic control is true both in upward-younging structures (e.g. Rise and Shine Antiform, Southern Cross Antiform) and downward-younging structures (e.g. Paps Synform, Mt Robe Synform), implying that emplacement occurred before large-scale overturning. In the model of Laing et al. (1978) and Marjoribanks et al. (1980) regional overturning resulted from D1 nappes. If this is so, the pegmatitic sheets were emplaced before D1. The age of an associated leucogranite (Purnamoota road) is 1597±3 Ma (Page et al., 2005), indicating no significant time gap between emplacement of the leucogranite and commencement of D1. It is possible that the pegmatite-leucogranite masses crystallised at or below the top of the Broken Hill Group because the andalusite-sillimanite isograd was at that level before folding occurred. It is also likely that the isograd was overturned by the same event that overturned the stratigraphy. Both the Mt Robe and Paps Synforms (eastern limbs) preserve Sundown Group at andalusite grade, below Broken Hill Group at sillimanite grade. In other areas subsequent heating would have obliterated any similar relationship.

There are few options in the search for a heat source. The granitic and mafic magmas that intruded the Willyama Supergroup between ~1704 Ma and ~1683 Ma, during deposition of the stratigraphic sequence, were too early to have caused the ~1600 Ma high grade metamorphism. During the Olarian Orogeny (~1600-1590 Ma) only minor low melting-point granites and local masses of pegmatite were emplaced, far too little to have imposed granulite facies temperatures. The only likely options for heat production are crustal thinning with upwelling asthenosphere, extensive mafic underplating, or heating due to radioactive elements in the sedimentary-volcanic pile and its 1704-1683 Ma granitic sills. The lack of syn-Olarian mafic intrusions favours the last option, but was radioactive heating capable of producing ~900ºC (Frost et al. 2005)? McLaren et al. (2005) discuss the effects of radioactive heating below an insulating blanket of pelitic metasediments. Vernon et al. (1993) described pre-S1 microcline, biotite and andalusite porphyroblasts in the western Broken Hill Block. Marjoribanks et al. (1980, p. 214) refer to andalusite in the Mt Franks area that “appears to have grown during a pre-S_1 static metamorphic event”. Metamorphism in that area never exceeded andalusite grade. In the higher grade areas any pre-S1 sillimanite could have been reoriented into S_1, S_2.or S_3.

The conclusion that the Willyama Supergroup was hot before it was deformed has consequences for interpreting structural style. Hot rocks, particularly where they contain partial melt, have reduced strength and deform in a very plastic manner. Deformation models taken from such areas as low temperature fold and thrust belts are of little relevance. Hot rocks are more likely to fold than fracture, and melted areas could have been loci for displacement.

Temperature-Pressure History

If all of the heating resulted from radioactive elements in the pile, the following would be expected (Figure 2):

1. Prior to deformation, isotherms would approximately follow stratigraphic boundaries.
2. If D_1 involved extension and rise of a metamorphic core complex (Gibson and Nutman 2004), the rocks under the detachment would lose both pressure and temperature, while those above would become hotter. Alternatively, if D_1 involved recumbent folding (Laing et al. 1998), pressure would increase immediately in the lower limbs, and temperature would increase more slowly due to trapping of heat.
3. Laing (1998) suggested that D_2 pressure was only slightly higher than D_1 pressure, and temperature was about the same, only allowing a small amount of overall thickening. Given that folding took place, erosion must have kept pace with thickening. (The consequences do not change greatly if D_2 of Laing et al. (1978) becomes D_3.)

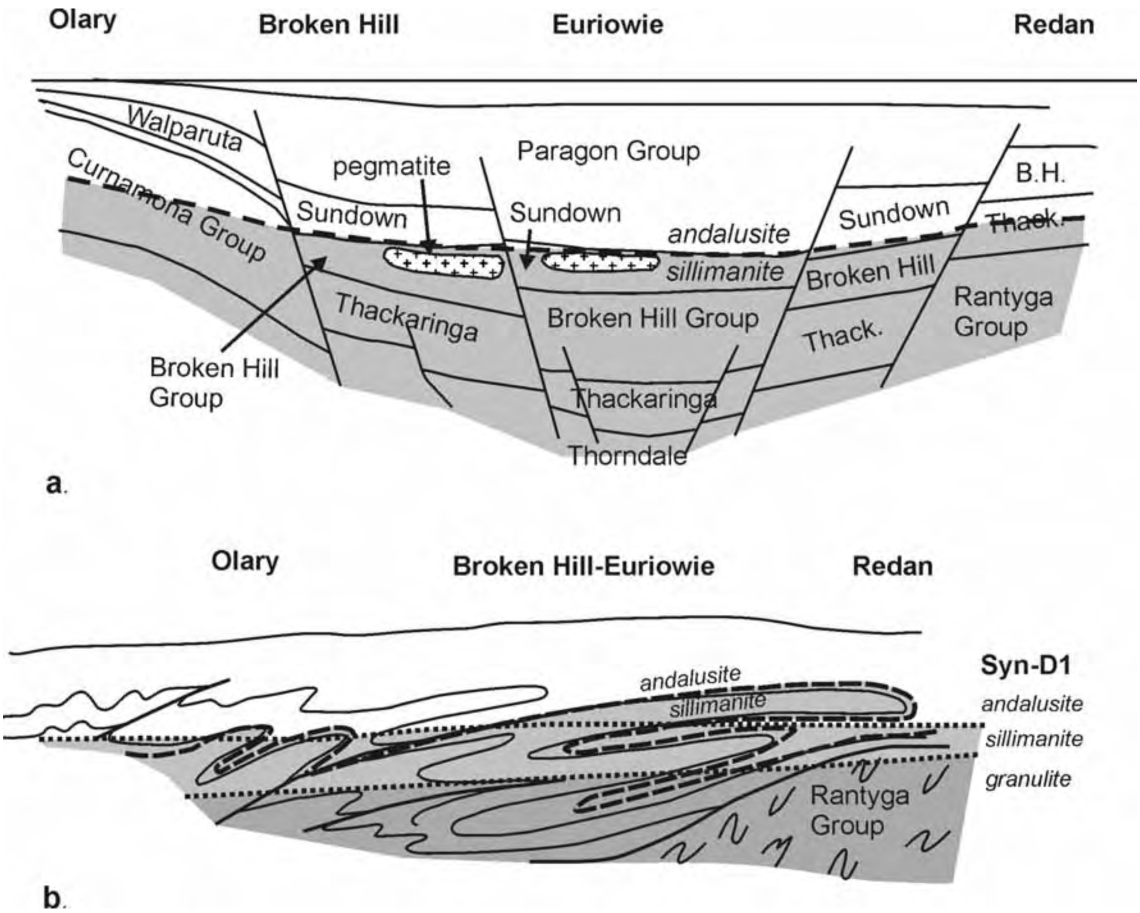

Figure 2. Sketch of (a) pre-D1 and (b) syn-D1 metamorphic isograds, assuming heat was derived from radioactivity within the pile. Shading in (b) indicates the resultant of D1 isograds overprinting pre-D1 isograd. The isograds were further deformed by D2, overprinted by D2 isograds, and deformed and partially exhumed by D3.

4. Laing's D_3 temperatures were lower than D_2, suggesting uplift and erosion between D_2 and D_3 and drop in pressure. This conflicts with the isobaric cooling path deduced by Phillips and Wall (1981). It is suggested that the staurolite-kyanite-bearing retrograde assemblages on which isobaric cooling is based, are the result of a separate metamorphic event.

Seismic profiling in South Australia (Korsch et al. this volume) shows thrusts overlain by undisturbed Adelaidean sediments. Field data from the northern Broken Hill Block also shows that major thrusts developed before Adelaidean deposition. It is likely that exhumation on thrusts compensated for fold thickening during D_2 and more than compensated during D_3. An important observation is that ~1585 Ma volcanics on the Benagerie Ridge (South Australia) rest on greenschist grade Willyama Supergroup, requiring up to 10 km of erosion of the Willyama before 1585 Ma (Korsch et al., 2006).

Pressure-temperature estimates (Phillips, 1980) place Broken Hill Group rocks at depths of 12 to 20 km below the surface during high grade metamorphism: the Little Broken Hill area ~20 km depth at 780ºC, and near Allendale (northern Broken Hill Block) ~12 km depth at 740ºC. Minimum metamorphic grade for Broken Hill Group was lowest sillimanite grade (perhaps 600ºC). Highest temperature may have been closer to the 900ºC estimated for Thackaringa Group at Black Bluff (Frost et al., 2005), than Phillips' (1980) 780ºC.

There is no indication of the drop in temperature and major decompression during D1, demanded by Gibson and Nutman's (2004) model. The question remains whether radioactive heat in the pile could have brought the Broken Hill Group temperature to around 600ºC before deformation, and increased the temperature at ~20 km by another 300 degrees, in the few million years duration of D_1 and D_2. Or was another heat source required?

Acknowledgements

I would like to thank all of those geologists whose careful observations, great skills and wonderful insights have built up our knowledge and understanding of Broken Hill geology. I have been able to play my part, only by standing on their shoulders. To those who believe they can do it all by themselves, ignoring previous work, you are deceiving yourselves.

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Tectonic links between the Gawler Craton and Curnamona Province

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Introduction

The southern Australian Proterozoic is dominated by two domains; the Gawler Craton and the Curnamona Province. Both these regions are of proven economic significance in that they host some of the largest base metal ore bodies ever found and have therefore been the focus of mineral exploration efforts for a number of years. In addition these regions also contain the record of the way in which the southern Australian Proterozoic system was assembled. While there has been considerable focus on the tectonic evolution of the Curnamona Province, and there is a growing focus on the development of the Gawler Craton, there has been little attempt to systematically explore tectonic linkages between the Curnamona Province and the Gawler Craton.

The importance of developing and understanding tectonic models lies in the fact that there is a proven link between the regional tectonic systematics and the development of mineral systems that are focus of mineral exploration.

Tectonic models describing the relationship between the now contiguous Archaean-Mesoproterozoic Gawler Craton and the Palaeo-Mesoproterozoic Curnamona Province, South Australia, have been described as either an amalgamation of individual cratons e.g. Betts and Giles (2006) or the development of younger Proterozoic basins on a single Archaean craton Glen et al. (1977).

Geochronological data from metasedimentary units in basement inliers located between the Gawler Craton and the Curnamona Province (The Barossa Complex) yield depositional ages between 1740-1715Ma; younger than eastern Gawler Craton but similar to depositional ages in the Lower Willyama Supergroup, Curnamona Province. Magmatic and metamorphic data from the basement inliers constrain magmatic events at *ca* 1715 Ma and *ca* 1580 Ma and temporally distinct metamorphic events at *ca* 1630 Ma and *ca* 1590 Ma.

Combining geochronological, Nd isotopic and geochemical data of metasedimentary rocks, magmatic rocks and metamorphic events, suggests a west to east, successive development of younger Proterozoic basins from the eastern edge of the Gawler Craton at ~1760Ma through to the Curnamona Province at ~1710Ma. This implies spatial and temporal linkages between the Eastern Gawler Craton and Curnamona Province from as early as 1710 Ma.

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Structural and Stratigraphic Controls on the Zoned North Portia and Kalkaroo Cu-Au-Mo Deposits

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Introduction

The Kalkaroo and North Portia deposits contain ~100 million tonnes of low grade Cu-Au-Mo mineralisation and therefore represent a significant accumulation of metals developed at a particular stratigraphic level within the Southern Curnamona Province. Recent drilling of the Kalkaroo deposit by Havilah Resources NL (Havilah) has outlined 70mt of 0.47% Cu, 0.46g/t Au and 124ppm Mo (Havilah, 2006). Mineralisation continues at depth and different styles of mineralisation have been recorded. The exploration potential of the southern Kalkaroo Dome is high as outlined by Havilah`s recent success with an intersection of 63m @ 0.41% Cu and 69m @ 0.67g/t Au in drillhole KKRC071 (Havilah announcement, 27 Feb, 2006). At the West Kalkaroo prospect Havilah have reported 39m @ 1.45g/t Au in drillhole KKRC099 and 60m @ 1.0g/t Au in drillhole KKRC101 (Havilah announcement, 16 June; 30, May, 2006) further extending the known domains of mineralisation on and adjacent to the Kalkaroo Dome. At Portia and North Portia Havilah continue to have success with their drilling programmes.

Detailed core logging and petrological studies have aided in building a firm stratigraphy in the generally low metamorphic grade and non-outcropping domains at North Portia and Kalkaroo. Approximately 1.2km of stratigraphy can now be recognised with Cu-Au-Mo mineralisation occurring within brecciated albitites, K-feldspar rocks and various carbonates. Carbonate-rich units thin dramatically up-dip and laterally at both Kalkaroo and North Portia and this has major ramifications for ore deposition. The juxtaposition of albitites and other brittle lithotypes with the more ductile carbonates is one of the important parameters for sulphide deposition. Albitisation pre-dated ore deposition occurring at 1628 ± 20Ma with the introduction of Cu-Au and some of the Mo at 1605± 12Ma (Teale and Fanning, 2000; Teale and Fanning, in prep.).

The Kalkaroo and North Portia sequence

Prior to albitisation the North Portia and Kalkaroo stratigraphic package consisted of finely laminated to planar bedded carbonaceous and non-carbonaceous shales, evaporitic and carbonate-rich beds and other saline silts and shales. Possible local disconformities may have existed. Flaser cross beds indicate intertidal conditions for some of the rock-types and much of the sequence is considered to have been deposited in shallow water. Rare tuff marker horizons are present at North Portia and have been dated at 1703 ± 7Ma (Teale and Fanning, 2000). Carbonate-rich units are present at this level in the stratigraphic package and can also be observed higher in the sequence. The latter are considered to represent Broken Hill Group age equivalents in this area of the southern Curnamona Province. They are anomalous with respect to base metals and are manganese enriched with spessartine-rich garnet common.

Abundant kimberlitic sills are present at North Portia but have not been observed at Kalkaroo. In the general vicinity two mica and muscovite granites are present and highly fractionated diorite intrusives are present at Kalkaroo and to the north of North Portia.

Styles of Cu-Au-Mo mineralisation at Kalkaroo and North Portia

Replacement, vein infill, “skarn” and breccia style mineralisation occur at both Kalkaroo and North Portia. In addition, bonanza gold veins occur at the Portia (eg 9m @ 237g/t Au in BEN478) and Shylock prospects (eg 5m @ 356g/t Au in BEN677). The Portia high grade veins represent the structural “top” of the North Portia system which has been off-set by faulting.

Breccia types in the two deposits are numerous and not always mineralised. Sulphidic and non-sulphidic milled breccias, fluidised injection breccias, crackle breccias and possible breccias developed by decompressive shock are present. At North Portia some of the best mineralisation occurs in sulphide breccias. These can be bedding parallel in stratigraphic and structurally lower domains or cross-cutting and less sulphidic structurally higher in the mineralised system. The bedding parallel breccias are usually hosted by meta-carbonate and albitites and clasts of these rock-types are located in the breccia. In addition some contain vein quartz, vein carbonate and exotic rock fragments. These breccias developed during bedding parallel shear which accompanied the introduction of mineralisation.

Replacement style mineralisation occurs at both deposits. Chalcopyrite and molybdenite can replace carbonate and earlier developed pyrite. This replacement front often emanates from nearby veins that are either calcic or potassic. Molybdenite for example often replaces, delicate, fine-grained, early bedding parallel pyrite in albitised domains adjacent to quartz-carbonate ± biotite ± sulphide veins. Molybdenite can also develop in biotite selvedges adjacent to carbonate-biotite-quartz veins where it is often intergrown with the biotite. These veins can be observed in both deposits and give way to Mo-rich breccias which sit structurally above the veins. Carbonate and carbonate-albite beds, lenses and ellipsoids are replaced by chalcopyrite in the structurally and stratigraphically lower areas of the North Portia deposit. In the carbonate-albite beds chalcopyrite and albite form an unusual textured mosaic where the carbonate has been replaced and the albite retained.

Cross-cutting veins, infill veins and vein “faults” are more common in the upper levels of the North Portia system. The array of veins is far greater at this deposit than the larger, but lower grade, Kalkaroo deposit. At North Portia early, structurally low, calcic veins containing the assemblage tremolite-calcite-sphene-allanite can be partially replaced by quartz-REE-fluocarbonates-rutile-sulphides. Allanite and sphene, the dominant carriers of REE at Kalkaroo, are rare at North Portia being replaced by various REE fluocarbonates, rutile and monazite. The calcic veins at North Portia become more sulphide-rich and biotite decreases dramatically higher in the system. Quartz-calcite-K-feldspar-biotite-sulphides veins in turn give way to quartz-calcite-hematite-sulphides veins in the upper domains of the system.

Location of gold at Kalkaroo and North Portia

The abovementioned bonanza gold veins at Shylock and Portia contain primary gold grains (Ag-rich and containing sulphide and anhydrite inclusions) that can be up to 1cm in length. The Kalkaroo and North Portia deposits contain gold grains that are in the sub-micron to 50μ range. The gold at North Portia is usually located within chalcopyrite and to a lesser extent pyrite. When gold is observed it is often intimately associated with tetrahedrite, tennantite and various tellurides. The gold at North Portia has an average fineness (1000 x Au/[Au + Ag]) of 810 with a range from 741 to 909. Gold fineness increases from the structural bottom to the structural top of the mineralised system. This may be due to the early precipitation of hessite (Ag_2Te) which will markedly decrease the activities of silver and tellurium in the ore fluid. Gold at Kalkaroo is often observed as inclusions in pyrite and in chalcopyrite that is annealing shattered pyrite. The gold grains in pyrite are invariably associated with chalcopyrite + pyrrhotite inclusions that tend to occur as composite grains. Elsewhere, pyrite grains containing only chalcopyrite inclusions (no pyrrhotite) do not contain free gold. Gold is also present as inclusions in rare galena and within anatase.

Zoning within the Kalkaroo and North Portia deposits

The deposits are zoned with respect to location of the various metals and silicate, carbonate and oxide mineralogy. Molybdenite is developed structurally lower than the Cu-Au and there is a zonation from the structural and stratigraphic base to top of:
- Mo → Mo-Cu → Cu-Mo-Au → Cu-Au → Au → Pb-Zn

Some molybdenite is considered to have developed at ~1630Ma and is therefore older than the Cu-Au mineralisation. Molybdenite however can be observed in many textural and and/or mineralogical associations and cross-cutting vein relationships suggest a long history of deposition. Bedding parallel sphalerite and galena occur adjacent to the North Portia and Kalkaroo deposits. The sulphides occur as replacement of carbonate ellipsoids and in bedding parallel “veins” which always tend to be coarser grained than the adjacent meta-sediment. These veins, previously considered to be “syngenetic” sulphides, are associated with albite + quartz + tourmaline + carbonate ± garnet ± epidote ± pyrite. Pb-isotopic studies now indicate that the galena in these veins shares a similar isotopic composition to altaite (PbTe) in the Cu-Au mineralisation. It should be noted however that away from the Cu-Au-Mo deposits there are base metal sulphides where the galena shares an identical isotopic composition to galena from the Broken Hill deposit.

At North Portia the carbonates associated with mineralisation become progressively more Fe and Mn-rich from the structural/stratigraphic base of the mineralisation to the top. This carbonate zoning may be of use in exploring for this style of mineralisation, although studies on carbonates from the Kalkaroo deposit have not been carried out as yet. Distinctive chemistries for biotite may also be of use as an exploration pathfinder. As mentioned, gold fineness increases from the base to the top of the system. Another interesting observation is that tourmaline becomes progressively more vanadium-rich towards the top of the system. V_2O_3 and Cr_2O_3 can make up 7% combined in some tourmalines with vanadium in the ore fluid increasing with time. The bonanza grades observed at Shylock and Portia, associated with V-rich gangue, beg a comparison with bonanza grade gold associated with some V-rich micas (roscoelite) in mineralisation which sits above or adjacent to porphyry systems. The presence of abundant vanadium may indicate an input into the ore fluid from a fractionated mafic magmatic source.

Structural and stratigraphic controls on the mineralisation

The sequence in the low metamorphic grade, non-outcropping regions of the southern Curnamona Province appear distinct from the higher metamorphic grade, largely outcropping, metamorphics of the Olary Domain. The latter contain significant thicknesses of meta-felsic volcanics, former probable coarse grained “sandy” meta-sediments and minor carbonates. The sequence hosting and enveloping the Kalkaroo and North Portia deposits contains abundant carbonate, impure carbonate and calc-silicate. It is devoid of coarse grained sediment and hosts only three very thin tuff marker horizons, the largest being 10cm in thickness. Detailed logging has shown that there are significant facies changes in the sequence with Cu-Au-Mo mineralisation located in areas that contain the thickest carbonate and calcareous units. At North Portia these carbonate-rich units thin to the west and to the south and there is a concomitant reduction in the mineralisation. South of North Portia the carbonate-rich units thin dramatically and there is a greater abundance of silty sediment. The Pb-Zn discussed above develops in these siltier sediments. To the north of North Portia the carbonates are still well developed however the units are strongly carbonaceous and lack the Cu-Au-Mo mineralisation. In the Kalkaroo area thick carbonates are developed in the “Upper Carbonate” or probable

Broken Hill group position. These carbonates, however, are thin to almost negligible proportions in adjacent drill-holes.

Major ENE structures are present at the North Portia and Kalkaroo deposits and are considered to have been conduits for high temperature magnetite-K-feldspar ± biotite alteration. At Kalkaroo "breccia swarm" mineralisation is developed along this structure and is composed of sulphur-poor mineralisation (quartz-K-feldspar-calcite-magnetite-chalcopyrite-allanite ± bornite) which is extremely siliceous (the West Kalkaroo mineralisation and its eastern equivalent). The timing of this mineralisation and its relationship to the stratabound Kalkaroo mineralisation is difficult to reconcile. At both North Portia and Kalkaroo bedding parallel faults and shears are common and are usually mineralised. These structures may have developed during the formation of the domal structures. North Portia is severely disrupted by NNW trending vertical to steep west dipping faults which drop and lift the mineralisation. This can be beneficial in some instances where mineralised units are repeated by this faulting but in some areas up to 30m of mineralisation has been "lost".

The mineralisation at both deposits is present where there is an abundance of carbonates or calcite-rich calc-silicates. Aeromagnetic images also outline the ENE trending structures (as well as NW trending structures which can be traced back to the Broken Hill region) that run through the mineralised domains. The lithotypes within the higher grade North Portia deposit are strongly fractured and brecciated with ultra-fine grained albitites "shattering" between ductile carbonates. This extreme of competency and chemical differences coupled with an abundance of large fault structures, which are known to have been major conduits for fluid movement, make the two deposit sites ideal for the development of major mineralised bodies. Add the presence of carbonaceous sediments juxtaposed against oxidised magnetite-bearing strata and the ingredients for a major Cu-Au-Mo province become clear.

The ultimate source of the ore fluid is conjectural however the presence of fractionated and highly altered diorites in the region indicate that they could be responsible for some of the hydrothermal input. The presence of Te, Hg, Se, in addition to the Cu-Au-Mo may support this.

Acknowledgements

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Mineralisation in the Potosi Extended to Flying Doctor area, Northern Leases, Broken Hill

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Introduction

The Potosi mineralisation extends from the former Potosi open pit to north of the historic Barrier Main Shaft (to the north of Flying Doctor), a distance of over 3km. Between 1996 and 2000 a resource of 670,000t grading 9.6% Zn, 2.0% Pb and 26g/t Ag was mined from the Potosi open pit. Resources for the various areas are as follows; Potosi North 303,583t @ 7.2%Pb, 63.8g/tAg, 12.7%Zn (inferred resource 2006) and Potosi Extended (inferred resource 2006) 1,309,426t @ 2.1%Pb, 38.3g/tAg, 13.0%Zn, Total Indicated and Inferred 2006 1.613mt @ 13.0% Zn, 3.1% Pb, 0.26%Cu and 43.1g/t Ag; Flying Doctor, 330,000t @ 4.8% Zn, 6.2% Pb and 63.1g/t Ag (2005 indicated resource >5% Pb+Zn cut off). More mineralisation is present at Silver Peak and Central Blocks however no reserves or resources have been announced at this stage. The ore body is ribbon-shaped and plunges north-east at 15^0 from the Potosi pit. There is a plunge reversal under the Globe Vauxhall to Central Blocks area at ~650 vertical metres depth with mineralisation to the north east of this area plunging back towards the south-west (fig. 1).

The ore body is hosted in psammitic rocks of the upper Fryers Metasediments (4.5 stratigraphy). The distinctive coarse garnet and sillimanite-rich 4.6 Pelite and associated medium-grained psammopelite form the structural hangingwall to mineralisation and is overlain by Potosi Gneiss (Hores Gneiss). Roughly concordant pegmatite bodies are present in the footwall of the ore body (eastern side) and separate the 4.6 Pelite from the Potosi Gneiss.

The Potosi mineralisation contains two distinctive, roughly stratabound, ore lenses and minor subsidiary lenses. There is a lead lode and a zinc lode and both can be extremely coarse grained. The mineralisation is often highly deformed and has been remobilised into sub-vertical (?D_3) shear zones. For example, in the centre of the Potosi Pit, where the Potosi Shear intersects the ore lenses, mineralisation is incorporated into and remobilised along the Potosi Shear, creating complex boudinaged ore geometries. The ore lenses are often breccia textured with milled breccia ore common. The lead lode is geochemically distinctive, with a Pb:Zn ratio of 0.5 or higher (average 1.8) and a high proportion of coarse-grained galena. The lead lode is terminated against the Potosi Shear approximately 60m below surface (Silver Peak area) and therefore does not outcrop. It was not mined in the upper part of the Potosi Pit. There are as many as three zinc lodes, vertically above and southeast of the lead lode. These lodes are sphalerite rich, with variable lead and moderate to high copper (up to 1.5% Cu). The Pb:Zn ratio is less than 0.15 and as low as 0.01. The zinc lodes at Potosi North are high-grade and narrow (<3m width), but average 5m wide at Potosi Extended. Shear hosted ore in the Potosi Shear (or Western Shear) is highly deformed and with variable composition and texture. Mineralisation in the Flying Doctor area can exhibit mylonitic textures which have been subsequently recrystallised. High temperature mylonitic fabrics can also be observed in the Round Hill workings area.

A vertical NE trending fault controls in part the geometry of the lodes and runs sub parallel to stratigraphy. Previous interpretations of mineralisation controlled by a regional synform are not supported by mapping and sectional interpretation. Several large crosscutting faults between Potosi North and Potosi Extended have up to 29m of horizontal displacement.

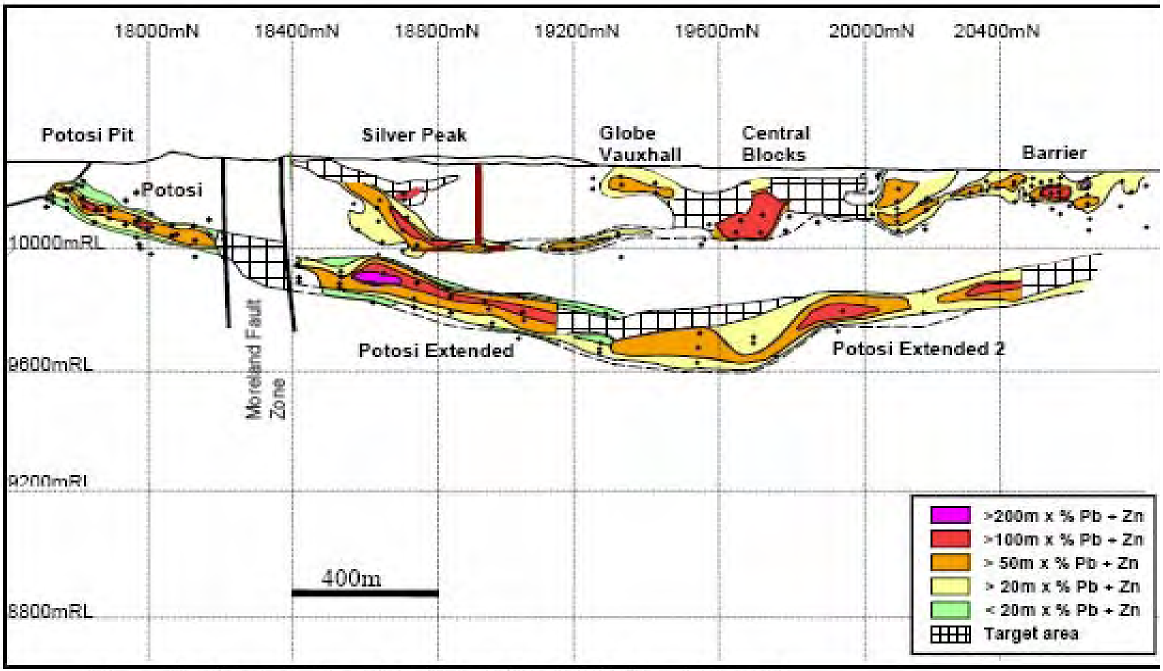

Figure 1 – Long section of the Potosi Trend (CRAE grid shown)

The sulphide assemblages can be complex with an apparent increase in arsenopyrite within lodes going to the north-east and a decrease in Sb-Fe sulphides (gudmundite, berthierite). No previous detailed study on the ore mineralogy of this mineralisation has been undertaken. Observed sulphides (and other non sulphide phases) are outlined below;

Major: sphalerite, galena, pyrrhotite

Minor: pyrite, secondary pyrite, bismuthinite, berthierite, arsenopyrite, chalcopyrite, cubanite

Trace: marcasite, tennantite, tetrahedrite, loellingite, famatinite,
dyscrasite, mackinawite, native silver, gudmundite, molybdenite,
bornite, miargyrite, ? stephanite, electrum, scheelite

Sphalerite is coarse grained and usually greater than 1mm in size. Grains to 1cm were noted at Potosi Extended and grains to 0.5cm can be observed at the Flying Doctor. The abundance of inclusions in sphalerite is highly variable however most samples contain very “clean” sphalerite. The dominant inclusions are chalcopyrite (± cubanite) and pyrrhotite and these two minerals can also be located along sphalerite-sphalerite grain boundaries. Only rarely were bismuthinite, berthierite ($FeSb_2S_4$) or arsenopyrite present as inclusions in sphalerite. Analysed sphalerite exhibits a wide range of iron compositions (0.8%-12.7%) usually in the 8% to 11 % range. The lower iron values (~1%-6%) relate to minor, late, remobilised sphalerite. Manganese and cadmium concentrations are usually low with values never exceeding 0.3% for Mn and 0.27% for Cd. Manganese concentrations are generally in the 500ppm to 1000ppm range.

Galena, like sphalerite, is often extremely coarse grained and generally free of inclusions. It contains low concentrations of silver with most analysed samples containing less than 200ppm. Bismuthinite inclusions are relatively common and are present as small (usually less than 10 micron) “blebs” within the galena and can also occur at galena-sphalerite and galena-gangue grain boundaries. It is seldom observed within galena of the main “line of lode” and in the Potosi to Flying Doctor mineralisation it occurs in two textural variants. The exsolution “blebs” are the main variant and there is also an association with berthierite (or gudmundite) + chalcopyrite ± arsenopyrite ± pyrrhotite ± tetrahedrite. This latter assemblage most likely represents a replacement of tetrahedrite. Discrete, tabular crystals of berthierite can also occur within galena. Arsenopyrite grains can also occur as discrete rhombic grains in both sulphides and in the quartz gangue. In the Flying Doctor area arsenopyrite (± loellingite) can make up to 5 modal percent of the mineralisation where it occurs as deformed grains up to 3mm in diameter.

Chalcopyrite and cubanite are the dominant copper-bearing phases with rare primary bornite also noted. In some samples cubanite dominates and chalcopyrite is present as exsolution lamellae. It has previously been mistaken for pyrrhotite and to the authors` knowledge it has not been previously reported from the Potosi Mineralisation. It occasionally breaks down to pyrrhotite-pyrite aggregates, however this is minor. Pyrrhotite in the sample can be slightly oxidized or can be replaced by late (supergene) pyrite. In many samples the pyrrhotite shows some features of oxidation.

Tennantite, tetrahedrite, famatinite-($Cu_3(As,Sb)S_4$, gudmundite, stephanite, miargyrite, molybdenite, loellingite, dyscrasite, native silver and scheelite are rare accessories and most are found as inclusions in galena or at galena-sphalerite or galena-gangue grain boundaries. Gold (electrum) is very rare and was noted in only one sample where it occurs as inclusions in galena.

Pyrrhotite-rich lenses are also present and these can contain up to 18% pyrrhotite with only trace galena and sphalerite. Remobilisation of sulphides throughout the often brittle host to mineralisation tends to create a partially continuous sulphide network. Within milled breccia ore pyrrhotite and sphalerite are present as trains of grains in galena and these define the ore fabric. Sheared quartz (± gahnite) contains remobilised sulphides (usually galena and pyrrhotite) which create a network of grains which parallel the shear fabric.

The gangue is dominated by quartz, gahnite, garnet, muscovite and biotite. Observed gangue phases are outlined below;

Major: quartz, gahnite, garnet, muscovite

Minor: biotite (brown and green), chlorite, fluor-apatite

Trace: andesine, albite, K-feldspar, siderite, calcite, tourmaline, rutile, staurolite, chloritoid, allanite, Zn-ilmenite, ilmenite, hedenbergite, epidote-clinozoisite, sub-aluminous hornblende, alkali amphibole, monazite, zircon, barite, celsian, cummingtonite

Garnet (+ sphalerite) replaces gahnite and gahnite can also be pseudomorphed by muscovite + biotite + sphalerite. In the latter case relict gahnite exhibits an inner reaction rim of muscovite ± biotite and an outer selvedge of sphalerite. The micas are randomly oriented and exhibit no fabric indicating that the sphalerite selvedge is “late”. Some deformation of these micas can however be observed in samples of sheared mineralisation from the Flying Doctor area. Gahnite does not contain sphalerite inclusions whereas garnet is invariably rich in sphalerite inclusions. Two types of biotite are present, one is typical brown biotite and the second is a retrograde, Ti-free, green coloured variety. The latter replaces garnet and gahnite. In addition to this biotite there is also retrograde muscovite, chlorite, chloritoid, staurolite and gahnite. Retrograde gahnite exhibits a specific chemistry and usually occurs within sheared meta-pelite containing remobilised sphalerite. Apatite is a major phase in some samples. It is a fluor-apatite (+ 3% F) and can contain sulphide inclusions. In some areas (Flying Doctor) coarse- grained apatite grains sit within a massive galena groundmass.

Barite can be found in the Potosi Extended domain and occurs as intergrowths with sulphides and as remobilised calcite-barite veins. This is the first reported occurrence of barite associated with sulphide mineralisation from the Broken Hill line of lode.

Garnet composition within the ore lenses is variable and Mn-poor garnet (~3%-7% MnO) tends to be associated with sphalerite-rich mineralisation containing no or negligible galena. Higher contents of Mn are present in garnet associated with galena-rich mineralisation (~10%-18% MnO).

Intense alteration can be observed within and adjacent to the ore lenses. Garnet content increases in the meta-pelites as mineralisation is approached and some of this garnet is retrograde in origin and associated with muscovite ± chlorite. The contacts of ore with country rock often host quite coarse grained garnet which developed, in this case, pre retrograde deformation. In some areas this garnet is separated from the mineralisation by a thin selvedge of gahnite. Sphalerite-rich mineralisation can often be separated from country rock by a development of coarse grained cubanite at the ore lens contact. In addition, a restricted halo of blue to white quartz with trace gahnite, chalcopyrite, pyrrhotite and garnet can often be present around the ore lenses. Plumbian and grey feldspar and garnet are common in pegmatite proximal to mineralisation. In the Potosi Extended domain some of the siliceous ores (quartz-gahnite-garnet-sulphides) are altered to hedenbergite-calcite-garnet (Ca-rich)-epidote assemblages. Rounded, milled quartz clasts in ore often contain trace gahnite and/or Ti-oxide. These clasts are viewed as being originally country rock which has undergone intense alteration during mobilisation of the ore.

The ores of the Potosi Extended to Flying Doctor area should be metallurgically similar to C and B-lode mineralisation. They are generally siliceous with a quartz, garnet and gahnite dominated gangue. Minor As, Sb and Bi-bearing phases are present and most would report to the lead concentrate.

South Australia: On PACE in the Curnamona

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Introduction

Exploration Activity

The discovery of Prominent Hill in November 2001 marked the beginning of South Australia's re-emergence as a recognised mining state, having great mineral potential and a very supportive and pro-mining government. Since that time, exploration activity and our reputation for encouraging mining development have continued to grow. This was recently reaffirmed in The Fraser Institute's 2005-06 Annual Survey of Mining Companies, where the State has risen to an international ranking of 6th place against 64 jurisdictions on the Mineral Potential Index – an impressive increase from 18th in 2004-05.

In April 2004, the South Australia Government launched an innovative mineral exploration initiative: the Plan for Accelerating Exploration - PACE. In the first two years of PACE, mineral exploration expenditure increased from $55 million in 2004 to $99.4 million in 2005. The latest ABS figures for annual exploration expenditure of $110 million to the March 2006 quarter, now places South Australia in third place behind Australia's mining giants Western Australia and Queensland.

The PACE Collaborative Drilling Program has attracted the attention of explorer's worldwide and has been acclaimed as the most proactive government initiative the industry has seen. To date, 115 exploration projects have been awarded PACE funds of more than $5 million for minerals, oil, gas and geothermal prospects in South Australia, including the highly prospective Gawler Craton, Curnamona Province, Adelaide Geosyncline and Musgrave Province.

In the Curnamona Province, 20 projects have been supported, with uranium, copper-gold and geothermal energy the principal targets. Positive PACE drilling outcomes in the region include:

- Havilah Resources' Benagerie Kalkaroo Domes Cu-Au-Mo mineralisation project. 58 holes for over 9 500 m of drilling was completed with the best intercept: 84 m of 1.03% Cu, 0.78 g/t Au and 159 ppm Mo.
- Petrotherm's Callabonna Geothermal project. Yerila 1 was drilled to 670 m and recorded a geothermal gradient of at least 68^0C/km – one of the highest ever recorded in Australia.
- Quasar Resources Yudnamutana uranium project
- Havilah Resources' Eurinilla Dome project. EURC002 with18m @ 0.54% Cu from 138 – 156m confirmed earlier indications of copper mineralisation.
- Minotaur Exploration/JOGMEC Border project

In addition to drilling, PACE has provided full funding or co-funding for other minerals geoscience projects in the Curnamona Province including:

- Acquisition of ground gravity data over highly prospective areas of the northern Curnamona Province (2005).

- A deep crustal seismic survey targeting structures associated with the Broken Hill mine in partnership with New South Wales and Geoscience Australia.
- Development of a new 3D geology model of the Curnamona for online viewing via SARIG.
- A geological and mineral prospectivity assessment of the Bimbowrie region.
- Reconnaissance airborne electromagnetic surveys.
- Mt Painter stream geochemistry project.
- CRC-LEME supported baseline geochemical transects across buried mineralisation at Gould's Dam uranium deposit and Kalkaroo Cu-Au-Mo deposit.
- CHIM electro-geochemical investigations over Gould's Dam uranium deposit and Kalkaroo Cu-Au-Mo deposit.
- Hylogger scanning of White Dam exploration drill core.

The PACE initiative has achieved a high level of success in its first two years. The plans for the next phase of the initiative should ensure that this momentum will be sustained for the remaining three years of PACE and that mineral exploration and development will continue to increase across the State, particularly in the highly prospective Gawler Craton and Curnamona Province.

PACE Collaborative Drilling Round Four was opened for submissions on 1 August 2006, closing on 29 September, with successful projects expected to be announced on 1 December 2006. South Australia anticipates that through the PACE Drilling program and a commitment to fund other PACE projects, exploration activity in the Curnamona Province will continue to increase in the foreseeable future.

Broken Hill - The anatomy of a giant

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Introduction

The scientific literature contains few mineral deposit studies that have taken full advantage of the geological data that is routinely gathered in mining operations. Mines exploit mineral deposits and mining geologists collect vast quantities of information about these exploited mineralised systems during their day-to-day activities. A comprehensive reinterpretation of the BH mineralised system was undertaken using such data and the result was a detailed model of the geological architecture and structure of this complex mineralised system. To the author's knowledge, this is the first comprehensive re-examination of the geology of the Broken Hill mineralised system since the work of the Central Geological Survey (Gustafson, 1939). The model that has been developed has a greater breadth and clarity than could otherwise be achievable by a more typical ore deposit study and has highlighted several problems with the accepted structural and stratigraphic model of the mining field (Laing et al., 1978).

The Deposit

The Palaeoproterozoic Broken Hill lead-zinc-silver deposit is one of the largest, richest and metallurgically simple accumulations of base metals in the world. It is a stratified complex of sulphide-silicate-carbonate rocks, manganiferous garnet-rich rocks of various types and textures and minor associated elements such as calc-silicate ellipsoid and banded layers, magnetite-bearing metasediments and thin 'banded iron formation'. The stratified orebodies and their associated 'lode rocks' are concordant with the surrounding stratigraphy.

The BH deposit comprises at least nine spatially associated, flattened and ribbon-like stratiform orebodies. Most historical production has come from 2 Lens and 3 Lens, which extend over most of the length of the field (approximately 8.5km). Several lesser-mineralised horizons predominate at the southwest end of the field and now account for most of the production from the field:

- A Lode Upper
- A Lode Lower
- 1 Lens Upper
- 1 Lens Lower immediately above 2L.

Southern A Lode lies in the same stratigraphic position relative to BL as ALU but is a distinct occurrence to the southwest, and Southern 1 Lens is a separate ore horizon occupying the 1L stratigraphic position in the southwestern Perilya Mine.

'C Lode' is a tenth body of economically significant, structurally mobilised and disseminated stratiform mineralisation that lies above BL in the Perilya Mine (Mackenzie and Davies, 1990; Stockfeld, 1993). 'C Lode' is composed mainly of BL mineralisation (Webster, 2004) and is not really a separate mineralised horizon.

The Mine Sequence

The Broken Hill orebodies are hosted within a distinctive package of gneissic rocks that was informally named the “Mine Sequence” by Carruthers and Pratten (1961) and Johnson and Klingner (1976). The MinSeq crops out as a northeast-southwest trending arcuate belt extending from Kelly’s Creek in the southwest to Stephen’s Creek in the northeast; a strike length of 27-kilometres (Johnson and Klinger, 1976, Morland and Webster, 1998). The sequence dips steeply north to northwest throughout the mining field except locally, on short limbs of mesoscopic folds. The MinSeq is known to a depth of 2.5 kilometres on the mine leases because of exploration drilling (Carruthers and Pratten, 1961; Carruthers, 1965; Johnson and Klingner, 1976, Larsen and Webster, 1996, Morland and Webster, 1998). It ranges in thickness from approximately 2 kilometres to less than 100 metres, becoming markedly thinner in the immediate near-ore position. Within the MinSeq, there are several key marker horizons that have been recognised since the earliest days of mining (e.g. Marsh, 1893; Jaquet, 1894; the Scientific Society of Broken Hill, 1910) and the stratigraphic succession was first formally defined and described by Andrews (1922) and Browne (1922).

The uppermost and lowest units of the succession are thick quartzofeldspathic gneiss units (Carruthers and Pratten, 1961). In this study, they are named the Footwall Quartzofeldspathic Gneiss (southern or lowermost unit) and the Hangingwall Quartzofeldspathic Gneiss (northern or highest unit). The boundaries of the MinSeq are defined as follows:

- The upper boundary is defined by the top of the Hangingwall Quartzofeldspathic Gneiss
- The lower boundary is defined as the bottom of the lowest amphibolite unit of the several that lie immediately below the Footwall Quartzofeldspathic Gneiss.

Between the bounding quartzofeldspathic units the MinSeq is characterised by a package of pelitic to psammitic metasediments interspersed with more or less lenticular members comprised of varieties of quartzofeldspathic gneiss, amphibolite, and other distinctive units, including calc-silicate horizons, magnetite-bearing pelites and thin banded iron formations (BIF). The members do not represent formal stratigraphic units but marker horizons. Often, the lithologies of interest are repeated at multiple levels and part, or all, of some may be intrusive.

Most units of the MinSeq are formally assigned to the Broken Hill Group, with some Thackaringa Group elements (Willis et al., 1983), and it forms a particularly diverse interval in the transition from the predominantly feldspathic composite gneisses of the Thackaringa Group to the predominantly pelitic facies of the Broken Hill Group and upper Willyama Supergroup (Stevens et al., 1983). In the mining field area, the footwall of 3L lies within tens of metres of the Footwall Quartzofeldspathic Gneiss (the Rasp Ridge Gneiss of the Thackaringa Group according to the GSNSW, e.g. Willis et al., 1983). The target horizon for exploration for BHT style mineralisation throughout the district is the transition from the Thackaringa Group to the Broken Hill Group.

The MinSeq was interpreted to be overturned by Laing et al. (1978) and Haydon and McConachy (1987), and to be structurally repeated in the hangingwall and footwall of the mineralisation, as a result of a major F2 antiform – the ‘Broken Hill Antiform’. The Broken Hill Antiform was a structural necessity because the mining field was thought to be bounded by two regional F2 synforms; the Hangingwall Synform (to the northwest) and the Broken Hill Synform to the southeast and the major folds affecting the mineralised system were interpreted to be F3.

However, a “Broken Hill Antiform” is not necessary to explain Laing et al’s (1978) facing data. Webster (2004) has shown that the folds in the orebodies (such a those known in the Perilya Mine known as the Western Antiform and Eastern Synform) are high grade F2 structures and that they verge to the south, suggesting that they lie on the northern limb of a major regional antiform. Based on this information, Webster (1996; 2004) suggested that the major regional fold southeast of Broken Hill was an antiform; the Airport Antiform and not the 'Broken Hill Synform' as it has been known for the last 80 years.

With the recognition that most folds in the orebodies are F2, the published facing data of Laing et al (1978) actually supports a model that the Mine Sequence is north facing and not overturned (except locally). The removal of the Broken Hill Antiform from the structural model of the near mine area removes the mechanism for producing the structural repetition of the Mine Sequence in the hangingwall and footwall of the orebodies. The Mine Sequence is not structurally repeated but is considered to be continuous, the right way up and north facing, as was suggested by Carruthers and Pratten (1961) and Johnson and Klingner (1976).

Lode Sequence

Within the Mine Sequence, there is a package of mineralised rocks that hosts the most significant sulphide occurrences in the Broken Hill region and is known as the Lode Sequence (Webster, 2004). It is characterised by 'lode rocks', including 'garnet quartzite', 'garnet sandstone', blue quartz-garnet (± gahnite) rocks, blue quartz-bearing psammopelitic rocks and green feldspar pegmatite. In the mines area, it is a package ranging from 50 to 250 metres thick comprising:

- the orebodies
- sub-economic sulphide occurrences
- associated companion lithologies, and
- intervening pelitic & psammitic clastic metasediments.

The Lode Sequence is best developed in association with the main orebodies in the Perilya and South (CBH) Mines where it has a well defined stratification that is capable of sub-division (e.g. Johnson and Klingner, 1976; Morland and Webster, 1998; Webster 2004). It consists of following units in the mines area:

- The 4.5 Horizon
- The Upper Potosi Type Quartzofeldspathic Gneiss
- The B Lode Horizon (mainly southwest & central regions)
- The Garnet Quartzite Horizon (southwest region only)
- 2 Lens, and
- 3 Lens.

The Lode Horizon is the regionally extensive equivalent of the Lode Sequence and contains elements of the Lode Sequence strata, particularly B Lode Horizon rocks.

Problems with the correlation of the Mine sequence and the Regional Stratigraphy

Reassessment of the stratigraphy of the Broken Hill Mine Sequence by Webster (2004) has implications for regional exploration. The Mine Sequence is not structurally repeated by a Broken Hill Antiform, as suggested by Laing et al. (1978) and is a single, northwest facing succession, as suggested earlier by Carruthers and Pratten (1961). The orebodies lie within tens of metres of the Rasp Ridge Gneiss, a unit that is classified with the Thackaringa Group by Willis (1983) and Stevens et al. (1983). If the Rasp Ridge Gneiss is correctly classified, then the BH orebodies lie at the base of the Broken Hill Group. 2 Lens is the largest accumulation of calcite in the Willyama Supergroup. Webster (2004) recognised the important association between calcic lithologies and the main BH orebodies. The most significant regionally extensive calc silicate horizon in the Willyama Supergroup is the Ettlewood Calc-silicate Member, which lies near the base of the Broken Hill Group and is known to contain base metal occurrences (Barnes, 1988). It is therefore possible that both the main lodes at Broken Hill and the regionally significant Ettlewood Calc-Silicate lies in the same stratigraphic position within the Willyama Supergroup.

The relationship between BH mineralisation and calcium carbonate, or calcium-bearing silicate rich rocks is considered one that could be important in exploration programmes for orebodies of this type. Calcium-rich rocks are rare in the Willyama Supergroup and such rocks located on the thinner margins of complexes of Potosi gneiss and amphibolite may be a means of focussing exploration.

The 4.5 Horizon of the Mine Sequence is probably not the Freyers Metasediments, but a separate mineralised horizon in the Broken Hill Group that forms part of the main mineralised system. Mineralisation hosted in 4.5 Horizon-like sediments below the main lodes in the BH area is a more likely contender for being the equivalent of the Freyers Metasediments.

The definition of the Hores Gneiss of the Broken Hill Group, the host unit of the Broken Hill mineralisation used by the GSNSW (Willis, 1983; Stevens et al., 1983) largely ignores the increase in the stratigraphic complexity in the mines area. Only the relationship between the Potosi type gneiss units of the Mine Sequence and the regionally recognised Hores Gneiss are dealt with. Other elements of the mineralised stratigraphy of the Mine Sequence may in fact be correlates of other units of the Broken Hill Group and/or Thackaringa Group. The relationship between the Mine Sequence and the regional stratigraphy requires revision. Serious consideration should also be given to revising the stratigraphic nomenclature of the contact of the Broken Hill Group and the Thackaringa Group and placing the amphibolites, ABM Potosi Type Gneiss and Footwall Quartzofeldspathic Gneiss into the same unit of the Broken Hill Group.

Structure of the Mineralised System.

The BH mineralised system has undergone four major periods of deformation, as summarised in the table below.

Regional Deformation	***Webster (2004)***	**Features in mineralisation identified during this study**
OLARIAN (M1)	**D1**	Lode Pegmatite intrusion /S1, Grainsize annealing.
	D2/D3A	Tight-isoclinal folding, S2 (ore & wall rocks), initiation of early retrograde shearing. High-grade attenuation/metasomatism, transposition & local F3 folds/S3.
	D3B	Biotite-muscovite shear zones Minor folds in shear zones
DELAMERIAN (M2)	**D4A**	Fault systems & locallised high temperature hydrothermal activity (alteration of ore & wall rocks). Dolerite intrusion into orebodies & then dismembered & altered. Locallised folding (plunge reversals).
	D4B	Late, brittle chloritic faulting & milling of ore.

High grade, south verging, asymmetric F2 folds comprise all of the significant macroscopic folds in the Mine Sequence and cause much of the present orebody geometry. They are parasitic to, and lie within the north limb of, a major regional F2 antiform; the Airport Antiform (this is the 'Broken Hill Synform' of Laing et al., 1978). The intensity of F2 folding is greater in the northeastern end of the field and is associated with a pervasive galena-defined S2 axial plane foliation in 3 Lens and 2 Lens. Folding and transposition equally affected both ore and adjoining wall rocks. S0 banding and syn-depositional stratigraphic variations within the orebodies are folded around F2 axes and modified by syn-D2 mobilised sulphides. F2 folds also deform a well-defined layering in 2 Lens, B Lode and A Lode Lower. All significant fluid phase sulphide mobilisation, and most mechanical sulphide mobilisation, took place within the orebodies during D2 and D3A.

Space does not allow a detailed description of all of the structural events that have affected the Broken Hill mineralised system (refer to Webster, 2004; in press). Only the results of some recent work on the nature of D4 are presented here.

The De Bavay Fault Zone

The De Bavay Fault Zone (DBFZ) (Andrews, 1922) is one of a related curvilinear array of north-south trending D4 faults and fractures systems that traverse the mining field in the region between the Block 14 Mine and the Flying Doctor Prospect. It is a north-south trending (20°NW to approximately 15°NE), curviplanar, steep northeast to east dipping (65-70°), brittle-ductile structure comprised mainly of parallel fractures and brittle faults. It is variable in width and prominence (Andrews, 1922) but the major effects of the zone occupy a region approximately 650 metres wide**.**

The DBFZ outcrops poorly and the main evidence for the structure seen at surface is the sinistral northerly offset observed in key marker horizons of the Mine Sequence (Andrews, 1922; Gustafson, 1939), including the Footwall Quartzofeldspathic Gneiss, the Consols Amphibolites and the ABM Potosi Gneiss. The D3 Globe-Vauxhall Shear System is also offset by the DBFZ. All are offset to the north and the Footwall Quartzofeldspathic Gneiss northeast of the fault is juxtaposed with the ABMPG on the footwall side of the fault. The horizontal displacement is at least 0.9 to 1.4 kilometres. Vertical displacement northeast of the fault has been estimated to be at least 1 kilometre by North Broken Hill Ltd geologists (unpublished data). The DBFZ is therefore a reversed structure with a northeast block up sense of movement.

Marginal zones of intense parallel fractures and minor faults can be seen at surface in the Imperial Lake area, and are a characteristic feature of the region affected by the DBFZ. These features can also be seen in the underground workings of North Mine, particularly in the Fitzpatrick Area. So rather than being a discrete fault plane, the evidence that is available in outcrop, and which is seen in related fault structures such as the British Fault Zone, Lords Hill Fault Zone and in the Morland Fault Zone, suggests that the DBFZ is mostly comprised of a dense zone of parallel and anastomosing fractures that become more dispersed on the outer margins of the zone. Displacement along individual fracture planes may be relatively small, from 10's of centimetres to 10's of metres, but it is the cumulative effect of the relatively small amounts of movement on each fracture, multiplied by there being many fractures, that produces much of the displacement of the DBFZ. Only in the core of the structure is there significant schist developed (e.g. south of the North Mine waste rock dumps). The fault may not have been identified as a discrete fault plane in underground workings and in deep exploration drilling because the true nature of the structure has been misunderstood.

Both the Fitzpatrick Zinc Lode and the Potosi Orebody (and the Potosi Extended mineralisation) are similar in metal ratio's, grade, geometry, and in their host rock associations. The Silver Peak Mineralisation is similar in grade and host rocks to distal mineralisation hosted within the B Lode Horizon. So given the displacement and sense of movement of the DBFZ, it is possible that the Potosi mineralisation is the dislocated continuation of the Fitzpatrick Zinc Lode on the northeastern side of the DBFZ and the Silver Peak Mineralisation is the distal margin of the main lode system. If the Potosi and Silver Peak mineralisation northeast of the DBFZ is the continuation of the main lode system, which was last encountered in the mines in the '2K Zone', then the geology in this area has been up-thrown by 2 kilometres.

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Updated Geological Structure of the Pinnacles Mine, Broken Hill, NSW

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Updated Geological Structure of the Pinnacles Mine

The Pinnacles Mine lies 15km south of Broken Hill. The Mine with four levels and a shaft to 80m depth, has had intermittent production since 1884, with an estimated total historical production of 170,000 tonnes, Johnson, 1966. The mine has been owned and operated by the Williams family since 1954. Broome 1999 calculated an open cut resource of 2 million tonnes of 2.39 % Pb, 92 g/t Ag, and 8.03 % Zn, using a block cut-off grade of 4 % (Pb + Zn).

There is now more than 36,000 m of drilling and 22,000 m of costeans in and around the Pinnacles Mine. As a result of detailed geological mapping and sampling of these costeans and logging of core, there has been considerable elucidation of the structure of Pinnacles Mine and a substantial increase in the size of the resource. A major revised tonnage calculation using Surpac is currently in progress.

There are four major problems which in combination have dogged the understanding of Pinnacles Mine Geology, in common with that of Broken Hill, see Hopwood 1993:

(1) The finely laminated thin bedded nature of the host pelitic/psammitic stratigraphic succession and large variation of additional rock types such as amphibolites, and granitoids.
(2) The diversity of ore-associated rock types such as garnet quartzite, blue quartz-gahnite, biotite-garnet rock, magnetic-iron formations which all form stratigraphic units correlable over large distances.
(3) The complex and multiple sequence of overprinted deformation-associated metamorphic events in reactive rock types (Upper Greenschist Facies).
(4) These complex deformational events have been followed by shear-associated regional retrogression.

The stratigraphy at the Pinnacles can be divided into three Stratigraphic Units as follows:

Upper Unit	Quartz-rich gneisses, Biotite quartzites, Silicified gneisses – Ore lenses are associated.	70m
Middle Unit	Intermediate Gneisses, Pelitic Gneisses, Feldspathic Gneisses form host rocks to numerous lenses of garnet quartzite, blue-quartz gahnite, biotite-garnet rock and magnetitic iron formations, which are all associated with ore lenses.	250m
Lower Unit	Granite Gneiss, Migmatites, Albititic Gneiss, Amphibolites	60m

As a result of detailed mapping at 1 to 500 scale it is believed that the ore zones of the Pinnacles Mine can be correlated across the major east-west trending Pine Creek Shear to join with magnetic iron formation units in the Village Blocks, extending northwards to a gently south plunging syncline-anticlinal complex ore-associated iron formation at the Lady Bevis and Monarch mine-shafts. Furthermore the multiple blue-quartz gahnite units in the Middle Unit within the syncline enclosing the Pinnacles Mine (revealed in mapping and on drill sections) are thought to correlate with multiple blue quartz gahnite units (also in a syncline) extending northwards from the Kingston mine-shaft, on the northern side of the Pine Creek Shear.

Many of these garnet quartzite lodes, blue-quartz gahnite lodes, magnetic iron formations and biotite-garnet lode horizons are associated with significant mineralised intersections, of Pb, Zn, Cu and Au. It is commonly observed that ore lenses increase in grade in fold hinges adjacent to sericite schist shear zones.

One of the academic questions with respect to the Pinnacles has been the perception that the Pinnacles Mine is on a “different stratigraphic horizon” to that of the main Broken Hill Lode, see King 1953. It could be argued, that if a substantial tonnage of ore is found at the Pinnacles Mine, is the question relevant ?

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Investigating the role of lithospheric architecture in the evolution of the Curnamona Province

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Significance of long-wavelength, linear potential field gradients

Long-wavelength potential field gradients and linear anomalies have long been observed and described, termed as lineaments, in literature spanning the last 50 years. Numerous authors have commented on the observed coincidence of these features with belts or corridors of ore deposits, magmatic provinces and active deformation zones, leading to the implication that deep seated architecture in the component form of long, linear structures has exerted control over the formation of these observed geological phenomena. More directly, these correlations imply that the observed features at the surface of the Earth are in fact surface counterparts to the deepest linear structures and that they are physically linked throughout the vertical strength profile of the lithosphere. However, the observation that these deep-seated structures connect through rocks of different ages causes difficulty when reconciling their apparently maintained linear geometries during repeated deformational events.

One of the challenges in tectonic theory is to explain the evolution of these shear zones in continental interiors when subjected to distal forces. This can be partially addressed by understanding the stress distribution of the continent today (e.g. Coblentz and Sandiford, 1994; Hillis and Reynolds, 2000) and by understanding the recent geomorphological responses of those stresses in the continent interior (e.g. Sandiford, 2003). These studies provide important contributions to solving the issue, but by their nature are merely snapshots of a continent as it is today. There is little emphasis on how the internal structure of a continent evolves through time in a plate tectonic context. The theory of plate tectonics was primarily developed from observations within oceanic lithosphere (e.g. Vine, 1966) and it has long been recognized that it provides an incomplete description of the deformation zones within continental lithosphere (e.g. Molnar, 1988; Holdsworth et al., 1997). This is not to say that plate tectonic theory is not applicable to the evolution of continents, but rather the response of continental lithosphere to plate tectonic processes is not as simple as the behaviour of the more rigid oceanic lithosphere. Placing the evolution of continental lithosphere in the context of plate tectonic theory has been more difficult because the strength profile of continental lithosphere is more complicated than that of oceanic lithosphere and is generally characterized by a strong upper crust, weak lower crust and a strong upper mantle (e.g. Molnar, 1988; Kohlstedt et al., 1995). This rheological profile influences the way stress is distributed and strain is accommodated. Furthermore, inefficient recycling of buoyant continental lithosphere results in the preservation of elements of protracted tectonic histories that can span billions of years. Superposition of these tectonic events produces an increasingly convoluted association of geological structures that become progressively harder to unravel.

The recognition that these shear zones affect rocks of different age suggests that they are long lived and prone to reactivation (e.g. Rathore and Hospers, 1986) however the mechanism by which these shear zones evolve spatially and temporally and how they may control the distribution of geological phenomena at the surface has not been systematically assessed. This can be attributed to a number of problems, including: 1) that due to the vertical strength profile of the continental lithosphere, the behaviour of deep-seated structures should be different to that of their surface manifestations. Such differences may include geometry, kinematics, width and connectivity; 2) that for the most part, these structures exist beneath the surface, under cover; and 3) the use of potential fields to image these links is an application, which has had little attention.

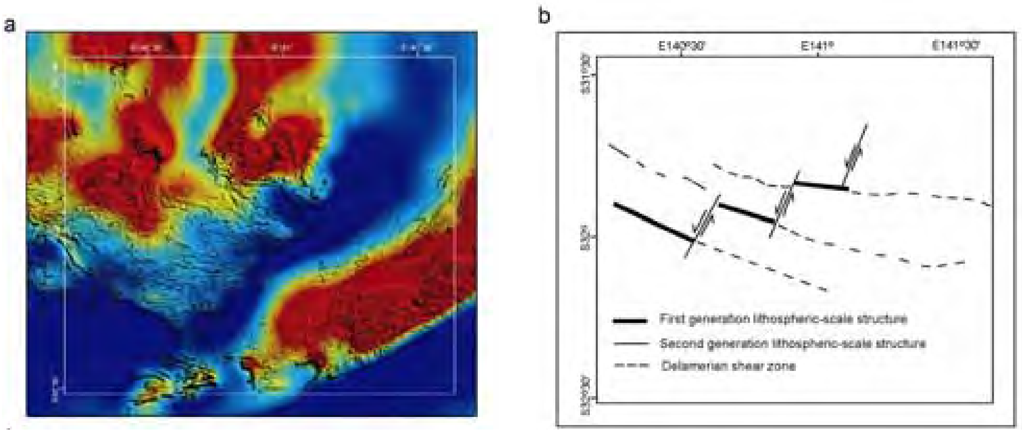

Figure 1. (a) Pseudocolor layer of aeromagnetic data upward continued to 4 km overlain by an intensity layer of the first vertical derivative of aeromagnetic data. We interpret this image as illustrating that a first-order, deep-seated structure has been overprinted by a later series of orthogonal NNE-oriented structures, which are expressed as long-wavelength magnetic gradients (i.e. are also deep-seated). In the intensity layer, high frequency anomalies associated with Delamerian shear zones at the surface (Dutch et al., 2005) can be seen to nucleate off segments of the first-order structure; (b) Structural interpretation.

Here, we image deep-crustal structure of the Proterozoic Curnamona Province, Australia, in aeromagnetic and gravity datasets, and establish spatial and temporal links between deep structures and near surface geological features by superimposing first vertical derivative responses on upward continued images. Upward continued gravity and aeromagnetic data show NW-SE, NE-SW E-W and N-S oriented long-wavelength gradients, interpreted as deep-seated structures. These structures pre-date the oldest known tectonic events recorded in outcropping rocks and appear to have been long-lived, influencing the tectonic history of the province. For example, outcropping Cambrian shear zones, evident in vertical derivative data, appear to have nucleated off displaced segments of a once continuous deep-seated structure of Proterozoic origin imaged in upward continued data (Fig. 1).

In another example, shown in Figure 2, a NW-SE oriented, long-wavelength, linear magnetic gradient, changes character along strike due to the range of surface geological phenomena and shallowly sourced potential field responses, which occur along its length. In the NW of the Curnamona Province (Mount Painter region), this interpreted deep-seated structure overprints Delamerian aged folds (ca. 500 Ma; Harrison and McDougall, 1981; Webster, 1996) within basement Willyama Supergroup rocks and overlying Adelaidean sediments. In the Central Curnamona Province (Benagerie Ridge region; Fig 2b), this same structure manifests as a 10 km wide, magnetically quiet corridor, which disrupts the high frequency magnetic texture associated with the Benagerie Volcanics. Here we interpret that the deep-seated structure may have acted as a control on the emplacement of the Benagerie Volcanics and the associated suite of granites (ca. 1580 Ma; Fanning et al., 1998). The southeastern section of this structure, in the Broken Hill Domain (Fig 2c), coincides with a NE-dipping normal fault at the surface, which separates basement Willyama Supergroup rocks, to the SW from Adelaidean sediments to the NE. At this location, the normal fault and surrounding rocks are folded placing important constraint on the age of normal faulting (i.e. pre-Delamerian Orogeny). Here, we interpret normal faulting to have occurred during or after deposition of the Adelaide Rift Complex (ca. 800 Ma; Powell et al., 1994; Preiss, 2000) and before the Delamerian Orogeny.

From our observations, the earliest activity along this structure, associated with the emplacement of the Benagerie Volcanics (~1600 Ma), occurs in the centre of the Curnamona Province. The next episode observed involved normal faulting in the SE (Broken Hill Domain), which juxtaposed Adelaidean sediments against Willyama Supergroup basement rocks and is probably associated with development of the Adelaide Rift Complex (~800 Ma). Following this, the next episode of activity is in the NW where Delamerian folds are clearly overprinted by this large-scale structure (i.e. movement on structure is either contemporaneous with or occurred after folding) (~500 Ma). Finally, the disruption of the high-frequency magnetic signature of the Benagerie Volcanics (i.e. magnetically quiet zone) implies activity along this segment of the structure after the emplacement of the volcanic rocks, whereby fluid flow has dissipated magnetic minerals within the shear zone. Interestingly, these observations imply that either propagation of the shear zone itself or of the activity along it has moved in a continuous direction over the last 1600 million years. Moreover, whilst the surface expression of this deep-seated structure has been deformed by ongoing tectonic events (e.g. it is folded in the Broken Hill region), the deepest extent of it apparently remains linear and continuous (as can be seen in upward continued potential field images). This generates a key question: "How do lithospheric-scale shear zones propagate, both vertically and laterally?".

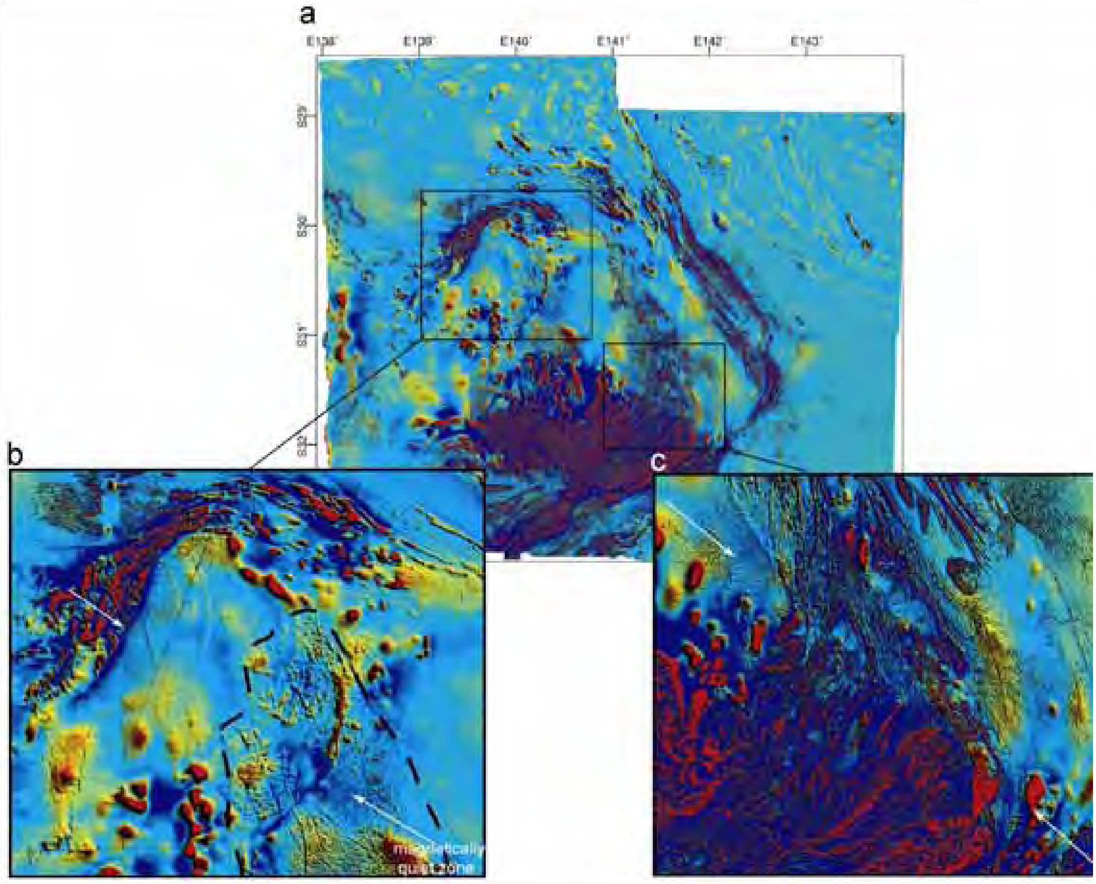

Figure 2. (a) First vertical derivative of aeromagnetic dataset of the Curnamona Province, with magnified images of: (b) the NW Curnamona Province, including the Benagerie Volcanics (characterized by high frequency stippled magnetic texture, boundaries annotated by dashed line) and (c) the northern Broken Hill Domain in the SE of the province. The continuation of a deep-seated NW-SE oriented structure can be seen in each area.

When we consider the Curnamona Province in a plate tectonic context then we would not expect to see the continuation of long-lived deep-seated structures outside the Curnamona Province. Rather, we would expect to see these large structures truncated against the known boundaries of the province. However, on a continental scale, the deep-seated NW-SE oriented structure can be seen to persist beyond the Curnamona Province to the NW and continues into the Musgrave Province. This observation, which appears to contradict plate reconstructions for the South Australian Craton, actually highlights our limited understanding of the link between deep structural architecture and the shallow crust as well as the propagation mechanisms involved with the evolution of these lithospheric-scale shear zones.

Conclusions

Tectonic implications of this study include: (1) Deep-seated structures in the Curnamona Province have protracted histories; (2) These structures have controlled the location and distribution of younger shear zones, igneous activity, and possibly basin subsidence in the upper crust; (3) Geophysical lineaments are likely to have evolved and propagated during multiple tectonic cycles and hence record the protracted evolution of a geological province.

These results show that lithospheric-scale structures can remain remarkably linear over long periods of geologic time. Hence, while periods of significant stress are known to have deformed mid- to upper-crustal rocks in a region (e.g. the Curnamona Province), the lower crust apparently remains relatively rigid and undeformed such that structures, which persist to lower crustal depths, are long-lived and prone to repeated reactivation. These observations imply a vertical partitioning of strain between the lower and upper crust, a factor, which requires consideration when unravelling the deformation history of a craton.

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Stratigraphic and depositional aspects of the Portia and Kalkaroo prospects, Mulyungarie Domain, SA

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Introduction

The Willyama Supergroup (1720-1640Ma) in the Olary Domain has been divided into 3 groups and 5 subgroups (Conor in this volume) and contains thick siliciclastics with minor carbonates that in the Portia and Kalkaroo Prospects host epigenetic Cu-Au-Mo deposits. The Willyama sediments were deformed by the ~1600 Ma Olarian Orogeny and mineralisation is in part controlled by Olarian structures.

The carbonate succession traversed by the Portia and Kalkaroo drillholes (Figure 1) is here referred to as the Portia Formation (Conor in this volume), and can be generally divided into three units: lower marble, middle albitic siltstone/calc-silicate and upper marble. Three units are transitional and the thickness and lithology are variable (Figure 2). Magnetic susceptibility of the formation is generally low when compared with the footwall metasediments. A long north-south–trending anticline with west-east interference has placed the Portia Formation at the Tertiary unconformity as a set of domes.

The Kalkaroo Prospect is marked by a distinct magnetic high to the north of the Kalkaroo Homestead and hosts some approximately 70 million tonnes of ore at a grade of 0.47% copper, 0.46 g/t gold and 124 ppm molybdenum (Havilah Resources NL., 2006, internet publication). Exploration drilling of the anomaly by Placer Ltd began in the early 1990s, and was followed by Newcrest Ltd., MIM Exploration Ltd. and now Havilah Resources NL. Dozens of RAB holes and some tens of deep diamond holes have been drilled, of which five of the latter are considered in this stratigraphic study (Figure 2).

Footwall sediments to the Portia Formation at Kalkaroo consist of psammitic and albitic metasiltstones. These have the characteristic of being magnetite-bearing (i.e. magnetic metapsammite, Hayward, 1999) and contribute to a steep magnetic gradient of regional scale. The metasiltstone contains albite, K-feldspar, ±quartz, biotite, magnetite, scapolite, calcite, ±epidote, ±hematite. Scapolite and calcite become more abundant upwards and hematite alteration is prominent in the lower part. The metasiltstones becomes coarser-grained downwards with thin beds of pelitic psammite, 1-10cm thick, the base of the unit is not intersected. Distribution of magnetite in the metasiltstones is variable but there are many magnetite-rich layers. The metasiltstones are generally layered, laminated and locally cross-bedded. In KND007 (421.2m – 464.2m), some enhanced graded bedding is also present in the upper part. Sedimentary features suggest that the lower part of the unit was deposited in a shallow inner shelf setting but the upper part was deposited under deeper water conditions.

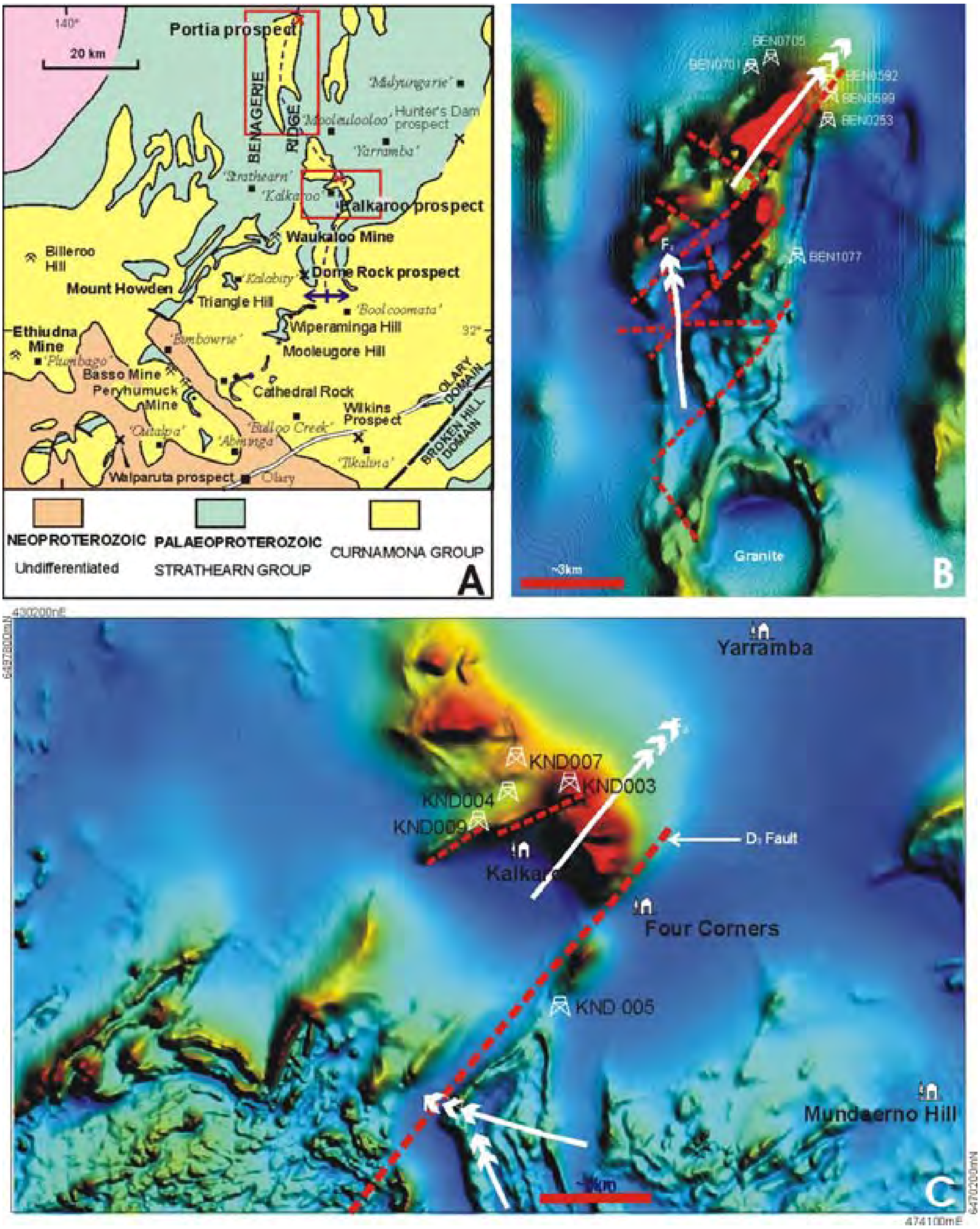

Figure 1. A. Regional geology and drill hole locality. B. Total magnetic intensity image of the Portia Prospect. C. Total magnetic intensity image of the Kalkaroo Prospect.

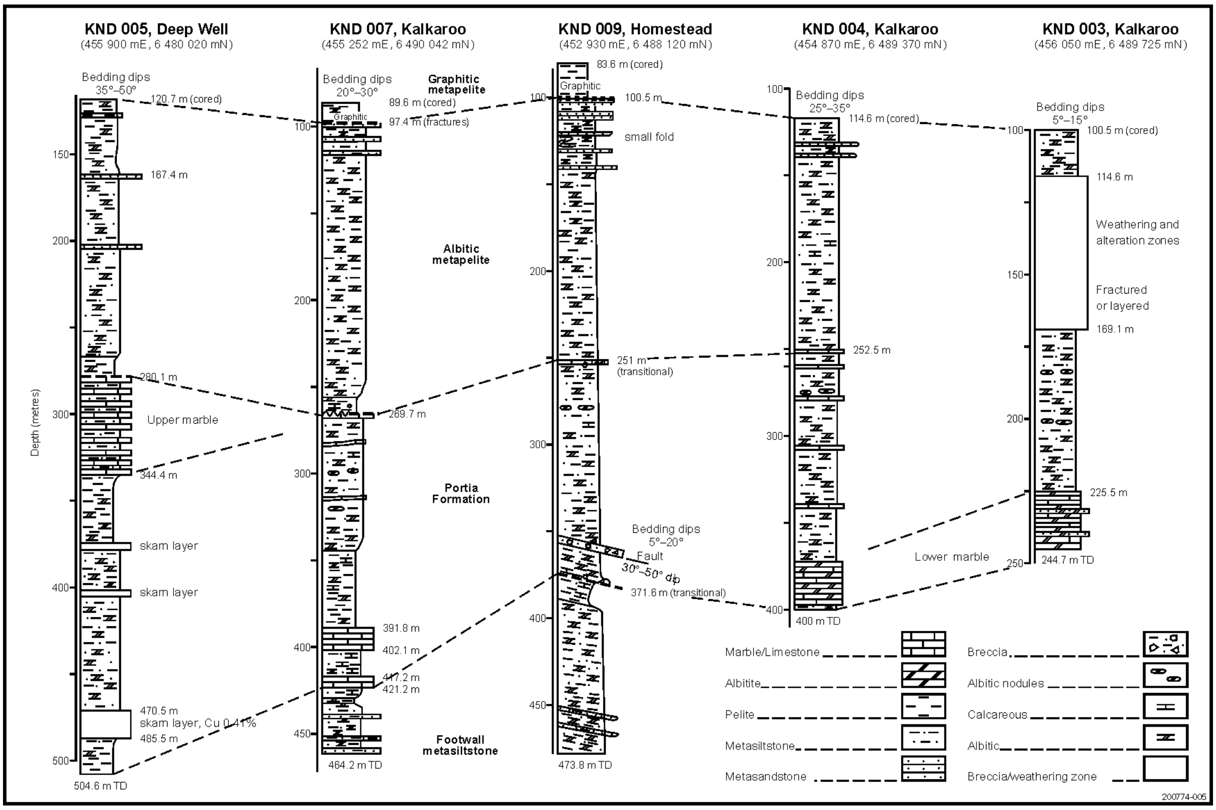

Figure 2. Kalkaroo drillholes and stratigraphic correlation.

The contact between the footwall metasiltstone and overlying Portia Formation is transitional with increasing calcite and scapolite contents. The basal Portia Formation is commonly defined by the layered marble bands. Although in KND 007 and KND 009 drillholes, dark-grey, pyritic, laminated pelite underlies the lower marble layer, and at the Portia and Polygonum Prospects, the base is commonly marked by massive sulphide (pyrite/pyrrhotite).

The lower marble unit consists mainly of calcite (up to 90%), and pelitic interlayers contain abundant scapolite and amphibole (tremolite/actinolite) with minor albite (Figure 3). However, in KND 003 and KND 004 this unit has been albitised. The lower marble is generally layered to laminated but also shows enhanced graded bedding and cross-bedding. These sedimentary features suggest a mid-shelf carbonate build-up, below or at the storm-wave base.

The middle unit of the Portia Formation contains thin-bedded albitite or albitic pelite/psammopelite with minor calc-silicate. The unit is generally thinly layered to laminated and sediments are characterised by mineral assemblage of albite – feldspar –quartz –biotite – actinolite-chlorite ±magnetite. In drill cores it is most recognisable by albite – k-feldspar – quartz layers and round carbonate and biscuit-shaped albite nodules within bedding planes (Fig. 3). Nodules and albite layers are variably distributed, and are attributed to facies changes within the unit. Actinolite-carbonate-chlorite layers are present and commonly contain less albite. The pelite component is commonly layered, but locally laminated and cross-layered. Enhanced graded bedding is present in lower dark-grey laminated, pyritic pelite and the bedding often has a scoured base. A coarser-grained psammite layer contains small pyrite blobs and fine-grained layers are albitic. The upper part of the middle unit is locally psammitic. The bedding may represent an enhanced tempestite parasequence, indicating mid to outer shelf ramp settings. The middle unit of the Portia Formation is interpreted to have been deposited under shallowing upwards conditions.

The upper marble layer in KND 007 is less distinct, about 20cm thick (depth 269.5m-269.7m), but in KND 005, the equivalent is more than 40m thick (280.1m – 344.4m). The upper marble is layered and transitional with the underlying psammopelite. The contact between the upper marble and overlying albitic pelite seems transitional in KND 005, but in KND 007, a vuggy bed (? former karst) is present, possibly suggesting a sedimentary break in the area.

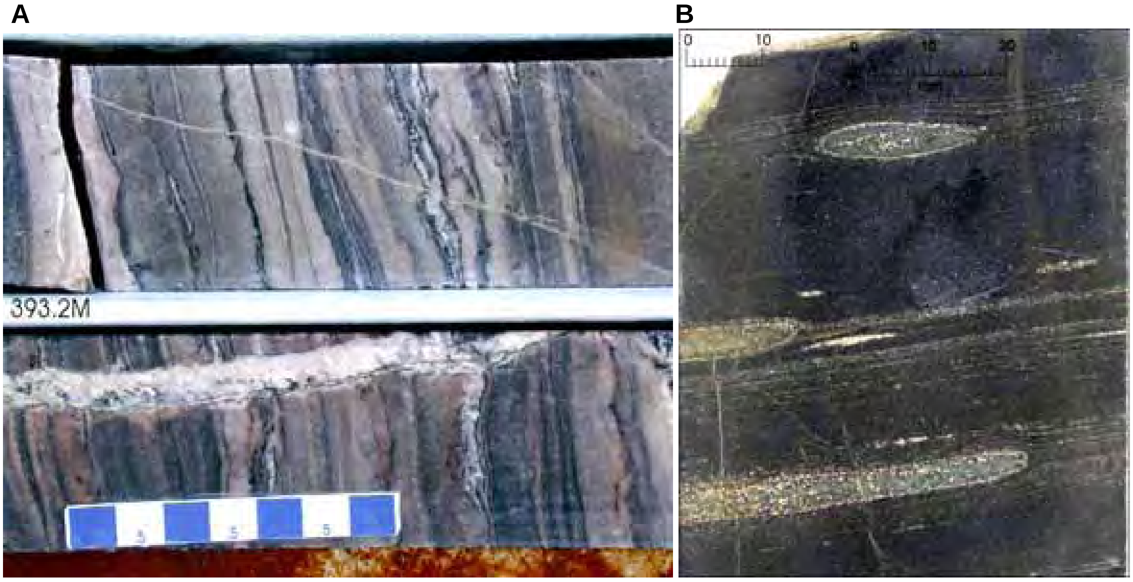

Figure 3. A. Layered to cross-layered marble (Portia Formation, photo at left), KND 007 – 393. 2m. B. Pyrrhotite-bearing metasiltstone with albite 'biscuits', middle unit of Portia Formation, KA 11 – 293.35m.

The hanging wall pelite sequence in the Kalkaroo area contains two units, lower albitic, laminated pelite and upper graphitic pelite. The graphitic pelite is massive to laminated and low-angle cross-bedding is locally present. Enhanced graded bedding with scoured bases occurs in KND 007 (depth 90.2m). The graphitic pelite is a deep-water (basinal) deposit.

The Portia Formation in the Portia Prospect is similar to that at Kalkaroo, containing upper and lower marble units, separated by a siliciclastic- calcsilicate unit. Of great significance at North Portia is a tuff-bearing tuff layer within the middle-upper unit (depth 303.6m, BEN 599, unit 5, Teale, 2000). A tuff was dated at 1703±6 Ma (Teale and Fanning, 2000) and the age corroborated by further work of Jagodzinski (in this volume).

Correlation of the Bimba Formation (cf. Hemming, 1981) observed to the west in inliers of the Olary Domain with the mineralised carbonate-bearing succession at Kalkaroo and Portia has proved difficult, hence the decision to name that latter succession separately as the Portia Formation. The upper surface of the Bimba Formation is constrained by deposition of the Plumbago Formation at ~1693 Ma (Conor 2004), but this unit has not as yet been located at Portia, Kalkaroo or Polygonum. The Bimba Formation in outcrop generally contains one thick carbonate unit and is associated with a gossan layer, which is possibly equivalent to the upper marble unit of the Portia Formation. The precise stratigraphic relationship requires more detailed study (see Jagodzinski et al., this volume).

The Cu-Au-Mo sulphides in the Portia and Kalkaroo prospects are present as disseminated replacement of original pyrite/pyrrhotite, in veins, and associated with breccias (Figure 4). It is suggested that mineralisation was trapped by the sulphidic Portia Formation with late Olarian Orogeny folds and faults providing suitable channel-ways and sites for accumulation A SHRIMP U-Pb date, ~1588-1583 Ma, on titanite (Skirrow and Ashley, 2000) indicates the timing of at least a part of the mineralising event. Better understanding of the stratigraphy, geochemistry, structural geology and timing will be of value to future exploration in the region.

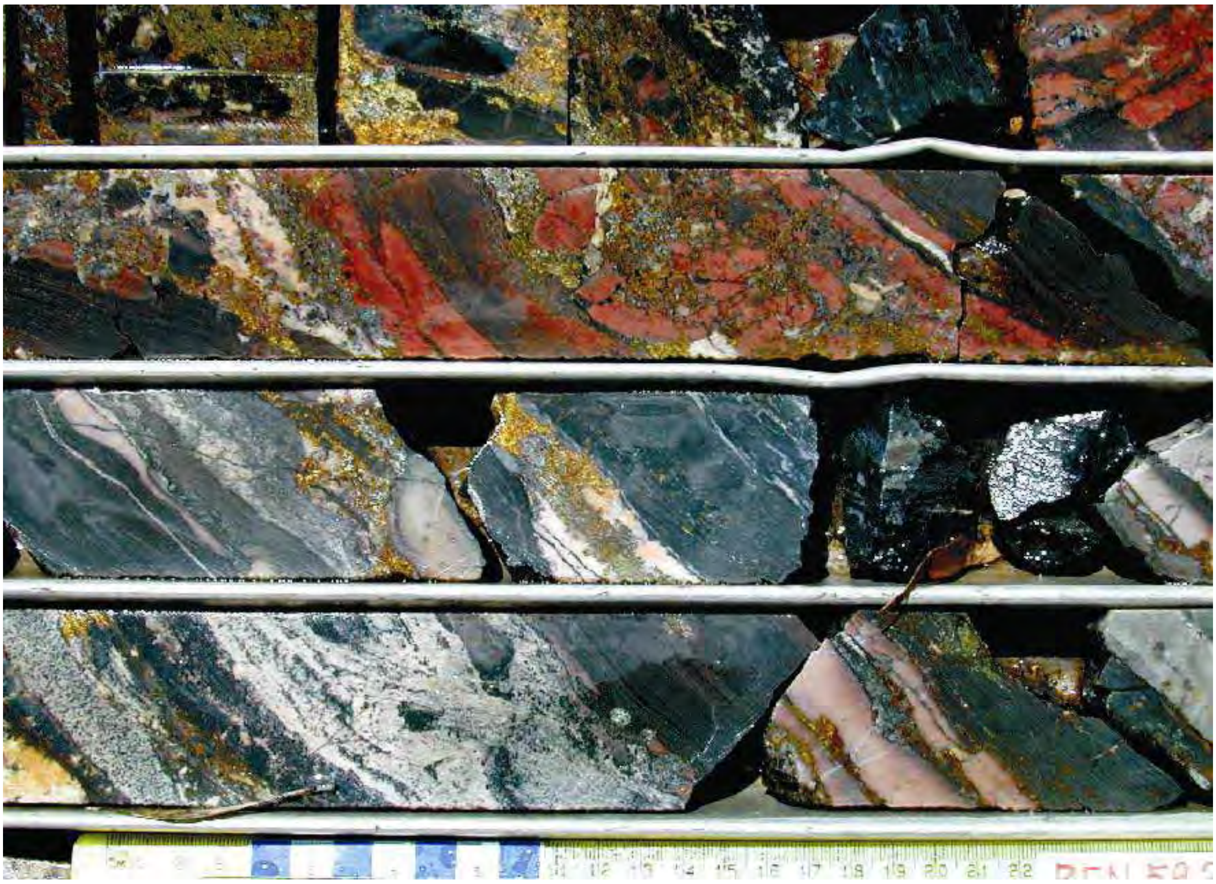

Figure 4. Primary mineralisation zone in BEN 592, depth 367 m, Portia Formation.

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