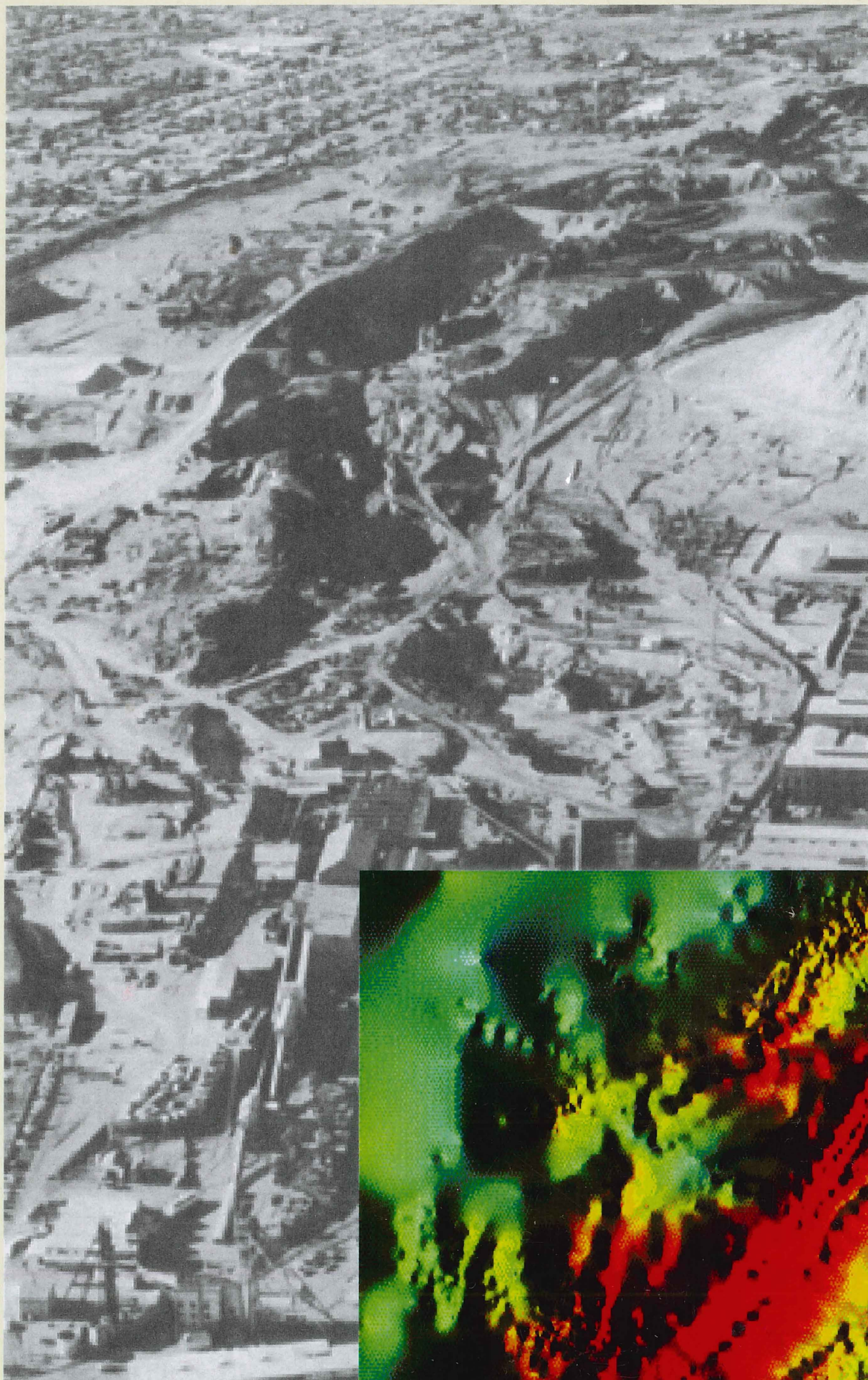
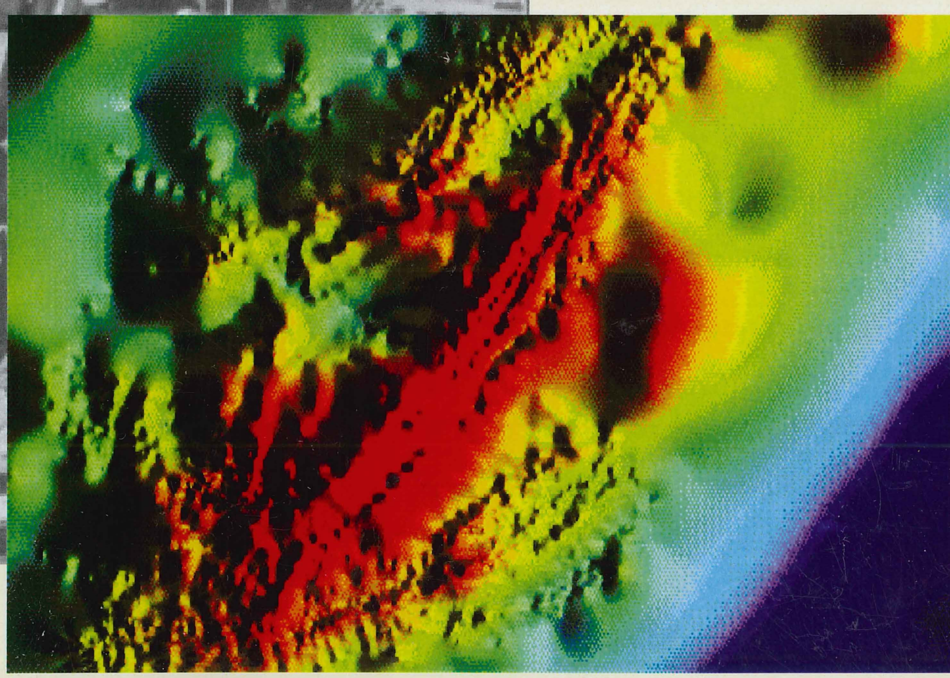
BROKEN HILL EXPLORATION INITIATIVE

Abstracts from 1998 Annual Meeting





Record 1998/25

AGSO
AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

MINERAL RESOURCES

PRIMARY INDUSTRIES AND RESOURCES SA

Broken Hill Exploration Initiative: Abstracts of papers presented at fourth annual meeting in Broken Hill, October 19-21, 1998

AGSO Record: 1998/25

Compiled by G. M. Gibson

The Broken Hill Exploration Initiative is a collaborative National Geoscience Mapping Accord project between the Australian Geological Survey Organisation, the NSW Department of Mineral Resources, and Primary Industries and Resources, South Australia

DEPARTMENT OF PRIMARY INDUSTRIES AND ENERGY

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AUSTRALIAN GEOLOGICAL SURVEY ORGANISATION

Executive Director: Neil Williams

ISSN:1038-0073
ISBN:0 642 27361 8

Foreword

This volume incorporates the Abstracts of papers presented at the fourth annual meeting of the Broken Hill Exploration Initiative (BHEI) which took place in Broken Hill from October 19-21, 1998. Technical sessions encompassed several main themes, including regional geology and structure, metallogenesis and geochemistry, exploration and mineral deposits, regolith mapping and landscape evolution, petrophysics, and geochronology. Other talks focussed on the impact of the BHEI and the future directions of geoscientific activity in the region. Many of the talks were given by staff from academia and the government surveys, but in a departure from previous years' meetings, the 1998 scientific program included many more talks from industry representatives whose subject matter ranged from Cu- Au mineralisation in the highly prospective Olary region to some exciting new developments in the less well known areas immediately to the southeast of the Broken Hill Block.

Abstracts are listed alphabetically according to the surname of the first author. No attempt was made to have the abstracts formally reviewed and thus any analyses or scientific opinions expressed in this Record are the sole responsibility of the authors.

The BHEI is a joint Commonwealth/State program, carried out under the National Geoscience Mapping Accord, which aims to provide a new generation of geoscientific information for the Broken Hill - Olary region in New South Wales and South Australia. This program has been undertaken as a means of securing the future development of the region through increased exploration activity and the subsequent discovery of new mines.

Involved with the BHEI program are:

- the Australian Geological Survey Organisation, the New South Wales Department of Mineral Resources, and the Department of Primary Industries and Resources, South Australia
- the Co-operative Research Centres for Australian Geodynamics, Australian Mineral Exploration Technologies, and Australian Landscape Evolution and Mineral Exploration
- Universities of Adelaide, La Trobe, Melbourne, Monash, New England, Tasmania, and the Australian National University
- Mineral exploration and mining companies

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AGSO

STRATIFORM Pb-Zn-Ag MINERALISATION IN THE BROKEN HILL AND EURIOWIE BLOCKS

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INTRODUCTION

The aim of this paper is to review the features of stratiform Pb-Zn-Ag mineralisation in the Broken Hill and Euriowie Blocks and to look at the plausibility of the various models which attempt to explain its origin. The most abundant type of stratiform Pb-Zn-Ag mineralisation in the district is Broken Hill type (BHT) and the bulk of this discussion will focus on this. Corruga type calc-silicate hosted Pb-Zn-Ag-Cu-W mineralisation is also discussed as it is probably genetically related to Broken Hill type.

Stratiform Pb-Zn-Ag mineralisation is almost exclusively confined to the Broken Hill Group. The only exception is the Pinnacles deposit and related occurrences in the Pinnacles area, which are interpreted to be within the underlying Thackaringa Group.

BROKEN HILL MAIN LODE

The Broken Hill Main Lode (BHML) is the most significant BHT deposit within the region. It contained about 300 Mt of mineralised rock prior to mining. It comprises a series of six stacked lenses with their own distinctive Pb:Zn ratios and gangue mineralogy. Sulphides comprise chiefly argentiferous galena and sphalerite with lesser chalcopyrite, arsenopyrite, loellingite and pyrrhotite. The gangue minerals comprising the inner parts, or cores, of the orebodies are chiefly Mn, Ca, F and P bearing minerals such as rhodonite, bustamite, hedenbergite, calcite, fluorite and apatite. The outer parts of the orebodies comprise fine-grained, granular, garnet-rich rock ("garnet sandstone"), garnet-quartz rock and quartz± gahnite rock. The important feature of this relationship between the rock types is that 'typical' Broken Hill style mineralisation throughout the district is most like the envelopes around the BHML.

OTHER BROKEN HILL TYPES

There are nearly 500 occurrences of Pb-Zn-Ag mineralisation associated with "garnet sandstone", garnet-quartz rocks, and/or quartz-gahnite rock in the Broken Hill and Euriowie Blocks. These bodies are typically less than one metre to several metres thick and range in length from a few metres to several tens of metres. They are generally hosted by metasediments, though in rare instances the host is amphibolite or Potosi type gneiss.

It is very rare to find characteristic BHML minerals in other BHT deposits in the district. Apatite is present in some garnet-quartz and quartz-gahnite rocks and calcite and hedenbergite are present at the Pinnacles mine. Rhodonite is present at the Melbourne Rockwell mine, in the Little Broken Hill area.

In the Little Broken Hill area several garnet-quartz bodies have associated magnetite, either intimately distributed through them as quartz-garnet-magnetite rock, or in distinct quartz-magnetite layers. These compositions are akin to those of Broken Hill type mineralisation in South Africa and Cannington.

CORRUGA TYPE

Corruga type mineralisation consists of calc-silicate rock with generally only minor amounts of argentiferous galena, sphalerite, chalcopyrite, pyrite and scheelite. The calc-silicate comprises quartz with variable amounts of grossular-andradite garnet (as opposed to the spessartine - almandine compositions of BHT deposits), and various amounts of amphibole. Epidote is common but is a retrograde mineral replacing garnet. The rock type may represent a calcic variety of garnet-quartz rock. Calcite, wollastonite, diopside (manganiferous) and apatite are present within some Corruga type deposits, indicating some similarity to parts of the BHML (ie 1 lens and 2 lens). Some have quartz-gahnite rock associated with them, and in the Little Broken Hill area some contain quartz-magnetite rock, similar to that present within some quartz-garnet rocks of that area. These features suggest a connection between Corruga and BHT deposits.

ORIGINS OF STRATIFORM MINERALISATION

There is much debate over the origins of stratiform Pb-Zn-Ag deposits in the Broken Hill area. When attempting to evaluate the most likely origin of stratiform Pb-Zn-Ag mineralisation we can first start by considering all possible models, then sequentially testing them against the available evidence to see how they perform. Broadly there are four possible genetic models - 1) syngenetic (ie exhalative); 2) diagenetic; 3) syn-tectonic/metamorphic; and 4) post-tectonic/metamorphic.

POST-TECTONIC/METAMORPHIC MODELS

The idea that the stratiform Pb-Zn-Ag mineralisation is post-tectonic/metamorphic is untenable. The gangue minerals commonly display high grade metamorphic textures and mineralogy and Maiden (1975) noted gangue minerals defining a foliation within high grade ore of the BHML. Hodgson (1975) described exsolution features in gangue minerals of the BHML which he considered must have formed at high temperature. Sulphides must pre-date metamorphism as they are coarsely recrystallised and in places remobilised. Examples of this are seen in sulphide injections across fold noses (Maiden 1975) and droppers in the BHML (Maiden 1976). Layering in some lode rocks is folded and the BHML is quite obviously deformed and folded. The occurrence of green feldspar pegmatite, in places containing sulphides, within lode rocks shows that the lodes and mineralisation must predate partial melting.

SYN TECTONIC/METAMORPHIC MODELS

If the mineralisation has been emplaced during deformation/metamorphism then there are two ways in which this could have happened. a) both gangue and sulphides have been emplaced purely structurally (ie as veins); or b) both gangue and sulphides are replacing a particular rock type.

If the mineralisation has been emplaced as veins, the lode horizons should be structurally controlled and be independent of the host rock sequence. The fact that Pb-Zn-Ag stratiform mineralisation is almost entirely confined to the Broken Hill Group argues against it having been emplaced via regional scale deformation/metamorphic events. While some localised quartz+gahnite veining (on a scale of tens of centimetres at most) is present in places (and this can readily be explained by remobilisation during metamorphism), on a larger scale the lode rocks do not display cross-cutting relationships with bedding. The occurrence of lode horizons within well-bedded metasediment argues against them having been emplaced within shear zones.

In the case of replacement there are two alternatives - a) the progenitor to the lode rock/s was no different to the enclosing host rock (ie metasediment); or b) the progenitor was a chemically reactive rock, the most likely option being a carbonate.

In the first case it would be expected that the lode horizons would have gradational boundaries with the host rock. Hodgson (1974), concluded that some garnet-rich rocks adjacent to the BHML are metasomatic replacements of metasediments. However, he demonstrated that this process must have occurred before folding as the distribution of garnet-rich rocks adjacent to the BHML has affected the fold styles. Away from the BHML the lode rocks have a sharp contact with their hosts.

A carbonate unit would be the best option for replacement and the idea that the BHML is a skarn has been suggested. The BHML is the only BHT deposit in the district with calc-silicate mineralogy. This fact can be interpreted in two ways - either the BHML is unique in its size and composition because there was replacement of a large carbonate mass, while the smaller BHT deposits were not originally carbonates and hence were only weakly mineralised; or, the absence of carbonate minerals in smaller BHT deposits demonstrates that carbonate mineralogy is not a prerequisite for BHT mineralisation so that the BHML need not be a skarn either. The occurrence of large amounts of sulphide in quartz-rich rocks (±garnet and/or gahnite) supports the second alternative eg the Potosi orebody, and B and C lodes of the BHML.

DIAGENETIC MODELS

Diagenetic models are of two types - a) those which require fluid flow on a regional scale, for example the model proposed by Wright et al. (1993); and b) those which envisage local fluid movement such as sub-sea floor convection related to an exhalative vent. Wright et al. (1993) proposed that metal-bearing fluids, sourced from the lower parts of the stratigraphic package, moved upwards along growth faults and were preferentially channelled into psammitic units in the Broken Hill Group. However, the model does not adequately explain the separate, stacked lenses of the BHML, the distribution of BHT deposits throughout the Broken Hill Group, nor the fact that the BHML has a gangue mineralogy different from other BHT deposits in the district. In addition, no satisfactory explanation was given as to why psammites in the Broken Hill Group should have been favoured over those in other parts of the stratigraphic package. A possible modification to the Wright et al. model could include a carbonate unit having been replaced to form the BHML. However, the same objections to the syn-tectonic/metamorphic carbonate replacement model, as outlined above, still apply.

The second diagenetic model is closely associated with the syngenetic one and may have some merit (cf modern day sea floor vent systems).

SYNGENETIC (EXHALATIVE) MODEL

The syngenetic exhalative model is the best alternative to explain the origin of stratiform Pb-Zn-Ag mineralisation in the Broken Hill area ie some lode rocks are finely laminated, with laminae developed parallel to the enclosing rocks; variations in lode composition along and across strike can be explained by syngenetic exhalations; the series of stacked lenses such as in the BHML and Pinnacles; the concordance of lode rocks with the enclosing host rocks; the sharp contacts which the lode rocks have with their hosts; and the occurrence of lode rocks within the same suite of host rocks (ie Broken Hill Group).

The Pb isotope ratios from the BHML suggest an age consistent with the interpreted depositional age of the host rocks based on zircon U-Pb dating. The Pinnacles deposit has generally lower ratios of $^{206}Pb/^{204}Pb$ and $^{207}Pb/^{204}Pb$ to the BHML, suggesting that it is older than it by about 10 Ma. Firstly, this indicates that stratiform Pb-Zn-Ag mineralisation in the Broken Hill area cannot have formed all at one time, as would be expected with the syn- or post-tectonic model. Secondly, the relative ages are consistent with the relative ages of the enclosing host rocks, based on stratigraphic interpretations which place the Pinnacles stratigraphically below the BHML. Thirdly, the relative ages are consistent with U-Pb zircon ages of particular rocks at the corresponding stratigraphic levels.

Lottermoser (1991) demonstrated that the U:Th ratios of some BHT lode rocks are similar to those of modern hydrothermal deposits. Lottermoser (1989a) showed that the REE signature of some BHT lode rocks are similar to that of modern day hydrothermal sea floor vent fluids. Parr (1992) interpreted REE patterns of lode rocks from the Pinnacles deposit to reflect deposition from exhalative hydrothermal fluids, while Lottermoser (1989b) gave a similar interpretation for REE patterns of rocks from the Corruga No 1 deposit.

REFERENCES

Hodgson C.J. 1974. The geology and geological development of the Broken Hill Lode in the New Broken Hill Consolidated Mine, Australia Part I: Structural geology. *Journal of the Geological Society of Australia* 21, 413-430.

Hodgson C.J. 1975. The geology and geological development of the Broken Hill Lode in the New Broken Hill Consolidated Mine, Australia Part II: Mineralogy. *Journal of the Geological Society of Australia* 22, 33-50.

Lottermoser B.G. 1989a. Rare earth element study of exhalites within the Willyama Supergroup, Broken Hill Block, Australia. *Mineralium Deposita* 24, 92-99.

Lottermoser B.G. 1989b. Rare earth element behaviour associated with strata-bound scheelite mineralisation (Broken Hill, Australia). *Chemical Geology* 78, 119-134.

Lottermoser B.G. 1991. Trace element composition of exhalites associated with the Broken Hill sulfide deposit, Australia. *Economic Geology* 86, 870-877.

Maiden K.J. 1975. High grade metamorphic structures in the Broken Hill orebody. *Australasian Institute of Mining and Metallurgy, Proceedings* 254, 19-27.

Maiden K.J. 1976. Piercement structures formed by metamorphic mobilization of the Broken Hill orebody. *Australasian Institute of Mining and Metallurgy, Proceedings* 257, 1-8.

Parr J.M. 1992. Rare-earth element distribution in exhalites associated with Broken Hill-type mineralisation at the Pinnacles deposit, New South Wales, Australia. *Chemical Geology* 100, 73-91.

Wright J.V., Haydon R.C. & McConachy G.W. 1993. Sedimentary analysis and implications for Pb-Zn mineralisation at Broken Hill, Australia. James Cook University of North Queensland, *Economic Geology Research Unit Contributions* 48, 91pp.

Acknowledgment

This paper is published with the permission of the Director-General, NSW Department of Mineral Resources.

GEOSCIENTIFIC GIS DATASETS DEVELOPED FOR THE BROKEN HILL EXPLORATION INITIATIVE

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An integral component of the Broken Hill Exploration Initiative is the collection and validation of exploration and research data from the Curnamona Province. A wealth of geochemical, geophysical and geological data have been generated in this region dating as far back as the late nineteenth century. The capture and management of this large volume of historical information has been highlighted by industry as an important resource which it requires to develop its exploration strategies. Therefore, the three government agencies have conducted an intensive data capture program to provide industry with high quality digital data sets ready to use in a GIS environment.

A cooperative approach has seen the production of three geoscientific GIS datasets during the term of the BHEI. The Curnamona Province GIS was assembled in early 1996 to provide an overview of regional datasets available for the BHEI area, while the Olary and Broken Hill GIS datasets were produced as a means of distributing detailed geological data in these areas.

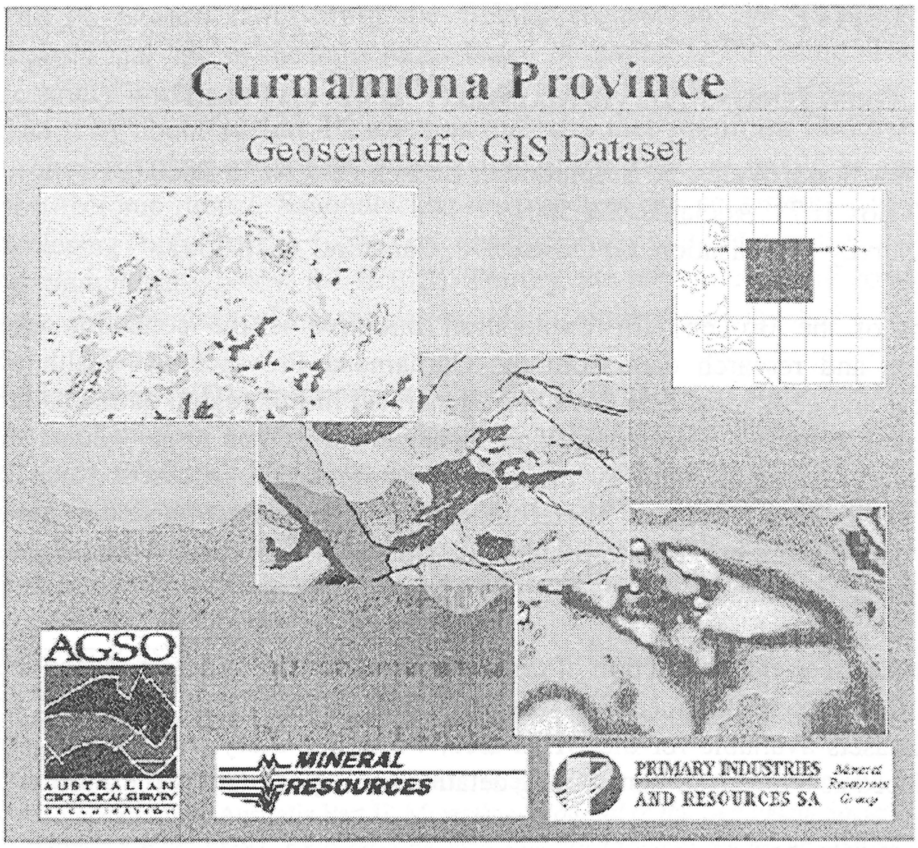
CURNAMONA PROVINCE GIS

The area covered comprises eight 1:250 000 mapsheets; namely Callabonna, Frome, Curnamona, Olary, Milparinka, Cobham Lake, Broken Hill and Menindee. The highlight of this package is the 1:500 000 geology and solid geology interpretation maps of the Curnamona Province and surrounding Neoproterozoic and Palaeozoic belts. These maps were compiled by Barney Stevens, Wolfgang Preiss and Bill Laing using all the available mapping.

The GIS also contains a number of cultural layers including roads, lakes, homesteads, national parks and the AUSLIG 1:250 000 drainage. There are summary data for 3400 mineral occurrences and 5500 mineral exploration drillholes in the region as well as upwards of 13 000 geochemical assays. These are presented along with current and lapsed tenement coverages and packaged with a spatially integrated bibliographic database.

Regional gravity and aeromagnetic images have been included on the first release of the dataset. Recent detailed gravity data collected over the Bancannia Trough and Koonenberry areas are included and have been stitched into the regional coverage.

Mapping and data capture have been progressing steadily since the CD was first released. The regional geological synthesis is ongoing and the solid geology interpretation is in the process of being updated with new data from the Olary Block and the Koonenberry region. The mineral occurrence database for NSW has been updated and mineral occurrence mapping has been undertaken in the Olary region. New, high-resolution aeromagnetic and gravity data collected by the South Australian and New South Wales governments will be stitched into the regional images. At this stage it is envisaged that an updated version of the Curnamona GIS containing the latest data will be released in early 1999.

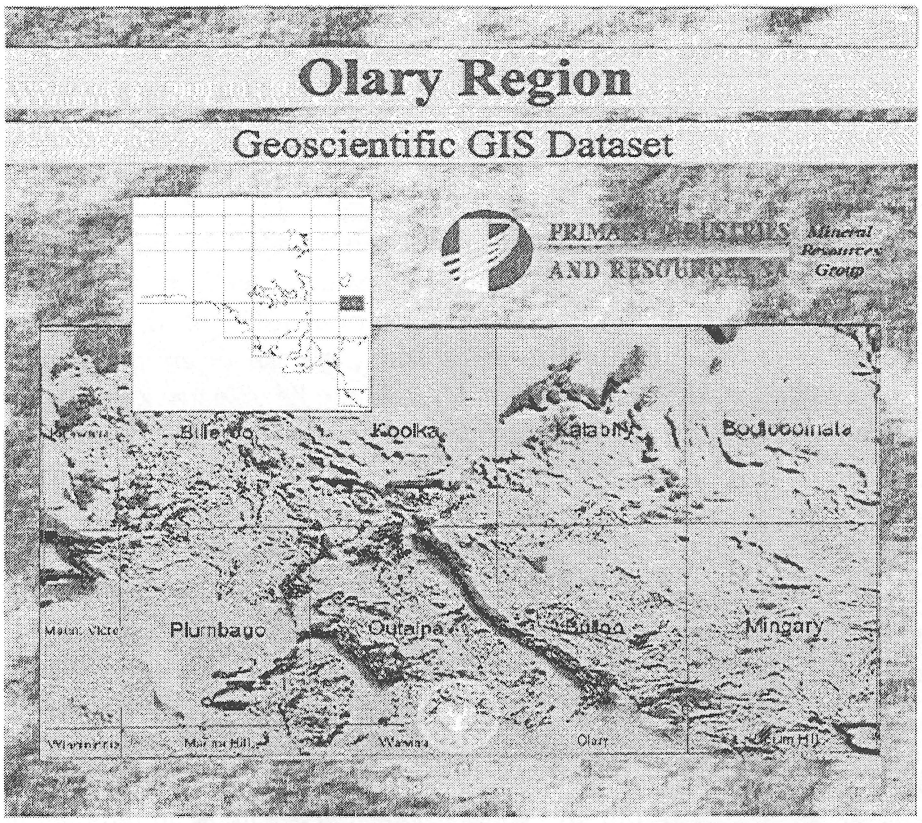


Cover of the Curnamona GIS CD-ROM

OLARY REGION GIS

The Olary region GIS was produced principally as a means of distributing the Olary Domain 1:25 000 basement compilation maps. Thirteen lithological maps of basement outcrop in the Olary Block have been generated by compilation of previous company, MESA and university mapping. A common classification scheme has been used by consultant Bill Laing to enable correlation of units between sheets. The outcrop boundaries have been validated against GPS rectified Landsat imagery.

The maps have been packaged with all the available topographic, bibliographic, geophysical and geochemical data available for the region. This includes some of the higher resolution gravity and aeromagnetic data collected by PIRSA.



Cover of the Olary GIS CD-ROM

BROKEN HILL GIS

The Broken Hill CD is centred on the highly prospective areas of outcropping and covered Palaeoproterozoic terrain in western NSW. The 21 published 1:25 000 scale geological maps produced by the Geological Survey of NSW have been converted into digital coverages and form the core of the package. The published 1:100 000 scale lithostratigraphic interpretation map is also included in the package

Topographic data from the 1:25 000 series of base maps prepared for the Broken Hill mapping project have been scanned and vectorised. These data have been separated into layers comprised of drainage, roads/tracks, rail and fences. Property boundaries have also been included as a digital coverage.

This GIS contains a number of layers not found on the Curnamona Province CD including:

The solid geology interpretation maps for the Mount Gipps and Stephens Creek 1:25 000 sheets.

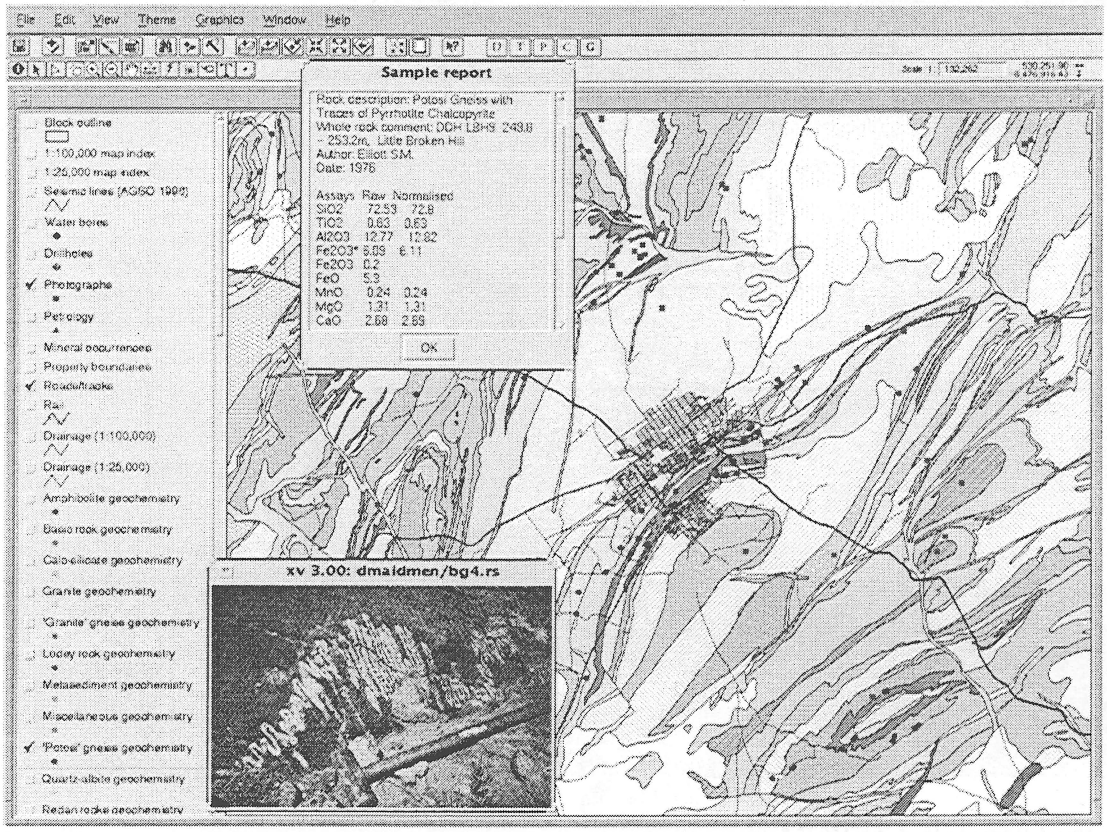
Some 21 coverages generated for the whole block showing the distribution of individual lithologies.

The regionally extensive auger drilling program conducted by Broken Hill South, in the late 1960's, is included as a set of pseudocolour images to highlight the base metal geochemistry.

A photo library of representative rock types with individual images hotlinked to their locations.

An image of the Broken Hill gravity survey recently completed by the BHEI.

A whole rock geochemical dataset comprising 2050 samples split into coverages containing analyses for the major lithologies. (eg. Potosi gneiss, amphibolite).



Screen snapshot of the Broken Hill GIS, Arcview version

The three packages have been designed to allow companies to quickly carry out a first pass assessment of the ground they are interested in. Exploration in high grade metamorphic terranes is very challenging and companies need all of the data available to make informed decisions. By producing these GIS datasets, the partners in the BHEI are providing industry with valuable information to assist with their exploration programmes.

MINGARY MAPPING: PROGRESS TO DATE

ALISTAIR CROOKS

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Massive, fine to coarse grained, leucocratic quartz-albite rocks outcrop on the Mingary 100K sheet, eastern South Australia. These have recognisable similarities to the quartz-albite lithologies in the Thackaringa Group of the Broken Hill Region to the east. In rare places, layering and layer parallel schistosities exhibit north-east trending, upright, shallow plunging folds with vertical axial planes. A compressional deformation event is inferred, and correlated with the widely-recognised, D_2, compressional, deformation event seen throughout the Curnamona Craton.

Nearby, at Pinery Hill, layer parallel amphibolite bodies which intrude these quartz-albite rocks, also show evidence of this same style of folding.

In addition, within the same quartz-albite rocks are highly attenuated, highly foliated augen gneiss bodies similar in appearance to the Alma Gneiss at Broken Hill. The Alma Gneiss has been interpreted as a metamorphosed, intrusive granite (Vernon and Williams, 1988) and this interpretation is accepted for these gneisses on the Mingary 100K sheet. The intense foliation in the granitic bodies is considered to be syn–intrusion; that is, the granite was injected into a zone of high strain (Gibson pers com). The majority of the stress has been partitioned into this melt zone but there is evidence of some foliation, leucosome and metamorphic mineral development in neighbouring rocks. The foliation within these Mingary bodies shows the same north-east trending, upright, shallow plunging parasitic folds as both the quartz-albite host rocks and the amphibolites.

If these rocks were to be unfolded, with the compositional layering in the quartz-albite rocks brought back to the horizontal, both the amphibolite intrusions and the granitic bodies would form subhorizontal, layer-parallel, sill-like sheets.

Zircon dating of the Alma Gneiss at Broken Hill gives an intrusive age of 1691 ± 12 Ma (Nutman and Ehlers, 1998). The Alma Gneiss granitic intrusions are considered coeval with the sedimentation of the Broken Hill Group, and in particular, its extrusive equivalent, the Hores Gneiss (Wyborn pers com). The Hores Gneiss has been zircon dated at 1689 ±5. (Page and Laing, 1992). If this interpretation of the Alma Gneiss is correct then the subhorizontal fabric observed within the Alma Gneiss, cannot be the same as the layer-parallel fabric previously recognised in the region and referred to as S_1, as it is also seen in the overlying, and hence younger, Sundown and Paragon Group sediments of the Broken Hill Block and Pelite Suite sediments of the Olary Block. S_1 is an axial plane fabric linked to F_1 recumbent folds of Hobbs et al (1984) and the nappes of Laing et al (1978), Marjoribanks et al (1980).

Hores Gneiss and other Broken Hill Group lithologies are consistent with a regional extensional depositional environment implying that the coeval granite and amphibolite bodies were also intruded under an extensional regime.

Comparison with the Wonga Belt, in the Mary Kathleen Fold Belt is invited. The Wonga Granite, a foliated augen gneiss, is interpreted to have been injected into a subhorizontal décollement surface undergoing active extension (Holcombe et al, 1991). This was also accompanied by basic intrusives as layer-parallel sills. While the oldest dated intrusive which shows evidence of this early fabric is 1759 ± 22 Ma (Page, 1983), the dates range down to 1671 ± 8 Ma (Page, op cit), (Page et al, 1984). This overlaps the suggested ages for a similar bimodal intrusive suite into an extensional setting on the Curnamona Craton.

REFERENCES

Hobbs BE, Archibald NJ, Etheridge MA and Wall VJ, 1984. Tectonic history of the Broken Hill Block, Australia. In Kröner A and Greiling R (eds) *Precambrian Tectonics Illustrated.* E.Schweizerbart'sche, Stuttgart, pp 353-368.

Holcombe RJ, Pearson PJ and Oliver NHS, 1991. Geometry of a middle Proterozoic extensional décollement in northeastern Australia. *Tectonophysics* 191:255-274.

Laing WP, Marjoribanks RW and Rutland RWR,1978, Structure of the Broken Hill mine area, and its significance for the genesis of the ore bodies. *Economic Geology* 73:1112-1136.

Marjoribanks RW, Rutland RWR, Glen RA and Laing WP, 1980. The structure and tectonic evolution of the Broken Hill region, Australia. *Precambrian Research* 17:209-240.

Nutman AP and Ehlers K, 1998. Evidence for multiple Palaeoproterozoic thermal events and magmatism adjacent to the Broken Hill Pb-Zn-Ag orebody, Australia. *Precambrian Research* 90:203-238.

Page RW, 1983. Chronology of magmatism, skarn formation and uranium mineralization, Mary Kathleen, Queensland Australia. *Economic Geology* 78:838-853.

Page RW, McCulloch MT and Black LP, 1984. Isotopic record of major Precambrian events in Australia. *Procedings of the 27th International Geological Congress Moscow* 5:25-72.

Page RW and Laing WP, 1992. Felsic Metavolcanic Rocks Related to the Broken Hill Pb-Zn-Ag Orebody, Australia: Geology, Depositional Age, and Timing of High-Grade Metamorphism. *Economic Geology* 87:2138-2168.

Vernon RH and Williams PF, 1988. Distinction between intrusive and extrusive or sedimentary parentage of felsic gneisses. Examples from the Broken Hill Block, NSW. *Australian Journal of Earth Sciences* 35:379-388.

LANDSCAPE EVOLUTION AND MINERAL EXPLORATION IN THE BROKEN HILL REGION: A NEW INITIATIVE BY CRC LEME, 1998-2002

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The Basins Program of CRC LEME aims to provide the minerals industry with improved methodologies for exploration in areas covered by thin sedimentary and regolith cover (generally <300 m). The strategy of the Program is to apply a multi-disciplinary investigation approach to areas where sedimentary sequences onlap onto basement lithologies of high mineral potential, as well as where the concealed basement rocks are believed to be barren.

The Broken Hill Block is an area of significant mineral exploration potential. The emerging block hosts several deposits, including the world-class Broken Hill Ag-Pb-Zn mine. Over the last century, outcropping basement rocks have been the target of intensive and protracted mineral exploration, which has failed to discover any other deposits of the size of the Broken Hill deposit. Attention is now turning to the sediment-covered margins of the block. The neighbouring Curnamona Province and Olary Block also present highly prospective basement lithologies, which become gradually covered by sedimentary and regolith sequences from south to north (eg, the Portia prospect). Both Broken Hill and Olary are region of active exploration at the moment.

The Basins Program is launching a strategic project at Broken Hill that will constitute a framework for CRC LEME activities at and around Broken Hill and Olary from 1998 to 2002. The project is a basis for discussion and negotiation between CRC LEME and individual - or groups of - exploration companies, and is a foundation on which several tenement-based sub-projects will be built.

The principal objective of the project is to develop and provide tools to industry for the exploration and characterisation of prospective mineral deposits under shallow (<300 m) regolith and sedimentary cover surrounding the Broken Hill and Olary Blocks. The specific objectives of the project are the development of Lithological, Geochemical and Geophysical Models for the study regions. These models will define the regional baseline regolith characteristics, from which the variations due to localised mineralisation may be discriminated. Each of these models forms an essential component to the principle objective outlined above. Each model will initially be generated using existing data. These will then be evolved iteratively as new data are integrated.

The strategy of the project is:

1. to compile existing open-file and company data to erect preliminary lithological, geochemical and geophysical models

2. to set up a series of industry-sponsored sub-projects on tenements held in the Broken Hill/Olary region
3. to undertake multi-disciplinary research (landforms, regolith materials, sedimentology, groundwater, geophysics) to refine the lithological, geochemical and geophysical Models for the detailed study areas
4. to integrate these models to derive regional models of physical and chemical dispersion, as tools for exploration in the region.

THE BROKEN HILL EXPLORATION INITIATIVE: IMPACTS ON THE SEARCH FOR NEW ORE DEPOSITS

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INTRODUCTION

Ore from the Broken Hill Mine is the lifeblood of Broken Hill (NSW) and Port Pirie (SA). However, the mine is nearing the end of its economic life and the estimated reserves are only expected to last for another ten years at current production rates.

This situation is already having an effect in Broken Hill and the population of the city in 1996 (20 963) was lower than at any other time this century. New ore deposits need to be found to sustain the region.

It was against this background that the Broken Hill Exploration Initiative (BHEI) was started in 1994. The BHEI is a National Geoscience Mapping Accord (NGMA) project involving the Australian Geological Survey Organisation (AGSO), Primary Industries and Resources SA (PIRSA) and the Department of Mineral Resources (DMR) NSW.

The objective of the project is to encourage mineral exploration and facilitate new ore discoveries in the Broken Hill region by providing new geoscientific information for use by mineral exploration companies.

The project area includes the Broken Hill and Olary regions, the Mount Painter and Mount Babbage Inliers, and the Koonenberry Belt.

Over the last four years new data sets have been collected, new maps and images produced and new interpretations developed. As a result of this work our knowledge of the Broken Hill region has significantly improved and exploration activity has increased by an order of magnitude.

OUTCOMES THUS FAR

Exploration expenditure has increased significantly in the Curnamona Province following the start of the BHEI; annual expenditures for each State are listed below:

Annual private sector expenditure on mineral exploration in BHEI region

South Australia		New South Wales	
1992	$2.70M		
1993	$2.64M		
1994	$2.76M	1994/95	$7.20M
1995	$5.19M	1995/96	$7.20M
1996	$4.98M	1996/97	$8.10M
1997	$10.70M	1997/98	$9.00M

The full impact of this investment has yet to be realised but the area taken up by exploration licences has increased by more than a factor of ten since 1994 and several significant discoveries have already been made. These include:
Benagerie (Pasminco/Werrie Gold), where a series of significant drill intersections of gold, copper and other base metals have been discovered within the Benagerie Ridge magnetic complex (including the Portia, North Portia, South Nerrissa, Shylock and Lorenso prospects) and White Dam (MIM), where encouraging gold-copper intersections have been encountered. In NSW, prospects have been identified by PlatSearch at Mundi Mundi, Mundi South, Thunderdome, and Wahratta, although these have yet to be properly tested.

We are optimistic that the improved framework for mineral exploration generated by the BHEI, and the increased level of exploration activity in the region, will lead to the identification of further prospects and the eventual development of significant new mines.

ACTIVITIES AND OUTPUTS

Investment by Geological Surveys

Since the BHEI started in 1994, AGSO and the NSW and SA Geological Surveys have invested approximately $13 million on the project.

The table below summarises the contributions of each organisation since 1994.

Financial year	AGSO	DMR	PIRSA
1994/95	$1.015M	$1.130M	$1.168M
1995/96	$2.307M	$1.290M	$1.081M
1996/97	$1.036M	$0.450M	$0.526M
1997/98	$0.580M	$0.390M	$0.430M
1998/99 (estimate)	$0.492M	$0.670M	$0.309M
Total	$5.430M	$3.930M	$3.514M

The totals include estimates of direct salary costs but not overheads. The AGSO contribution includes its in-kind contribution to the Australian Geodynamics CRC but not the funds contributed by the Australian Geodynamics CRC to undertake its research activities.

Data Acquisition

A key component of the BHEI has been the acquisition of new geophysical data sets. The main outputs are listed below:

Airborne geophysical surveys flown for BHEI

Operator	Survey area	line-km
AGSO	Broken Hill, Taltingan 1:100k Sheet areas, 100/400 m line spacing	56 310
AGSO	Curnamona 1:250k Sheet area, 100/400 m line spacing	62 542
AGSO	Thackeringa, Redan 1:100k Sheet areas, 100/200m line spacing	55 233
AGSO	Frome 1:250k, 400 m line spacing	68 300
AGSO	Fowler's Gap, Corona 1:100k Sheet areas, 100/200 m line spacing	47 943

PIRSA	Olary and Curnamona (part) 1:250k Sheet areas, 100 m line spacing (BHEI-1)	60 002
PIRSA	Parts of Curnamona, Olary and Chowilla 1:250k Sheet areas, 400 m line spacing (SAEI Areas B1 & B2 acquired before BHEI)	25 998
PIRSA	Lake Charles 1:100k Sheet area, 200 m spacing (BHEI-4)	10 585
DMR	Cobham Lake & Broken Hill 1:250k Sheet areas, 400 m line spacing, (Discovery 2000 Area A3)	21 000
DMR	Cobham Lake/Wilcannia 1:250k Sheet areas, 250 m spacing (Discovery 2000 Area A4 Koonenberry)	67 000
Total		474 913

New Gravity Observations

Operator	Survey area	Number of stations
DMR	Koonenberry, (4×4 km grid)and Broken Hill Block, (0.5×0.5, 1×1, & 2×2 km grids)	2 625
PIRSA	Olary/Curnamona 1:250k Sheet areas, 1×2 km grid (completed in 1995)	3 400
PIRSA	Curnamona 1:250k Sheet area, 1×1 km grid (completed in 1996)	5 000
Total		11 025

These geophysical data sets have been used extensively to interpret the geology of the region, and rock property studies have also been carried out to understand the magnetic properties of the rocks causing the magnetic anomalies.

In addition to the geophysical data sets a large number of other key outputs have been produced. The main ones are listed below:

GIS data sets

A compilation of geology, geochemistry, culture and drill sites for the Curnamona Province has been released jointly by AGSO, PIRSA and NSWDMR on CD. PIRSA have also released a CD of the Olary data sets; GIS coverage for Broken Hill has also been made available on CD (Maidment et al., 1997) and incorporates the Corona, Fowlers Gap, Broken Hill, Taltingan, Redan and Thackeringa 1:100 000 Sheet areas and the CD contains more than 3500 mineral occurrences, 1400 drill holes, 2050 geochemical analyses and a petrology database of more than 8200 samples.

Deep Seismic surveys

Approximately 300 km of deep seismic reflection surveys in the Broken Hill region have produced some of the most spectacular results of the BHEI.
This includes a major contribution from the AGCRC.

The structures revealed by the seismic surveys show a regional dip to the southeast in the upper- and mid-crustal levels of the Broken Hill Block. The results indicate a much greater degree of shallow dipping faulting and lateral movement within the crust than had previously been envisaged (Gibson *et. al.*, 1998). The results also indicate a much thicker crust beneath the Broken Hill Block (43km) than beneath the surrounding regions (35 km)(Leven *et.al.*,1998).

Age dates

One of the most important new data sets produced under the BHEI umbrella are the ages derived from SHRIMP U/Pb and Ar-Ar studies. These results are important in the context of developing tectonic and mineralisation models in the region and some of the key results will be presented during this meeting.

Geological maps

Revised geological maps are key outputs from the project, and these are being produced when all the geophysical data and the age dates are available.

So far solid geology maps have been released for the Broken Hill, Mount Gipps and Stephens Creek 1:25 000 Sheet areas and standard geological maps have been produced for the Gairdners Tank and Corona 1:25 000 Sheet areas.

Geological mapping is in progress on the Mingary, Curnamona and Mulyungarie 1:100 000 Sheet areas and digital information is already available for parts of these areas.

In New South Wales, the geological and metallogenic mapping in the Broken Hill and Euriowie Blocks has been completed, with one sheet remaining to be published.

Stream sediment database

Digital stream sediment geochemistry is an important exploration tool. DMR has compiled approximately 4500 samples for the Broken Hill region and a similar number for the Koonenberry Belt (Lewis, 1998). These are available through Terra Search Pty Ltd. PIRSA has captured data for ~12 000 stream sediment and ~3000 rock samples from the Olary and Curnamona Sheet areas, but these data are yet to be loaded onto the corporate data bases.

REFERENCES

Gibson, G. M., Formin, T., Drummond, B.J., Maidment, D. & Wake-Dyster, K. 1998. Structure and tectonic Evolution of the Broken Hill Inlier Revisited in the Light of New Structural Mapping and Seismic Reflection Data. *Geological Society of Australia, Abstracts 49,* 165.

Leven, J.H., Finlayson, D.M., Owen, A., & Johnstone, D.W. 1998. A seismic Model of the Crust through the Broken Hill Block and Tasman Line. *Geological Society of Australia, Abstracts 49,* 269.

Lewis, P. 1998. Stream Sediment Database nears Completion. *Minfo, New South Wales Mining and Exploration Quarterly, 60,* 24.

Maidment, D., Peljo, M., Capnerhurst, K., Nichols, G., & Jenkins, G. 1997. Broken Hill, Geoscientific Geographic Information System. *Users Guide available from AGSO, PIRSA or DMR.*

THE PALAEOPROTEROZOIC THACKARINGA GROUP: DEPOSITION, DEFORMATION AND STRATIGRAPHY.

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Through mapping of structural fabrics and SHRIMP U-Pb geochronology in the region surrounding the type localities for the Thackaringa Group, the basal portion of the Willyama Supergroup, we offer two tectonostratigraphic interpretations, differing from that published, that satisfy the constraints of observed field and structural relationships. In the first interpretation, the Thackaringa Group consists solely of a quartz-albite lithology with minor pelite (retaining the name Himalaya Formation) and all other units previously ascribed to the Thackaringa Group are either metagranitoids or structural repetitions of stratigraphic units from higher in the sequence. In the second interpretation the Thackaringa Group consists of two units (retaining the names Cues and Himalaya Formations) while other units are similarly metagranitoids or structural repetitions.

The depositional environment of the Thackaringa Group is likely to be a lacustrine evaporite-rich basin with intercalated volcanogenic sediments deposited ~1710 Ma. The sediments were then diagenetically albitised in a process analogous to that observed today in the Eocene volcanosedimentary and evaporitic sequence of the Green River Formation in Wyoming. The sequence was then deeply buried and partially melted and deformed prior to being intruded at 1690 Ma by granite masses and gabbroic dykes and/or sills. Either the Thackaringa Group was then uplifted and eroded prior to deposition of the Broken Hill Group, or the Thackaringa and Broken Hill Groups were deposited at the same time and underwent the same deformation, anatexis and intrusion.

One of the key outcomes of this study is to highlight that any stratigraphic interpretation in a terrane as structurally complex as Broken Hill must take full account of the superimposing geometries resulting from the multiple Proterozoic high-strain deformation events. This has important ramifications for industry as one of the fundamental underpinning assumptions in any model for ore forming processes in Broken Hill, and any exploration strategies such models may develop, is the stratigraphic interpretation of the Palaeoproterozoic Willyama Supergroup.

WILLYAMA SUPERGROUP DEPOSITION AGE

The age of deposition of the Thackaringa Group is well constrained from SHRIMP U-Pb dating of detrital zircons from the distinctive albite-metasomatised metasediments and igneous zircons from metagranites and metagabbros that intrude them.

Detrital populations within the albitised metasediments are complex, with a large Archaean and Palaeoproterozoic component that terminate at a distinct population ~1710-1700 Ma. This correlates very well with similar lithologies from the nearby Olary region of South Australia (M. Fanning and R. Page pers. comm. 1998). Igneous populations from metagranite and metagabbro intrusives are 1693 ± 10 and 1690 ± 11 Ma respectively. These dates correlate well with others of granite and mafic intrusive throughout the Broken Hill Block (Nutman and Ehlers 1998).

STRUCTURAL EVOLUTION OF THE THACKARINGA REGION

The structural evolution of the Thackaringa region contains a long history of multiple high-strain deformations (D1-D5) producing extreme structural and metamorphic modifications of the protoliths. The identification of five regional scale deformational events, all of which were associated with widespread shearing and mylonite development, necessitates an alternative explanation for the present distribution of lithologies within the Thackaringa region. Particularly important in this reinterpretation are the D2 and D3 mylonite zones which, together with colinear folding during the D2, D3 and D4 events, have brought about large-scale transposition, gross attenuation and reorientation of lithological layering. Previously neither the mylonites nor the regional isoclinal D3 folds had been recognised. Moreover, folds previously mapped as F2 either;

(a) locally do not exist, but are the intersection of D2 and D3 mylonite zones;
(b) are F3 folds of D2 mylonite zones; or
(c) are F4 folds superimposed on F2 and F3 structures.

The regional effects of D1 are not well understood due to the texturally destructive nature of subsequent deformations and the paucity of outcrops exhibiting D1 structures. F1 folds are ductile structures, with small scale transposition of highly attenuated fold limbs and thickening of the lithological layering in the fold hinges. D1 occurred at high-metamorphic grade and was accompanied by anatexis with partial melt veins forming a gneissosity axial planar to isoclinal F1 folds and parallel to bedding on transposed F1 fold limbs. SHRIMP dating of mafic and felsic intrusives that crosscut the D1 fabric place D1 prior to 1690 Ma. This predates previous estimates for this event by ca 50-80 My and places this part of the Willyama Supergroup deep within the crust at the time of the previously widely accepted volcanosedimentary deposition age of 1690 Ma (Page and Laing 1992). Either the Thackaringa Group was uplifted and eroded prior to deposition of the Broken Hill Group, or the Thackaringa and Broken Hill Groups were deposited at the same time at 1710 Ma and underwent the same deformation, anatexis and intrusion at 1690 Ma.

Structural fabric development during D2 ranges from submylonitic to ultramylonite and accompanied intense isoclinal folding and the peak regional high-grade metamorphism which produced a sillimanite-garnet assemblage. Metamorphic zircon growth within quartzofeldspathic and mafic gneisses in the area at ~1590 Ma is interpreted to date the D2 event. A prominent stretching lineation and sillimanite mineral lineation (L2) plunges either steeply NE or near vertically NW due to refolding by F4. Rare F2 folds preserve an angle between L2 and F2 hinges of around 40-50 degrees in the F2 axial plane. However, F2 folds have usually been highly attenuated with transposition of the limbs and F2 hinges have rotated into the L2 lineation. Large kilometre-scale masses of quartz-albite gneiss behaved as competent masses during D2, partitioning strain preferentially into the surrounding pelites where S2 mylonite fabrics developed. Thus the quartz-albites gneisses best preserve D1 structures that have been destroyed in other metasediments.

The D3 deformation resulted in reclined isoclinal folding of the S2 mylonite fabric at all scales. F3 fold axes are colinear with the L2 lineation and rotated F2 fold axes. The S3 fabric is developed most strongly within the F3 fold limbs, attenuating them and forming small mylonite zones, with boudinage within the S3 fabric occurring at all scales; from pull-apart structures in microlithons to attenuating regional granitoids. The prominent stretching direction of L3 is orthogonal to L2. The S3 axial planar fabric post dates peak metamorphism, with retrogression of K-spar and sillimanite to white-mica and of garnet to biotite. S3 in mafics contains abundant amphibole. Retrogression flooded the country rock and is most intense within previous D2 mylonite zones. SHRIMP zircon dating of Mundi-Mundi style granite dykes that are late-syn to post the S3 fabric give an age of ~1560 Ma, placing D3 at most within 30 My of the D2 event.

S2 and S3 are overprinted by upright mesoscopic asymmetric F4 folds with variably developed crenulation cleavage as the S4 axial planar fabric. F4 largely forms broad, kilometre scale, monoclinal warps of the S2/S3 fabric. However, tight D4 folds with smaller 10-20m wavelengths also occur locally. This is particularly the case within zones of strain partitioning on the contact between metasediments and large quartzofeldspathic masses. F4 folds plunge moderately and trend between east and northeast, and may be associated with north-verging reverse movement on the east-west striking Thackaringa-Pinnacles Shear Zone (TPSZ). Both the F4 folds and the TPSZ are cross cut by a conjugate set of steeply dipping east-west and north-south striking shears (D5).

Together, these deformation events have transposed, attenuated and rotated lithologies which may originally have been transgressive relative to each other into parallelism and apparent conformity. Much of the original boundary relationships between lithologies are ambiguous due to the intensity of the deformation events and there are no reliable sedimentary younging criteria within the entire 1:25000 map sheet. Despite this, the region contains nearly all the type localities for the Thackaringa Group (Willis *et al.* 1983). The only units of the Thackaringa Group not to have type localities in the region are the Rasp Ridge and Alma Gneisses. However, the recent reinterpretation of these lithologies as metagranites (eg Vernon and Williams 1988, Nutman and Ehlers 1998, Donaghy *et al.* 1998) effectively removes them from the deposition sequence and they should not be relied upon as detailed stratigraphic markers. Hence, the stratigraphic validity of the remainder of the Thackaringa Group must be critically reassessed, and once detailed structural mapping is used to complement the existing, highly-detailed 1:25000 lithological mapping (eg Willis 1985) it becomes readily apparent that many units are structurally, rather than stratigraphically, repeated within the sequence.

ALTERNATE STRATIGRAPHIC INTERPRETATIONS

There is no direct evidence for splitting the quartz-albite lithologies into two distinct stratigraphic horizons. Mapping of the quartz-albite lithologies, as well as S2 and S3 fabrics, reveals that they form a single horizon repeated by regional D2 mylonites, F3 isoclines and local F4 folds. The validity of using other post-depositional features to differentiate between Willyama Supergroup units, such as degree of partial melting and minor Na-Fe metasomatism, is also questioned. Two alternate stratigraphic sections are postulated that satisfy the constraints of observed field and structural relationships:

(1) The Thackaringa Group consists solely of a quartz-albite lithology with minor pelite (retaining the name Himalaya Formation) and all other units previously ascribed to the Thackaringa Group are either metagranitoids or structural repetitions of stratigraphic units from higher in the sequence; or

(2) The Thackaringa Group consists of two units (retaining the names Cues and Himalaya Formations), while other units are similarly metagranitoids or structural repetitions, and is at most half its previous interpreted thickness.

Two alternate models are proposed because;

(a) The effects of the first regional deformation (D1) are not understood due to the texturally destructive nature of subsequent deformations and the paucity of outcrops exhibiting D1 structures; and

(b) The regional vergeance of D2 and degree of repetition by shearing is difficult to trace through subsequent deformations.

The former model requires that all quartz-albite outcrops contain anticlinal closures, otherwise basement would be exposed. However, this scenario cannot be discounted because;

(a) The nature of basement in the Broken Hill region is unknown;

(b) Recognising basement in a severely migmatised and mylonitised granulite-facies terrane would be extremely difficult;

(c) The regional effects of D1 are speculative; and

(d) The quartz-albite lithologies contain abundant F1 and F2 closures.

The latter model requires the least modification to the existing interpretation. However, the exact nature of the Cues Formation is controversial and currently under examination. It is largely defined by the presence of Na-Fe metasomatism, mafic-, quartzofeldspathic- and leuco-gneisses, and chemical lithologies (calc-silicates, quartz-gahnites, quartz-magnetites, etc.) of an ambiguous nature. Also, due to mis-interpretation of the quartz-albites as two separate units, not all lithologies currently mapped as Cues Formation belong to this unit, but should be attributed to the Parnell Formation within the Broken Hill Group.

REFERENCES

Donaghy, T., Hall, M., Gibson, G. And Nutman, A., 1998. The age of deposition and first deformation of the Palaeoproterozoic Willyama Supergroup, Broken Hill, Australia. Geological Society of Australia, Abstracts

Nutman, A. P. and Ehlers, K., 1998. Evidence for multiple Palaeoproterozoic thermal events and magmatism adjacent to the Broken Hill Pb-Zn-Ag orebody, Australia. *Precambrian Research*, 90, 203-238.

Page, R. W. & Laing, W. P., 1992. Felsic metavolcanic rocks related to the Broken Hill Pb-Zn-Ag orebody, Australia: geology, depositional age, and timing of high-grade metamorphism. *Economic Geology*, 87, 2138-2168.

Vernon, R. H. and Williams, P. F., 1988, Distinction between intrusive and extrusive or sedimentary parentage of felsic gneisses. Examples from the Broken Hill Block, New South Wales. *Australian Journal of Earth Sciences*, 35, 379-388.

Willis, I. L., 1985, Thackaringa 1:25 000 Geological Sheet, 7133-IV-N. *Geological Survey of New South Wales, Sydney, Australia.*

Willis, I. L., Brown, R. E., Stroud, W. J. & Stevens, B. P. J., 1983, The early Proterozoic Willyama Supergroup: stratigraphic subdivision and interpretation of high to low-grade metamorphic rocks in the Broken Hill block, New South Wales. *Journal of the Geological Society of Australia*, 30, 195-224.

Acknowledgments

We thank Rio Tinto Exploration Pty Ltd for financial support for this project and permission to publish.

CONSTRAINTS ON STRUCTURE AND COMPOSITION OF THE BROKEN HILL REGION FROM SEISMIC REFLECTION AND REFRACTION STUDIES

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INTRODUCTION

Gibson & others (1998) showed that the crust of the Broken Hill Block can be divided into a number of zones on the basis of structures seen in deep seismic reflection data. Owen & others (1997) extended the study to the southeast, across the Tasman Line, thought to be the boundary between the older shield regions to the west and the Phanerozoic fold belts to the east. The seismic reflection method is useful for studying structures at depth, but provides little information on rock types. Leven & others (1998a) analysed seismic refraction data recorded across the region and derived a crustal model of seismic wavespeed (velocity). Seismic wavespeed can be empirically linked to rock type. In this paper, we review these seismic data to derive constraints on the structure and composition of the crust of the Broken Hill region.

SUMMARY OF THE SEISMIC RESULTS

Figure 1 shows the locations of the seismic lines on a simplified geological map. The structure of the Broken Hill Block interpreted from the reflection data is shown in summary form in Figure 2. The southeast dipping reflection events are prevalent beneath the Willyama Zone; some of these penetrate to middle to lower crustal depths. By comparison in the Olary zone the reflection events are less coherent. The most prominent SE dipping event corresponds to the Mundi Mundi Fault, and separates the Olary Zone to the NW from the Willyama Zone. In the Broken Hill area, reflectors interpreted as faults and shear zones (because of their spatial association with mapped faults and shear zones) are seen to be steeply east dipping at the surface and to sole into sub-horizontal detachments in the middle crust (Gibson & others, 1998). Farther to the southeast, in the Redan zone, the crust is less reflective. Most reflectors have a southeast dip, although in the near surface, northwest dipping reflectors are interpreted as southeast directed thrusts. These thrusts may be Delamerian in age or older but have experienced recent reactivation which disrupts the base of the Murray Basin (Owen & others, 1997).

Figure 3 shows the seismic wavespeed model interpreted from wide-angle seismic data (Leven & others, 1998a). The crust is two layered, and thickest under the outcropping parts of the Willyama zone. To the southeast, the topmost upper crust has a zone of relatively low wavespeed beneath the Murray and Darling Basins.

IMPLICATIONS FOR THE COMPOSITION AND EVOLUTION OF THE CRUST

Figure 4 compares the crustal wavespeed beneath Broken Hill (Willyama zone) with that of the global average crust (Christensen & Mooney, 1995). The crustal wavespeeds for the Broken Hill region are higher than world average near the surface, reflecting the high

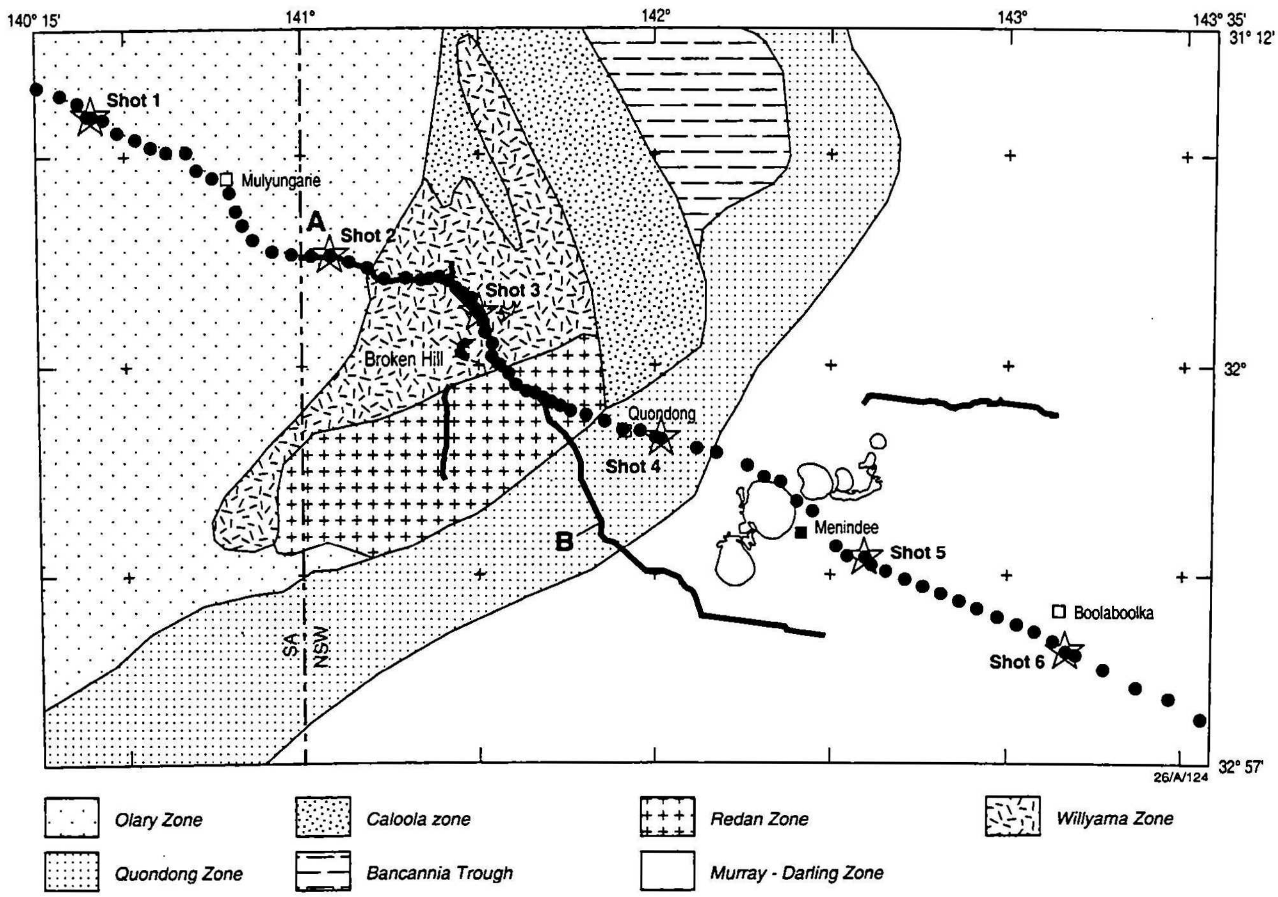

Figure 1. Map of the Broken Hill region simplified into a number of zones representing the major geological elements. The positions of the seismic reflection and refraction lines are superimposed. Black lines: seismic reflection lines; black dots: refraction recorder positions; stars: Refraction shot sites.

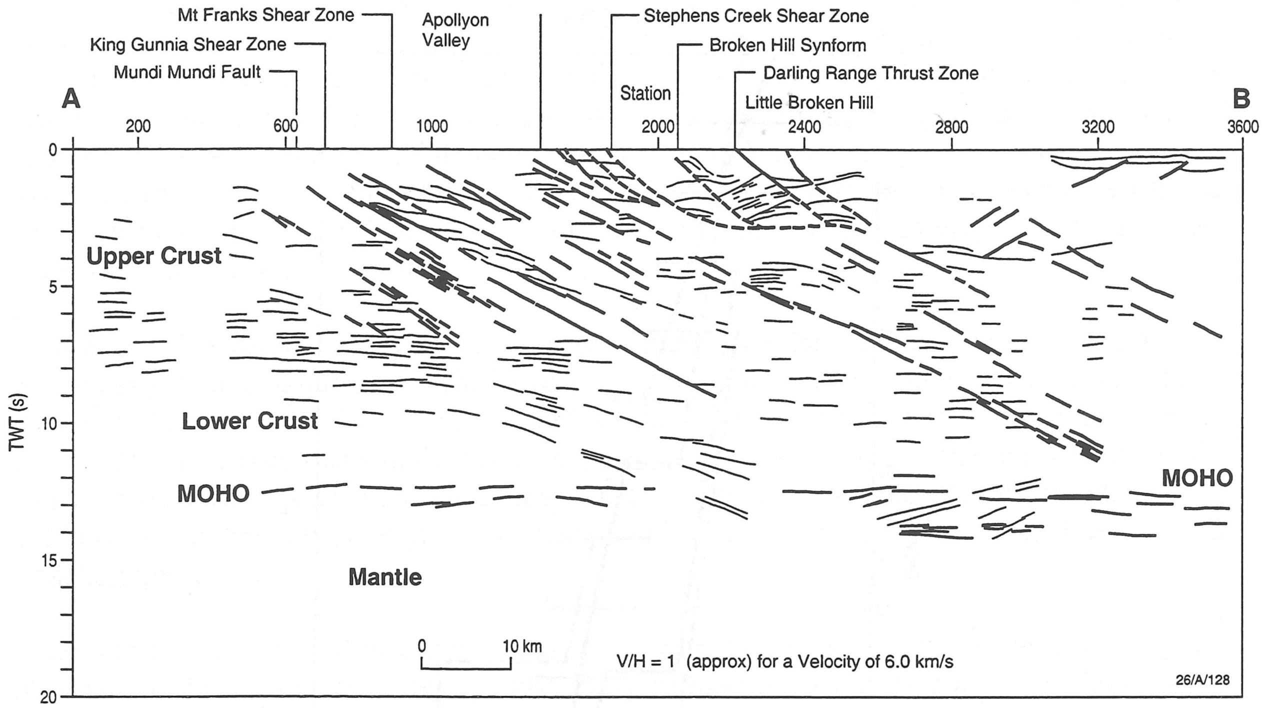

Figure 2. Line diagram summary of seismic reflection results. Thin lines: undifferentiated reflectors; dipping thick lines: faults and shear zones; sub-horizontal thick lines near 12-13s TWT: Moho.

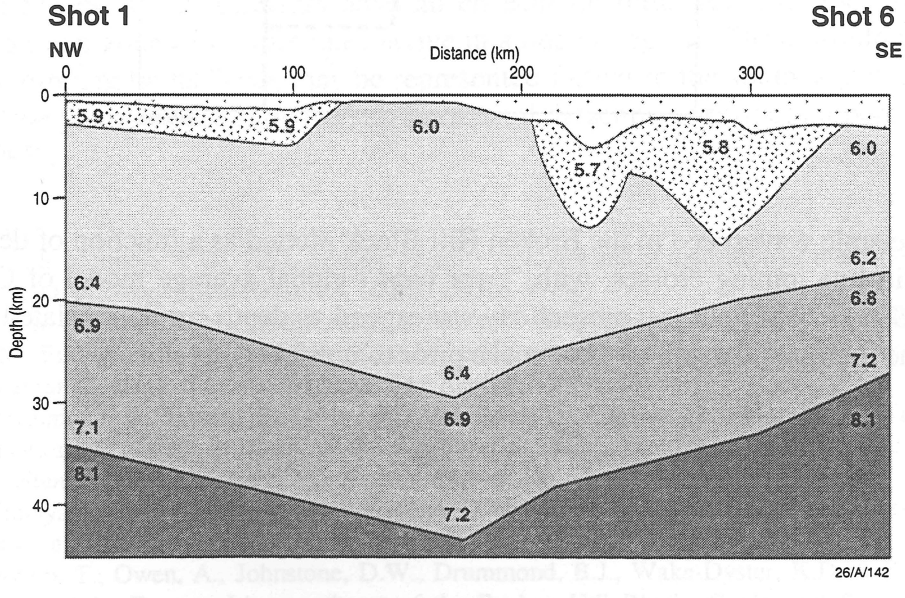

Figure 3. Seismic wavespeed model. Wave speeds are shown in km s^{-1}. Note the considerable vertical exaggeration.

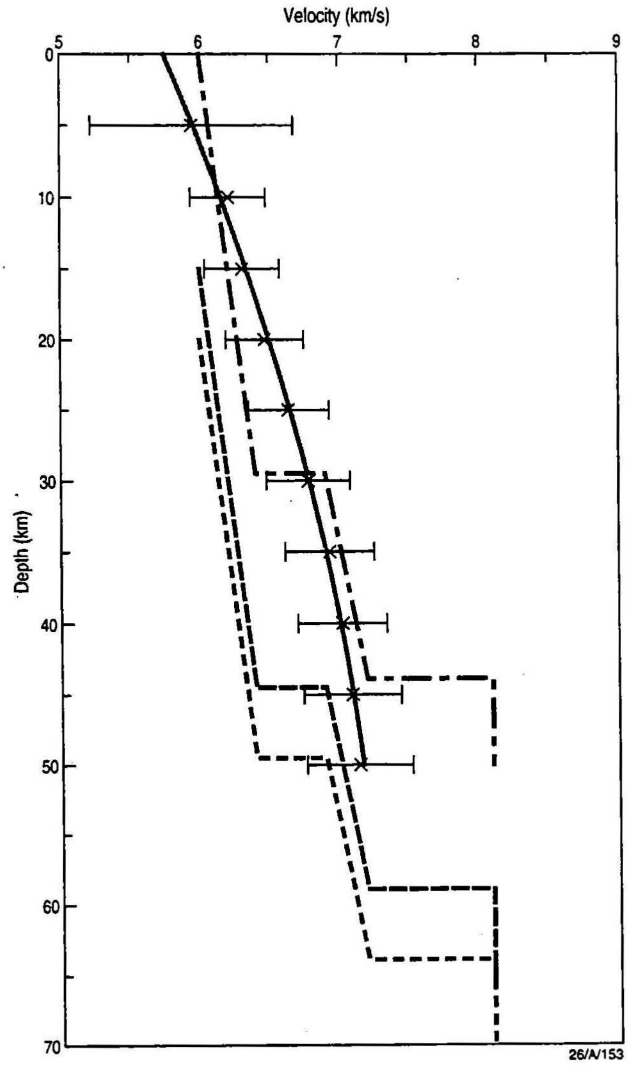

Figure 4. Seismic wavespeed in the Broken Hill Block plotted as a function of depth (dot-dash curve). Solid line joining crosses, with "error bars": global average model of Christensen & Mooney (1995); dashed curves: present day wavespeed vs depth curve translated down 15 and 20 km to the interpreted depth of these rocks prior to uplift and erosion.

metamorphic grade in the region of 0.5 - 0.6 GPa (5 - 6 kbars) (Phillips & Wall, 1981). Wavespeeds are below world average in the middle crust, and slightly higher in the lower crust. Fission track data and metamorphic grade suggest that about 15 km of material has been eroded from the Broken Hill Block. Figure 4 also shows the wavespeed curve positioned 15 and 20 km deeper in the crust, simulating where it would have been prior to uplift and erosion (dashed curves). Prior to this erosion, the 55 - 60 km thick crust would have had wavespeeds and densities consistently below world average. The resulting buoyancy would have been responsible for the region's uplift.

Drummond & Collins (1998) argued that the crust in the Broken Hill region is unlikely to contain significant amounts of mafic lower crust, which would be evidenced by wavespeeds in excess of 7.3 km s^{-1}. Such rocks would source I-type (granodioritic) intrusions, and the paucity of such I-type rocks in the region corroborates the absence of a mafic lower crust. The lack of higher wavespeeds in the wide-angle interpretation also implies that the middle crust is unlikely to contain remnant magma chambers for iron rich tholeiite rocks found in the Thackeringa region.

Drummond & Collins (1998) argued that crust with the thickness and seismic wavespeeds observed in the Broken Hill area is most likely to have achieved its maximum thickness by tectonic stacking of thin crust. The southeast dipping structures seen on the seismic section are unlikely to represent major thrusts of this stacking process, because of the inefficiency of stacking crust on such steeply dipping faults. Lower angle thrust surfaces are suggested (Leven & others, 1998b). Between these southeast dipping events, the section generally has a seismic reflection signature traditionally attributed to the "normal" layering in the crust. However, in places, some reflectors have an en echelon reflection character that might be interpreted as shear zones that were once active in a ductile regime. These would be older than the southeast dipping faults. They may be represented farther to the southeast (where the crust is not cut by the younger faults) by the sub-horizontal detachment surfaces reported by Gibson & others (1998).

REFERENCES

Christensen, N.I. & Mooney, W.D., 1995. Seismic velocity structure and composition of the continental crust: A global view. *Journal of Geophysical Research*, 100(B7), 9761-9788.

Drummond, B.J. & Collins, C.D.N., 1998. Crustal architecture and processes in southeast Australia from seismic studies. In D.M. Finlayson & L.E.A. Jones (Eds) Minerals systems and the crust-upper mantle of southeast Australia. *Australian Geological Survey Organisation, Record*, 1998/2, 59-64.

Gibson, G., Drummond, B., Fomin, T., Owen, A., Maidment, D., Gibson, D., Peljo, M. & Wake-Dyster, K., 1998. Re-evaluation of crustal structure of the Broken Hill Inlier through structural mapping and seismic profiling. *Australian Geological Survey Organisation Record*, 1998/11.

Leven, J.H., Finlayson, D.M., Owen, A., & Johnstone, D.W., 1998. A seismic model of the crust through the Broken Hill Block and Tasman Line. *Geological Society of Australia, Abstracts*, 49, 269.

Leven, J.H., Fomin, T., Owen, A., Johnstone, D.W., Drummond, B.J., Wake-Dyster, K.D. & Finlayson, D.M., 1998. The nature of the Tasman Line southeast of the Broken Hill Block. *Geological Society of Australia, Abstracts*, 49, 270.

Owen, A.J. , Drummond, B.J., Fomin, T. & Wake-Dyster, K.D., 1997. A geophysical transect of the Tasman Line. Geological Society of Australia SG2 and SGTSG Specialist Group Conference, Marysville, *Geophysics Down Under*, 24, 60.

Phillips, G Neil & Wall, V.J., 1981. Evaluation of prograde regional metamorphic conditions: their implications for the heat source and water activity during metamorphism in the Willyama Complex, Broken Hill, Australia. *Bulletin Mineralogie*, 104, 801-810.

Acknowledgments
This research was funded by the Australian Geological Survey Organisation (AGSO), the Australian Geodynamics Cooperative Research Centre (AGCRC) and the New South Wales Department of Mineral Resources. The authors publish with the permission of the Executive Director of AGSO and the Director of the AGCRC.

DISCOVERY OF CANNINGTON AND ITS RELEVANCE TO EXPLORATION IN THE WILLYAMA SUPERGROUP

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EARLY CONCEPTS

The Cannington Ag-Pb-Zn deposit represents the most significant example of Broken Hill-type (BHT) mineralisation discovered since the fabulous Broken Hill find itself in 1883.

The deposit consists of a resource of 43.8 million tonnes grading 11.6% Pb, 4.4% Zn and 538g/t Ag concealed beneath 10-60m of Recent and Cretaceous cover.

The Broken Hill and Cannington deposits are hosted by migmatitic quartzo-feldspathic gneisses and, in both cases, mineralisation has undergone a long and complex prograde and retrograde metamorphic, metasomatic and structural history (Walters and Bailey, 1998).

Mineralisation at Broken Hill and Cannington is associated with a diverse and unusual package of Fe-Ca-Mn-Si rich 'skarn-like' mineralogies, which includes bustamite, pyroxmangite, carbonate, knebelite, fluorite and hedenbergite. A wide variety of prograde and retrograde Fe-Mn garnet rich rocks are intimately related to mineralisation, and also occur as part of an incipient but large scale garnet-sillimanite-K-feldspar bearing alteration halo in the host migmatitic gneisses. At Broken Hill, laterally extensive 'alterite markers' define prospective regional horizons and include lensoid quartz-gahnite units and sub-ordinate quartz-magnetite BIFs. The Cannington deposit is associated with significant magnetite-rich ore zones.

A key component in developing an empirical 'BHT' exploration model was the provision of detailed regional mapping of the Broken Hill Block by the New South Wales Geological Survey in the early 1980s. This provided a coherent lithostratigraphic framework for understanding the distribution of mineralisation and defining regional geophysical signatures, and was the impetus for a number of BHP research projects.

An empirical exploration model was developed on the basis of these studies, and applied systematically to all prospective Proterozoic terranes in Australia. A key component of this strategy given the complex and unusual lithologies associated with mineralisation, was a re-examination of all known prospects and mineral occurrences in these terranes. Resistate phases related to these unusual mineralogies were also a useful regional evaluation tool. This reconnaissance phase quickly identified the Soldiers Cap Group in the eastern Mount Isa Inlier, as the most prospective sequence for BHT mineralisation outside the Willyama Supergroup in New South Wales, which hosts the Broken Hill deposit.

STEPPING OUT UNDER COVER

Initial interest by BHP in 1984 was focused on an outcropping belt of Soldiers Cap rocks, which contained many small occurrences of Pb-Zn mineralisation of BHT affinity (Skrzeczynski 1998). Unfortunately at the time the area was held under tenement by competitors. Evaluation of the available 1:250,000 government regional magnetic data had revealed the possible continuation of Soldiers Cap equivalents to the north-east under Mesozoic cover and, as a consequence, a tenement application was lodged to cover this previously unexplored magnetic package with a view to exploring its Pb-Zn-Ag potential. This land position formed the basis of a new thrust into the first under-cover exploration undertaken in this belt.

Detailed aeromagnetics was flown and drill testing of the most intense magnetic feature commenced in 1985 under 10-30 m of cover. This drilling intersected a typical sequence of BHT rocks at the Altia prospect with sub-economic Pb-Ag mineralisation (8 m at 3% Pb and 33 g/t Ag) hosted by BIF, garnet quartzite, carbonate and complex calc-silicate lithologies. This result gave encouragement to commence systematic exploration along the entire magnetic package.

In 1988, drilling of a combined magnetic-EM target resulted in the discovery of the Eloise deposit under 60 m of conductive overburden. Delineation drilling carried out during 1989 and 1990 outlined a geological resource of 3.2 million tonnes grading 5.8% Cu, 1.5 g/t Ag (Brescianini et al, 1992). The deposit consists of both stockwork and massive pyrrhotite-chalcopyrite mineralisation hosted in mafic-altered (biotite-hornblende +/- magnetite and carbonate) meta-sediments (Baker, 1996).

Although the Eloise Deposit is a shear zone replacement style and not the target BHT mineralisation sought, its discovery was very important in leading ultimately to the discovery of Cannington by providing the technical confidence to expand the exploration program to areas of non-outcropping Soldiers Cap terrane to the south and east of Eloise.

DISCOVERY PROGRAM

Interpretation of AGSO aeromagnetic surveys indicated the presence of Proterozoic rocks below shallow cover sequences on the eastern flank of the Mt Isa Block. However, data quality was very poor for interpretation purposes. Initial discoveries of the Altia and other sub-economic BHT systems and the Eloise Cu-Au deposit, indicated a strong association with significant magnetite-rich zones in the Soldiers Cap terrane. High quality regional magnetics was therefore chosen as the key exploration technique in guiding systematic exploration in areas of Cretaceous cover. Detailed aeromagnetic surveys were commissioned by BHPM in 1989 covering an area of approximately 5000 km^2 within this non-outcropping area. This was an aggressive move for the time and the decision was made to also apply for all ground covered by the survey.

The high-resolution aeromagnetic dataset provided the first ever coherent and detailed geological picture of this unexplored, covered extension to the Mt Isa Block. The challenge was to extract the geological content from what were state-of-the-art geophysical images.

The geological framework obtained was used along with conceptual knowledge of the Broken

Hill Type model to recognise prospective host rocks, structures and finally geophysical signatures that could be directly or indirectly related to ore.

In June 1990, Cannington was discovered by the third hole of a regional drilling program that was designed to test priority magnetic targets. This hole intersected 20 m of mineralisation averaging 12.1% Pb, 0.6% Zn and 870 g/t Ag under 40 metres of cover in what is now the Footwall Lead Lode of the Southern Zone. The Cannington aeromagnetic feature is a discrete 1000nT anomaly exhibiting most of the criteria and geological setting associated with the BHT model.

Some analogies can be made between the history of discovery of Cannington and exploration in the Curnamona Province. The relative maturity of exploration within the outcropping areas of both provinces has led to exploration under younger cover. New, high quality aeromagnetic data was required to aid interpretation and targeting and has also provided a detailed geological picture of extensions of both terranes under the covered areas.

The most significant discoveries were made by BHP very early in the programme using this new, quality data and while some of the earliest discoveries (ie. Eloise) may not have been the original target, it provided inspiration to continue to find the real prize (ie. Cannington).

The discovery of Cannington came at a time when a number of other significant deposits were being 'unveiled' in the Mount Isa Block (ie. Century, Osborne, Ernest Henry). This compares with the more recent discovery history within the Curnamona Province which has seen increasing exploration expenditure and activity, resulting in the discoveries of new prospects, particularly Kalkaroo and North Portia.

These new discoveries are providing inspiration to pursue the elusive 'big one!'

REFERENCES

Baker, T. 1996. Ore Fluid Chemistry and Conditions at the Eloise Cu-Au Deposit, North-West Queensland: *MIC'96, Extended Conference Abstracts*, Economic Geology research Unit Contribution 55, James Cook University, p. 10-13.

Brescianini, R.F., Asten, M.W. and McLean, N. 1992. Geophysical Characteristics of the Eloise Cu-Au Deposit, North-West Queensland: *Exploration Geophysics, v. 23*, p. 33-42.

Skrzeczynski, R. 1998. The Discovery of the Cannington Ag-Pb-Zn Deposit, Mount Isa Inlier NW Queensland, Australia. *Extended Abstracts, Pathways '98.*

Walters, S.G. and Bailey, A. 1998. Geology and Mineralisation of the Cannington Ag-Pb-Zn Deposit – an Example of Broken Hill Type Mineralisation in the Eastern Succession of the Mount Isa Inlier, NW Queensland Australia. *Economic Geology* (in press).

A GEOCHRONOLOGICAL PERSPECTIVE OF CRUSTAL EVOLUTION IN THE CURNAMONA PROVINCE

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OVERVIEW

The Curnamona Province is considered to include the Willyama Inliers (Olary and Broken Hill Blocks), the Mount Painter and Mount Babbage Inliers, the Benagerie Ridge and the Curnamona Craton *sensu stricto* (see Flint & Parker, 1993). The Palaeo- to Mesoproterozoic geology of the Olary Block (OB) comprises a supracrustal sequence of metasedimentary and metavolcanic rocks that are correlated with the Willyama Supergroup of the Broken Hill Block (BHB). These metasediments and metavolcanic rocks are intruded by syn to post Olarian Orogeny, *regional* granites (Ashley *et al.*, 1995). There are clearly similarities and differences between the OB and BHB; two such differences are the greater abundance in the OB of *recognised* granite intrusives and a general absence of granulite facies metamorphic rocks. Within the BHB, the granulite facies event has been dated at c.1590-1600 Ma. At this time the OB was intruded by granitoids, many derived from partial melting of the sedimentary sequence, whilst others may have mafic I-type affinities.

During the Olarian Orogeny, c.1590-1600 Ma, it is clear that the BHB was situated at a deeper crustal level than the OB. Both the OB and the BHB show a general decrease in metamorphic grade to the north. This trend for lower metamorphic grade and higher exposed crustal levels during Olarian time is emphasised by the eruption of felsic volcanics at c.1580 Ma on the Benagerie Ridge. It therefore follows that there has been significant vertical tectonic (and/or large crustal scale horizontal) movements within the Curnamona Province that resulted in juxtaposition of deep crustal level granulites of the Broken Hill area, with amphibolite facies gneiss of the Olary area, and essentially flat lying felsic volcanics and sediments of the Benagerie Ridge.

The effects of the Delamarian Orogeny are an integral part of any discussion of the OB. Structural and metamorphic overprinting has occurred to a wide and variable extent and there are ongoing isotopic studies attempting to fully understand the Delamarian effects.

PALAEOPROTEROZOIC SEDIMENTS OF THE OLARY BLOCK

Albitites are a prominent lithology in the quartzo-feldspathic suite of the OB Willyama Supergroup. A sample from near Mount Howden contains zircons that are morphologically quite unique, having a mottled surface texture. This texture is not pitted from mechanical abrasion as one may expect in a clastic sediment, rather the surface appears to have undergone some low temperature solution effects, giving rise to protrusions that could be interpreted as authigenic zircon growth. In section, any new surficial zircon growths are sub-micron in size and so it is not possible to determine the age of this proposed authigenic zircon growth. The SHRIMP analyses record a dominant group of near to concordant ages at about 1775 Ma. One analysis is concordant at about 1630 Ma and Cook (see Cook *et al.*, 1994) has speculated that this may constrain the maximum age for sedimentation. All other zircons analysed are older than 1775 Ma, ranging to c.3100 Ma. For the present, this metasediment is considered to have been deposited no earlier than 1775 Ma ago, but perhaps as young as 1630 Ma on the basis of that single zircon analysis.

A fine grained, well banded albitite from Burdens Dam, Kalabity Station contains an heterogeneous population of zircons with a range in SHRIMP U-Pb ages. There is a grouping of concordant analyses at 1785 ± 16 Ma, with older analyses ranging to c.2700 Ma. The maximum age of sedimentation for this albitite is 1785 Ma.

VOLCANISM COEVAL WITH SEDIMENTATION

The recognition of felsic volcanic horizons within the sedimentary pile has been significant to the understanding of the Willyama Supergroup in the OB (Buckley, 1993; Cook *et al.*, 1994: Ashley *et al.*, 1996). A "quartz-eye" rock from Abminga Station contains zircons that are considered to have formed in a volcanic to subvolcanic environment. The zircon population is heterogeneous, nevertheless there is a dominant grouping of near to concordant analyses at 1699 ± 10 Ma. Some inherited grains have ages of about 1800 to 1860 Ma. This rock is considered to be volcanic in origin, have A-type chemical affinities and crystallised at about 1700 Ma. Ashley *et al.* (1996) point out the specific chemical details of the Abminga "quartz-eye" rock and highlight the relatively depleted mantle Nd isotopic signature for this rock. The recognition of magmatism essentially direct from a depleted mantle source has far reaching implications for possible ore genesis in the OB.

Within the Weekeroo Inlier (WI) of the OB, recent mapping by Colin Conor of MESA (now PIRSA) has located a little deformed felsic volcanic rock which has a SHRIMP U-Pb zircon age of 1706 ± 6 Ma. Other quartz-eye rocks from nearby, within the WI have SHRIMP ages of 1722 ± 14 Ma and 1706 ± 13 Ma. There can be little doubt that felsic volcanism occurred between 1700 and 1720 Ma. Further, it can be inferred that this was contemporaneous with sedimentation of the Willyama Supergroup equivalents in the OB and WI. The Nd isotopic signatures for these volcanics and granitoids indicate that depleted mantle material was added to the continental crust at this time.

EARLY GRANITOIDS

Closely related to the "quartz-eye" rock in chemistry and time, A-type granite intrusives have been documented from the Ameroo Hill-Perryhumuck mine area (Cook, 1993). A sample of one such granite near Ameroo Hill was collected from an SA Mines and Energy blast site of Flint & Webb (1980). The exclusively homogeneous zircon population separated from sample 6933 RS972 is atypical for the Willyama Inliers. The SHRIMP U-Pb analyses are all on or near concordia giving an age of 1703 ± 6 Ma (Cook *et al.*, 1994; Ashley *et al.*, 1996). This magmatic crystallisation age is indistinguishable from that of the Abminga "quartz-eye" rock and places the time of sedimentation at or prior to c.1700 Ma. Further, as noted by Ashley *et al.* (1996) this granitoid has a depleted mantle-like initial Nd isotopic ratio, similar to that for the A-type 1700 Ma volcanic rocks discussed above. Quartz-feldspathic rocks concordant with the sedimentary package crop out in a number of areas. These are now interpreted to be granitoid sheets and two such rocks have SHRIMP U-Pb zircon ages of 1701 ± 8 Ma and 1717 ± 14 Ma. These are within uncertainty of the magmatic crystallisation ages for felsic volcanic rocks within the sedimentary sequences both in the OB and BHB. There is clear evidence for considerable magmatic activity during sedimentation, just after deposition, and perhaps during burial of the supracrustal pile.

"REGIONAL" GRANITES - RELATED TO THE OLARIAN OROGENY

Syn to post tectonic granites intruded around the time of the Olarian Orogeny have been termed "regional" granites in some studies (Ashley *et al.*, 1995). Such granites appear massive and little foliated in the field, though careful mapping is required to place such bodies in the Mesoproterozoic structural sequence. It is probable that most of the strain during the Olarian Orogeny has been partitioned into the more ductile metasediments, the more massive granites remaining as competent bodies registering little strain.

Near the Antro Woolshed, a rock with tonalitic affinities is intruded into the Willyama equivalent package (Ashley and Lawie, 1996). It has a zircon age of 1641 ± 11 Ma with inherited components at 1684 ± 11 Ma and c.1750 Ma. Poodla Hill is formed by granodiorite that is predominantly massive in this outcrop, though elsewhere it is foliated and considered to predate the Olarian orogeny D_1 event. SHRIMP U-Pb analyses give a magmatic age of 1629 ± 29 Ma for structured zircon, with inheritance at about 1710 Ma. The Poodla and Antro intrusives can be grouped together with other similar granite intrusives as part of a mafic I-type suite, intruded post sedimentation, prior to, or early in the Olarian Orogeny.

In contrast, the Triangle Hill granite is clearly S-type in nature and contains abundant inherited zircon. Magmatic rims are approximately 1590 Ma in age, with centres to such grains recording c.1670 Ma ages. Other zircon components range in age to about 2600 Ma. This granite zircon record is reminiscent of many Palaeozoic S-type granites, with little new zircon formed during granite emplacement. Rather the zircons record much of the source material with only thin, high U rims recording the time of magmatism.

The undeformed granite at the "Rock Wallaby" location near Triangle Hill also contains a zircon population rich in inherited components. In this case magmatic rims record an age of 1616 ± 9 Ma with a group of centres at 1723 ± 23 Ma and others between 1700 Ma and 1800 Ma. The magmatic age of 1616 Ma is intermediate between the Poodla granodiorite at c. 1630 and the so called regional granites at c.1590 Ma. It is possible that there has been either a protracted, or a series of punctuated, magmatic episodes in the OB. These most probably reflect various deformational and thermal events related to the Olarian Orogeny.

The youngest Mesoproterozoic magmatic event related to the Olarian Orogeny has been dated at Crocker Well (Ludwig & Cooper, 1984). Whilst these are "conventional" multi-grain zircon analyses, with ages calculated from upper intercepts with concordia, preliminary SHRIMP analyses of the Crocker Well suite confirm the age of c.1580 Ma. The Mount Victoria granite is thought to be of a similar age on the basis of discordant U-Pb analyses though it has not been studied with SHRIMP and requires further work.

In summary, granitoid intrusives were emplaced into the Willyama Supergroup at c.1680, c.1640, c.1620, and c.1590 to c.1580 Ma. Some of these are S-type in origin however others are more primitive and represent mafic I-type intrusives.

BROKEN HILL BLOCK

A summary of pre-1992 geochronology of the Broken Hill Block (BHB) is given by Page & Laing (1992) with more recent results and a refined interpretation to be found in Nutman & Ehlers (1998). For the Page and Laing (1992) SHRIMP zircon study, there is a progression of ages interpreted for the same stratigraphic horizon of the Hores Gneiss. At low grade the interpreted magmatic age is 1689 ± 5 Ma; decreasing at higher grade to 1680 ± 14 Ma, and then 1668 ± 10 Ma. At highest grade, the *two pyroxene granulite zone* sample retains an interpreted relict magmatic age of 1680 ± 12 Ma, metamorphic rims at 1604 ± 12 Ma and the usual range of older inherited zircon components.

Nutman and Ehlers (1996) demonstrate the presence of thermal events at 1690-1680, 1660-1640 and 1600-1570 Ma. The suggestion of a number of intrusive granites within the BHB, younger than 1700 Ma but older than 1600 Ma is identical to that already shown for intrusive events for the OB (Cook *et al.*, 1994, Ashley *et al.*, 1995 & Ashley and Lawie, 1996).

CURNAMONA CRATON - *sensu stricto*

A sequence of flat lying sediments and volcanics is recorded in drill core from the Benagerie Ridge, Curnamona Craton (Teale and Flint, in Flint & Parker, 1993). U-Pb zircon dating has been carried out on an altered porphyritic rhyolite from Mudguard DDH#1. The IDTIMS analyses are discordant and there is a considerable extrapolation of a discordia line to give an upper intercept of 1599 ± 40 Ma (MSWD of 20, see Fanning *et al.*, 1988). SHRIMP analyses of zircons from the same mineral separation give an age of 1581.5 ± 4.2 Ma for concordant data. This is younger than the 1592 ± 2 Ma age determined for the Gawler Range Volcanics, GC (Fanning *et al.*, 1988), but within uncertainty of the U-Pb ages for felsic volcanic rocks from Harts Creek and Gunsight prospect in the Mount Painter and Mount Babbage Inliers. It is clear that on the Benagerie Ridge, felsic volcanism and sedimentation took place almost contemporaneously with, or immediately following high grade metamorphism and granite emplacement in the mid to lower crust of the nearby OB and BHB.

MOUNT PAINTER AND MOUNT BABBAGE INLIERS

The Mount Painter (MPI) and Mount Babbage Inliers (MBI) are undoubtedly unusual pieces of Proterozoic crust within the Australian continent. Tectonic activity is almost continuous through time from the Mesoproterozoic, with a range magmatic, hydrothermal and metamorphic events. Deformed and little deformed porphyritic rhyolites from Harts Creek and the Gunsight prospect record similar U-Pb ages of 1576 ± 2 Ma and 1575 ± 14 Ma. SHRIMP zircons analyses for the Mount Neill granite porphyry are slightly younger though within uncertainty at 1569 ± 14 Ma. Thus sedimentation and volcanism are considered to have occurred at about 1570 to 1575 Ma in the MPI and MBI.

A younger period of volcanism is also recorded in the MBI with rhyolites and rhyodacites of the Petermorra Volcanics crystallising at 1560 ± 2 Ma (Sheard *et al.*, 1992). Subsequent intrusion of the Terrapinna Granite occurred at 1557 Ma (Thornton, 1980) with the Yerila granite intruding at 1556 ± 10 Ma (Johnson, 1980). A series of other granites from the MPI have been analysed using SHRIMP. These are the Camel Pad and Old Camp Granites, and a granite from Radium Creek. Despite exhibiting differing degrees of strain, all three rocks have simple populations of magmatic zircon which give concordant U-Pb SHRIMP analyses and record ages of 1551 ± 15 Ma, 1555 ± 8 Ma and 1560 ± 8 Ma respectively.

Thus in the MPI and MBI, early volcanism and coeval sedimentation is thought to have occurred at about 1575 Ma. Volcanism, and ?sedimentation continued at about 1560 Ma in the MBI, followed by widespread granite emplacement at about 1555 to 1560 Ma in both inliers. The notable absence of inherited zircon components in the samples analysed is significant and quite distinct from the OB and BHB. Clearly the magmatism in MPI and MBI is either of higher temperature and/or it represents addition of new crustal material. In contrast the OB and BHB record significant zircon inheritance, suggesting a lower heat source with most of the magmatism derived in part from reworking of older crust.

REGIONAL CORRELATIONS

The recent discovery of Archaean zircon protoliths in gneissic rocks from the Willyama Inlier (BHB; Nutman and Ehlers, in press) make for ready correlation in a time sense with the basement of the Gawler Craton (GC). Gneissic rocks with ages between 2400 and 2450 Ma are ubiquitous in the Sleaford and Mulgathing Complexes (GC).

A geologically reasonable correlation can be made linking the style of sedimentation, and subsequent albitisation of the Willyama Supergroup, notably in the OB, with similar sediments and alteration in the Wallaroo-Moonta area of the GC (Conor, 1996 & Teale, 1984). Conor rightly points out the similarity in age of Mesoproterozoic intrusives in both the Gawler Craton and Curnamona Province. However in a strict time sense, the Moonta Porphyry and associated volcanic horizons within both the Doora Schist and Wandearah Metasiltstone crystallised at 1740-1760 Ma. The felsic volcanism and inferred sedimentation in the Curnamona is closer to 1700-1710 Ma, or at c.1580 Ma. Note however that both the Moonta area and Curnamona have prominent 1580-1590 Ma granite intrusions.

The Moonta area is the easternmost exposure of the GC and perhaps was linked with the OB at c.1700-1750 Ma. Irrespective of whether the OB and GC were linked, a key and economically essential characteristic is the presence of the c.1580-1590 Ma magmatism in both the Gawler and Curnamona. In parts of the Curnamona, notably the BHB, this event is associated with high grade metamorphism of the supracrustal sequences. At high crustal levels, coeval felsic volcanics and intrusives are common in both the OB and GC. These intrusives can be directly linked to economic mineralisation on a wide range of scales, from Olympic Dam to the Tarcoola Gold field, Meninnee Dam Prospect to Crocker Well. Many explorers have been seeking a continuation of the deeper crustal level Broken Hill style mineralisation, but many have also realised the probability of Olympic Dam or Ernest Henry style deposits in the Curnamona, associated with the c.1580-1590 magmatism.

REFERENCES

Ashley, P.M., Cook, N.D.J., Lawie, D.C., Lottermoser, B.G & Plimer, I.R. 1995. Olary Block geology and field guide to 1995 excursion stops. *South Australia. Department of Mines and Energy. Report Book* , 95/13.

Ashley, P.M. & Lawie, D.C. 1996. Olary Block Field Excursion. Part 2; guide to 1996 excursion stops. South Australia. Department of Mines and Energy. Report Book . .

Ashley, P.M., Cook, N.D.J. & Fanning, C.M. 1996. Geochemistry and age of metamorphosed felsic igneous rocks with A-type affinities in the Willyama Supergroup, Olary Block, South Australia, and implications for mineral exploration. *Lithos* 38, 167-184.

Buckley, P.M. 1993. The geology and mineralisation of Abminga Station, Olary Block, South Australia. *University of New England. B.Sc. (Hons.) thesis*, (unpublished)

Clarke G.L., Burg J.P. & Wilson C.J.L. 1986. Stratigraphic and structural constraints on the Proterozoic tectonic history of the Olary Block, South Australia. *Precambrian Research* 34, 107-137.

Conor, C.H.H., 1996. Curnamona, Moonta and Cloncurry: Common styles of alteration and mineralisation linked by the Diamantina Orogen. Resources '96 Convention. W.V. Preiss (compiler) Mines and Energy SA. pp.40-41.
Cook, N.D.J, 1993. Geology of metamorphosed Proterozoic playa lake deposits, Olary Block, South Australia. *University of New England. Ph.D. thesis* (unpublished).
Cook, N.D.J, Ashley, P.M. & Fanning, C.M. 1994. New geochronological results from the Willyama Supergroup, Olary Block, South Australia. In: Australian Research on Ore Genesis Symposium. Adelaide, Australian Mineral Foundation, 19.1-19.5.
Fanning, C.M., Flint, R.B., Parker, A.J., Ludwig, K.R. & Blissett, A.H. 1988. Refined Proterozoic evolution of the Gawler Craton, South Australia, through U-Pb zircon geochronology. *Precambrian Research* 40/41, 363-386.
Flint, D.J. & Parker, A.J. 1993. Willyama Inliers, *in* Drexel, J.F., Preiss, W.V. and Parker, A.J. (eds.) The geology of South Australia. Volume 1 The Precambrian. *Geological Survey of South Australia, Bulletin* 54, p. 82-93.
Flint, D.J. & Webb, A.W. 1980. Geochronological investigations of the Willyama Complex, South Australia. *South Australia. Department of Mines and Energy. Report Book* , 79/136.
Glen, R.A., Laing, W.P. Parker, A.J. & Rutland, R.W.R. 1977. Tectonic relationships between the Proterozoic Gawler and Willyama Orogenic Domains, Australia. *Geological Society of Australia. Journal* 24, 125-150.
Johnson, G.I. 1980. The geology of the Mount Babbage area, Mount Painter Province, South Australia - A petrological, geochemical and geochronological study. *University of Adelaide. B.Sc. (Hons) thesis* (unpublished).
Ludwig, K.R. & Cooper J.A. 1984. Geochronology of Precambrian granites and associated U–Ti–Th mineralization, northern Olary province, South Australia. *Contributions to Mineralogy and Petrology* 86, 298–308.
Nutman, A.P. & Ehlers, K. 1998. Evidence for multiple Palaeoproterozoic thermal events and magmatism adjacent to the Broken Hill Pb-Zn-Ag orebody, Australia. Precambrian Research 90, 203-238.
Nutman, A.P. & Ehlers, K. in press. Archaean crust near Broken Hill, New South Wales? *Australian Journal of Earth Sciences*
Page, R.W. & Laing, W.P. 1992. Felsic metavolcanic rocks related to the Broken Hill Pb-Zn-Ag orebody, Australia: Geology, depositional age, and timing of high-grade metamorphism. *Economic Geology* 87, 2138-2168.
Sheard, M.J., Fanning, C.M. & Flint, R.B. 1992. Geochronology and definition of Mesoproterozoic volcanics and granitoids of the Mount Babbage Inlier, northern Flinders Ranges, South Australia. *South Australia. Geological Survey. Quarterly Geological Notes* 123, 18-30.
Teale, G. S. 1984. Summary report on Frome Project area: Origin of mineralisation and associated lithologies and suggestions for future exploration. Confidential report to Pan Australian Mining Ltd, March 1984 (now open file, held at PIRSA).
Thornton, G.D. 1980. Geology, geochemistry and geochronology of the eastern Mount Babbage Block, Mount Painter Province, South Australia. *University of Adelaide. B.Sc. (Hons) thesis* (unpublished)

CORRELATION AND DISTRIBUTION OF REGOLITH MATERIALS AND LANDFORMS IN THE BALACLAVA AREA, BROKEN HILL

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The Balaclava 1:25,000 sheet covers an area of more than 250 km2 approximately 30 km to the south of Broken Hill, central western New South Wales. Mapping of exposed Willyama Supergroup, host to the Broken Hill Pb-Zn-Ag ore body, has been restricted in this area due to a cover of aeolian, fluvial and colluvial regolith materials which are in places over 30 m thick.

Several highly prospective localities exist in the area. The Percys Dam, Ten Two, Blake, Balaclava Homestead, Magnetic Hill and Galena Hill prospects all occur where bedrock is close to the surface or cropping out. Many of these prospects were initially identified by a surface expression of ferricrete, perhaps thought to be gossanous.

Approaches to exploration in regolith covered terrain must differ from those methods applied where bedrock dominates. Detailed mapping of regolith materials and associated landforms is the first step in locating new deposits in regions where bedrock exposure is poor. The Balaclava 1:25,000 Regolith-Landform map aims to identify, characterise and correlate components of the landscape and regolith. Mapping has involved the preliminary interpretation of aerial photograph stereo pairs and enhanced red-green-blue airborne gamma-ray spectrometric imagery followed by detailed field delineation.

Over 80% of the Balaclava area is covered by regolith, including a significant aeolian contribution. The mapped units consist mainly of erosional rises shedding material onto gently sloping colluvial fans. Topographically the area slopes to the south-southeast. In the north and northwest, bedrock and ferruginous erosional rises dominate, giving way to much deeper regolith in the south and southeast. Duricrust materials present include ferricretes, silcretes, regolith carbonates and gypcrete. Both ferricretes and regolith carbonates are being examined to assess their possible uses as sampling media for mineral exploration.

Uses for the Regolith-Landform map include:
assisting exploration geologists to gain an understanding of an area largely void of bedrock mapping detail,
facilitating the location of appropriate surficial materials as exploration sampling media; and,
the development of landscape evolution models to help constrain surficial physical and chemical dispersion pathways.

An understanding of Australia's regolith materials and landforms is essential to the future of mineral exploration in this intensely weathered terrain. Developments in regolith mapping techniques and geochemical modelling are central to achieving this understanding

Acknowledgements
This project was undertaken as part of Honours work supported by the Cooperative Research Centre for Landscape Evolution and Mineral Exploration – the authors gratefully acknowledge this support, in particular assistance and comments from Steve Hill, Tony Eggleton, David Gibson, Leah Moore, Graham Taylor and Ian Roach. The support of Pasminco Exploration, Triaco Resources, Acacia Resources, the Australian Geological Survey Organisation and the New South Wales Geological Survey is also appreciated.

REGIONAL STRUCTURE IN THE WILLYAMA SUPERGROUP AND ITS RELEVANCE TO MINERAL EXPLORATION IN THE BROKEN HILL INLIER

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Regional structure in the Paleoproterozoic Willyama Supergroup is dominated by three episodes of folding (D1-D3) and several generations of shear zones, the most important of which dip east or southeast, and figure prominently in seismic images of the Broken Hill region (Gibson et al., 1998). Several of these shear zones (e.g. Lakes Creek Discontinuity) have effected measurable displacements of the regional stratigraphy and for a number of years the weight of opinion favoured a structural rather than stratigraphic control on the main line of lode. Structural analysis undertaken by AGSO as part of the Broken Hill Exploration Initiative has been less concerned with the origin of the main line of lode than with an evaluation of the controls on mineralisation (including magnetite distribution) in the less intensely deformed parts of the Willyama Supergroup north of the Stephens Creek Shear Zone (e.g. Allendale Mine area). In these areas, it is much easier to see through the superimposed strain and thereby reach some conclusion about the origin and timing of mineralisation. With this objective in mind, systematic mapping of the shear zones and D1-D3 structures has been carried out by AGSO to:

- determine the tectonic history and three-dimensional structural geometry of the Broken Hill Block, and assess whether there is any structural control on mineralisation and magmatism in the region
- construct one or more detailed cross-sections through the Willyama Supergroup, and thereby test the validity of previously proposed tectonic models for the Broken Hill region (Marjoribanks et al., 1980; White et al., 1995)
- better understand the origin and kinematics of the shear zones so that their effect on rock distribution is known and no longer masks the earlier pre - D3 structural geometry of the Broken Hill Block
- evaluate the extent to which magnetite distribution and its associated aeromagnetic anomalies are structurally, rather than stratigraphically, controlled in the Broken Hill region

Previous workers in the Broken Hill region (e.g. Marjoribanks et al., 1980; Laing et al., 1978) reported that the Willyama Supergroup had undergone three episodes of folding (F1-F3) prior to deposition of the unconformably overlying Neoproterozoic cover sequence (Adelaide Supergroup). The first two phases were coaxial and accompanied by amphibolite to granulite facies metamorphism whereas the third phase of deformation occurred under lower temperature conditions and was considered "retrograde" in character. Overturning of the regional stratigraphy was attributed the presence of km-scale D1 nappe structures.

Structural mapping carried out by AGSO in the Allendale, Sculptures and Southern Cross areas confirms the presence of three major deformational events (D1-D3) in the Willyama Supergroup although no early D1 fold closures or nappes have yet been recognised. Rather, the most conspicuously developed large-scale folds in these areas are of D2 age. In the Allendale and Sculptures areas, it is these folds rather than the D1 event which gave rise to the present outcrop pattern and distribution of the main rock units (e.g. Potosi gneiss). D2 folds are tight to isoclinal, reclined to recumbent and, in the Allendale area, plunge east or southeast at moderate angles (cf. steeper, variably plunging north-south-trending D3 folds). D2 folds in this same region are often downward-facing and were superimposed upon the overturned limb of an earlier D1 structure (cf. Marjoribanks et al., 1980). The regional stratigraphy in the Allendale region is inverted, and quartz-albite rocks of the Thackaringa Group lie structurally above, but stratigraphically below, pelitic and psammitic schists of the Broken Hill Group. In the Allendale region, the Willyama Supergroup had already been isoclinally folded and thickened before the onset of D2 deformation (cf. Marjoribanks et al., 1980).

The most conspicuous D1 structure north of Stephens Creek is a high-grade schistosity, S1, which for the most part lies parallel or subparallel to bedding. This fabric is shared by all metasedimentary units except the Paragon Group, implying that this unit is either in tectonic contact with the rest of the Willyama Supergroup or that it was deposited unconformably on the latter following the first phase of deformation.

Similarly, no D1 fabric has been recognised in the granite orthogneisses north of Stephens Creek. The fabrics in these rocks are of D2 and D3 age. A pre- or early syn-D2 age is indicated for emplacement of these granites, several of which have recently been dated at 1690 Ma (U-Pb SHRIMP ages; Nutman and Ehlers, 1998). These data therefore give a minimum age for the D1 deformation and a maximum age for the cessation of the D2 deformation. A pre- or syn-D2 emplacement age for these orthogneisses is compatible with the observation that almost all share the same high-grade D2 sillimanite fabric as their host rocks and thus must have recrystallised under peak metamorphic conditions; a few orthogneisses have even undergone limited amounts of remelting. Peak metamorphism is thought to have occurred around 1590-1600 Ma (Page and Laing, 1992; Nutman and Ehlers, 1998).

Several granite orthogneisses are sheet-like in form and exhibit a gneissic or mylonitic fabric consistent with a syn-tectonic origin. Granite emplacement may therefore have been structurally controlled although whether intrusion was controlled by the D1 or D2 structures is still uncertain. A D2 age is presently preferred although this would imply that granite magmatism followed, rather than accompanied, the earlier episode of D1 isoclinal folding and associated crustal thickening. A D2 age would also imply that granite magmatism and peak metamorphism were contemporaneous with formation of the shallow-dipping S2 fabric whose origin is currently under investigation. One possibility is that this D2 fabric resulted from gravitational collapse of crust thickened during the D1 event and is thus extensional in origin. Alternatively, it may be thrust-related. Too little information is presently available to test either possibility although it is interesting to note that granite emplacement was accompanied, and/or immediately followed, by the intrusion of mafic dykes and sills now represented by amphibolite.

Contrary to some earlier interpretations (e. g. Laing et al., 1978), the D2 and D3 folds are not coaxial but commonly lie at high angles to each other. The D3 deformation is primarily a flattening strain and overprints a sub-horizontal to shallow-dipping S2 fabric. Magnetite and base metal mineralisation in the Allendale region postdate S2 and are hosted by the more steeply-dipping D3 fabric and associated shear zones.

Structural mapping in progress around the Southern Cross, Parnell, and Sculptures regions lends little support to the conclusion (White et al., 1995) that the Willyama Supergroup comprises a stack of southeast-directed thrust sheets emplaced contemporaneously with high-grade metamorphism. Nor is there much evidence for reorientation of the earlier formed D1 fold axes into the direction of D2 regional extension during thrusting. Thrust faults of both D2 and D3 age have been identified by AGSO in the Willyama Supergroup but thus far only the geometry of the latter has been successfully established; these structures dip east or southeast, and correspond to the main shear zones identified in the AGSO seismic images. D3 thrust faulting was west or northwest-directed and in the same direction as that determined from D3 fold vergence. It is equally evident (e.g. in the Allendale area) that the D3 folds and associated thrust faulting postdate the peak of metamorphism and were associated with development of the "retrograde" S3 fabric. A post-metamorphic age for the D3 event is supported by the observation that the S3 fabric is present in Mundi Mundi - type granites dated at 1490-1500 Ma.

REFERENCES

Gibson, G. M., Drummond, B. J., Fomin, T., Owen, A., Maidment, D. W., Peljo, M., & Wake-Dyster, K. (1998): Re-evaluation of crustal structure of the Broken Hill Inlier through structural mapping and seismic profiling. AGSO Record 1998/11, 55p.

Laing, W. P., Marjoribanks, R. W., & Rutland, R. W. R. (1978): Structure of the Broken Hill Mine area and its significance for the genesis of the ore bodies. Econ. Geol. 73: 1112-1136.

Marjoribanks, R. W., Rutland, R. W. R., Glen, R. A., Laing, W. P. (1980): The structure and tectonic evolution of the Broken Hill region, Australia. Precambrian Res. 13: 209-240.

Nutman, A. P., & Ehlers, K. (1998): Evidence for multiple Paleoproterozoic thermal events and magmatism adjacent to the Broken Hill Pb-Zn-Ag orebody, Australia. Precambrian Res. 90: 203-238.

Page, R. W., & Laing, W. P. (1992): Felsic metavolcanic rocks related to the Broken Hill oerebody, Australia: geology, depositional age, and time of high grade metamorphism. Econ. Geol. 87: 2138-2168.

White, S. H., Rothery, E., Lips, A. L. W., & Barclay, T. J. R. (1995): Broken Hill area, as a Proterozoic fold and thrust belt: implications for the Broken Hill base-metal deposit. Trans. Instn. Min. Metal. 104: B1-B17.

Acknowledgements

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PETROPHYSICAL STUDIES IN THE BROKEN HILL BLOCK: IMPLICATIONS FOR MAGNETIC MODELLING AND THE CONTROL MECHANISM OF LINEAR MAGNETIC ANOMALIES

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OVERVIEW

One of the products that the Broken Hill Exploration Initiative (BHEI) has delivered as part of its brief to stimulate exploration activity, is a new-generation of high-resolution aeromagnetic data for the Broken Hill Block (Haren et al. 1997). Interpretation of those data is already leading to new insights into the geological development of the region with the expectation that more effective exploration strategies may be defined. However, in interpreting the magnetic anomalies and using them to trace sub-surface geology in concealed areas and at depth, it is important, for geological realism in projected maps and structure, that we understand what we are tracing and have an idea of the magnetic mineralogy and the magnitude and significance of the different parameters employed in magnetic modelling studies. As a contribution to those aims, the results to date are presented from two separate petrophysical studies that address those issues.

LINEAR MAGNETIC ANOMALIES: MODELLING, CONTROL (JG, GG, DM, UR)

We are conducting an integrated study of 5 prominent, NNE–NE-trending linear magnetic anomalies that combines magnetic profiling, magnetic property determination and detailed geological and structural mapping along a number of traverses orthogonal to the strike of the anomalies. The purpose of this study is to investigate whether the controlling mechanism of the anomalies be structural or stratigraphic, to examine how significant magnetic remanence is to the interpretation of such anomalies, and to find out whether the remanences recorded by the magnetic mineralogy of the anomalies retain any coherent signals that can be interpreted in terms of subsequent geological events that have affected the region.

The 5 anomalies selected for study are located, from north to south across the Broken Hill Block, as follows: just north of Waukaroo Bore, Brewery Creek mapsheet, trending ~27°E and hosted by the Sundown Group; just northwest of Acacia Vale HS, Lakes Creek mapsheet, trending ~38°E and hosted by the Thackaringa Group; the Monuments district, Broken Hill mapsheet, trending ~45°E and hosted by the Sundown Group; and the western and eastern arms of the Broken Hill Synform, Mount Gipps mapsheet, respectively trending ~49°E and ~23°E and respectively hosted by the Sundown-Broken Hill Groups and the Thackaringa Group. Apart from the Monuments anomaly (for which traversing and total field measurements were conducted by NSW DMR), our traverses were ~500 m long to ensure complete capture of anomaly profiles. Total field measurements were recorded every 5 m. Field susceptibility measurements were made every 10 m to locate the surface widths of the anomalous zones. Along one traverse per anomaly, as outcrop permitted, oriented cores of rock were collected from both anomalous and background zones in a ratio of 2:1 respectively, yielding ~190 samples (30–50 per traverse) for magnetic property measurements.

Identification of the magnetic mineral systems in the anomalous zones and an insight into their grain-size distribution was derived from the variation of magnetic susceptibility with temperature (Schmidt 1993) between -196°C and 700°C. Without exception, all strongly magnetic samples show sharp drops in susceptibility in the range ~585–595°C, a Curie point that tells us we are dealing with pure end-member magnetite in the titanomagnetite solid-solution series Fe3-xTixO4 (x=0, magnetite). They also all show, at low temperature, significant increases in susceptibility, with values peaking between -140°C and -150°C, indicating that a coarse-grained (multidomain) magnetite fraction is present (makes them easy to magnetize). These findings are consistent with the fact that metamorphic magnetite is generally pure and coarse grained (Thompson & Oldfield 1986) and confirm geological evidence for magnetite as the source of these anomalies. Minor maghemite (cation-deficient magnetite) is present (probably a weathering product); there is no indication of pyrrhotite (Fe7 S8), an important magnetic mineral after the iron oxides.

In view of the ideas circulating that certain structural fabrics are magnetite-enriched, we examined the relationship between magnetite and petrofabric in the samples by determining their petrofabric using the quick and sensitive technique of anisotropy of magnetic susceptibility (AMS). AMS is characterised by a susceptibility ellipsoid defined by the directions and magnitudes of the maximum (Kmax), intermediate (Kint) and minimum (Kmin) susceptibilities: the plane containing the Kmax and Kint axes defines plane of the petrofabric. For magnetite, AMS primarily defines grain-shape anisotropy (Borradaile & Henry 1997). Values for the bulk susceptibility of the samples, for use in magnetic modelling, were derived from the AMS measurements. Stereographs of the AMS data show that, for each anomaly, the source and host (background) rocks have the same well-defined fabric, but that the orientation of this fabric varies between anomalies. The northern three anomalies (Waukaroo Bore, WB; Acacia Vale, AV; Monuments, MA) fall into one simple pattern, the Broken Hill Synform anomalies into another. For the northern anomalies, as we come south, the magnetic fabric plane veers around from an azimuth of 19°E and steep ESE dip of 82° (WB, anomaly trend ~27°E), through 38°E and SE dip of 74° (AV, anomaly trend ~38°E), to 44°E and SE dip of 75° (MA, anomaly trend ~45°E). From the structural mapping it is evident that the AMS fabric tracks the S3 fabric of Gibson as it swings from northerly to easterly orientations going from north to south. Importantly, the anomaly trends lie along the magnetic fabric trends and hence S3. The AMS fabric certainly does not track S0 which, as a measurable fabric using AMS, is most unlikely to survive later fabric overprints given the high, post-S0, metamorphic grades the rocks have experienced. In the Broken Hill Synform, the magnetic fabric of each anomaly dips steeply (71° and 77°) WNW, reflecting S2/S3 fabric dips, here parallel, and lithological dip.

Detailed magnetic modelling to date has been conducted for the two northernmost anomalies, Waukaroo Bore and Acacia Vale. The shapes of the magnetic profiles indicate that each is a composite of two sources: a body 20–50 m below the surface that gives the gross shape of the profile, and a number of thinner, near-surface bodies that extend down to the deeper body and give high-frequency detail to the profile. To examine the importance of remanence in the modelling, we looked at the distributions of directions of initial remanence (freed of temporary components acquired prior to measurement and of lightning-struck samples). In each case the distributions are bipolar, with both upward-pointing (normal) and downwardpointing (reverse) vectors. For WB, the axis of magnetization lies close to the Earth's present field, but directions are streaked between it and the reverse group. For AV, directions are more scattered, are streaked between both polarity groups, but the axis is aligned more to the northwest. The important point is that in calculating mean underlying vector fields (background fields) for the anomalous zones, the reinforcement of the induced magnetization by the normal remanence is markedly diminished by the counteracting reverse remanence. As a result, mean remanent field magnetizations turn out to be 4–8 times smaller than individual sample magnetizations: we find that remanence, therefore, can be effectively ignored in modelling the gross shapes of the profiles that arise from the deeper features. We find individual sample remanences are useful for getting the best fits to the high-frequency detail caused by the near surface features, but in isolation overstate the importance of remanence for deeper features. For both anomalies, the models turn out to be similar. The gross shape of each profile requires a tabular body of great depth extent, ~40 m (WB) or ~25 m (AV) below the surface, ~125 m wide, and steeply-dipping at ~80° (WB) to the ESE or ~70° (AV) to the SE (preliminary modelling of the Monuments anomaly similarly requires a tabular body steeply-dipping to the SE). The high-frequency detail of each anomaly can be modelled with a number of variably-separated thin tabular bodies, variably extending from the near-surface to the deeper body below and dipping in a similar attitude. The finger-like thin tabular bodies mimic the observed and marked spatial variation in surface susceptibility (whereby variations of up to two orders of magnitude may occur within metres) that reflects the inhomogeneous distribution of magnetite within the anomalous zones. The modelling has been done using induced magnetization alone and in conjunction with magnetic remanence. In either case a fit to the profiles has been possible. The important point is that the fit from one method to the other basically requires only repositioning of the relatively-unimportant, near surface bodies to realign the computed profile: the shape and dip of the main tabular bodies remains unchanged. Hence our assertion from these two examples that remanence appears as though it can be ignored in modelling magnetite-sourced, linear anomalies.

How do the models fit with the mapping and AMS data and what is the bearing of the results to date on the debate concerning stratigrahic versus structural control of anomalies in the Broken Hill Block (Gibson et al. 1996; Haren et al. 1997)? We note that the dip and dip sense required of the tabular bodies by the shape of the anomaly profiles are consistent with the dip and dip sense of the magnetic fabrics measured for the anomalous zones and that those fabrics are the S3 fabric. Hence the tabular bodies must represent the magnetite-rich S3 fabric. For the Waukaroo Bore anomaly, the geological cross-sections for the anomalous zone show that the envelope of S0 (bedding) dips shallowly to the NE and to the SW. However, we have demonstrated that the anomalous zone here steeply dips ~80° to ESE and is the magnetite-rich S3 fabric. Clearly, we are dealing with an anomaly which is structurally rather than stratigraphically controlled. Most likely, the fluids causing magnetite-impregnation of the S3 fabric are coeval with the D3 event, because conditions in a deformation are optimal for triggering fluid movement. For the Acacia Vale anomaly, the situation is equivocal: S0 and S3 have similar steep dips (the AMS fabric is the S3 fabric) so the structural control case could be argued either way. It is a question of timing: whether the S3 fabric was imposed on a pre-existing magnetite-rich S0 fabric (stratigraphic control) to become an apparently-rich fabric or, like Waukaroo Bore, was enriched at the time of its development (structural). Characterisation of the magnetite in the two locations might provide an unequivocal answer by revealing a genetic source that is common or otherwise. Alternatively, more evidence like the Waukaroo Bore case may tip the scales to favour structural control. Irrespective of the control mechanism for the Acacia Vale anomaly, we have added another cautionary note to others concerning use of linear anomalies for mapping sub-surface geology in concealed areas: although some will reflect lithology, others will certainly reflect structural elements. Structurally-controlled anomalies and their association with fluid movement may be important to exploration strategies.

ANALYSIS OF THE BHEI PETROPHYSICAL DATABASE (PR)

This study presents an analysis of the BHEI petrophysical database generated by CSIRO under contract to BHEI. The database comprises a regional-scale collection of measurements of magnetic susceptibility and its anisotropy, remanence and density on ~1000 samples of drillcore and outcrop material. The database is designed so that the sample population is, as far as possible, representative of each rock formation under differing grades of metamorphism. The analysis sought to elucidate trends in the data between susceptibility, remanence, density, rock type and metamorphic grade and to assess the relative importance of remanence and anisotropy of susceptibility to the magnetic modelling process.

Most rock types display a magnetic susceptibility distribution that is bimodal: iron in the weakly magnetic subpopulation is incorporated into the paramagnetic silicate minerals as Fe2+, whereas in similar lithologies that are strongly magnetic, more iron goes into magnetite as Fe3+. Metasedimentary rocks, including those that are retrogressed, are generally weakly magnetic with susceptibility values densely clustered in the low range of 10–50 E-5SI. However, there is a significant tapering to high values of ~8000 E-5SI and, for the pelitic/psammitic metasedimentary fraction, up to 250,000 E-5SI, making the process of modelling over the stronger magnetic fraction more complex due to the wide variability in values. Amphibolites are the only rock group to exhibit susceptibility and gravity distributions that are dependant on metamorphic grade. As the Broken Hill orebody is approached, the magnetic susceptibility of the amphibolites rises, reflecting a regional increase in their magnetite/pyrrhotite content with increasing metamorphic grade. Concomitantly, there is an overall increase in their density. Metamorphic grade is clearly a parameter that should be taken into account when modelling amphibolites.

Comparison of susceptibilities obtained from surface samples with those obtained from drillcore material indicates that there is no distinguishable difference. This suggests weathering effects are minimal and that, for modelling purposes, surface susceptibility values are reliable indicators of those at depth. Eighty percent of drillcore samples reveal a low to moderate anisotropy of susceptibility (values between 1.0 and 1.2 i.e. up to 20%). However, such values are generally insufficient to significantly influence the form of a magnetic response.

Graphs of magnetic susceptibility against Koenigsberger ratio, Q (ratio of remanent magnetization to induced magnetization), reveal that most lithologies show three distinct sub-populations: low susceptibility with low remanence and low Q (46% of population); low susceptibility with high remanence and high Q (42% of population); and high susceptibility with high remanence and high Q (11% of population). Very few samples represent a fourth population comprising high susceptibility with low remanence and low Q. It is evident therefore that most rocks with high magnetic susceptibility will have a significant natural remanence. This will need to be considered in magnetic modelling.

Directions of natural remanence from surface samples are generally northerly-directed with preferred upward-pointing inclinations of between 45° and 90° (vertical). Most drillcore samples have similar remanent inclinations. As such directions are in the vicinity of the earth's present magnetic field for the region, the effect of remanence will be to reinforce the magnetization induced by the present day field. Dips interpreted from models that assume magnetization parallel to the present day field should therefore be consistent with mapped dips, a conclusion that accords with the findings of others (McIntyre 1979; Tucker 1983).

REFERENCES

Borradaile, G.J. & Henry, B. 1997. Tectonic applications of magnetic susceptibility and its anisotropy. *Earth Sci. Rev. 42,* 49-93.

Gibson, G., Maidment, D. & Haren, R. 1996. Re-evaluating the structure of Broken Hill: Implications for mineral exploration and the interpretation of airborne magnetic data. *AGSO Res. Newsletter 25,* 1–3.

Haren, R., Liu, S., Gibson, G., Gibson, D.L., Maidment, D. & Gunn, P. 1997. Geological interpretation of high-resolution airborne geophysical data in the Broken Hill region. *Exploration Geophysics 28,* 235–241.

McIntyre, J.L. 1979. Aeromagnetics — an effective geological mapping aid for the Willyama complex? *Bull. Aust. Soc. Explor. Geophys. 10,* 42–53.

Schmidt, P.W. 1993. Palaeomagnetic cleaning strategies. *Phys. Earth Planet. Inter. 76,* 169–178.

Thompson, R. & Oldfield, F. 1986. Environmental Magnetism. *Allen and Unwin,* London, 227pp.

Tucker, D.H. 1983. The characteristics and interpretation of regional magnetic and gravity fields in the Broken Hill district. *Aus.I.M.M. Conference,* Broken Hill, NSW.

Acknowledgements

Tony Meixner and Peter Gunn are thanked for introducing us to the process of magnetic modelling. Phil Schmidt is thanked for discussions concerning the BHEI Petrophysical database and Barney Stephens for help with the classification of rock groups therein.

^{40}Ar-^{39}Ar AND APATITE FISSION TRACK THERMOCHRONOLOGY OF THE BROKEN HILL INLIER: IMPLICATIONS FOR MESOPROTEROZOIC TO RECENT TECTONICS

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The Precambrian Willyama basement of the Broken Hill Inlier of western New South Wales and the overlying thin veneer of Neoproterozoic sedimentary rock have experienced an ongoing tectonothermal history post-dating the high grade Olarian Orogeny (~1600 Ma).

^{40}Ar-^{39}Ar and apatite fission track (AFT) data combined with petrological and structural observations reveal that the Broken Hill Inlier experienced several distinct tectonothermal disturbances.

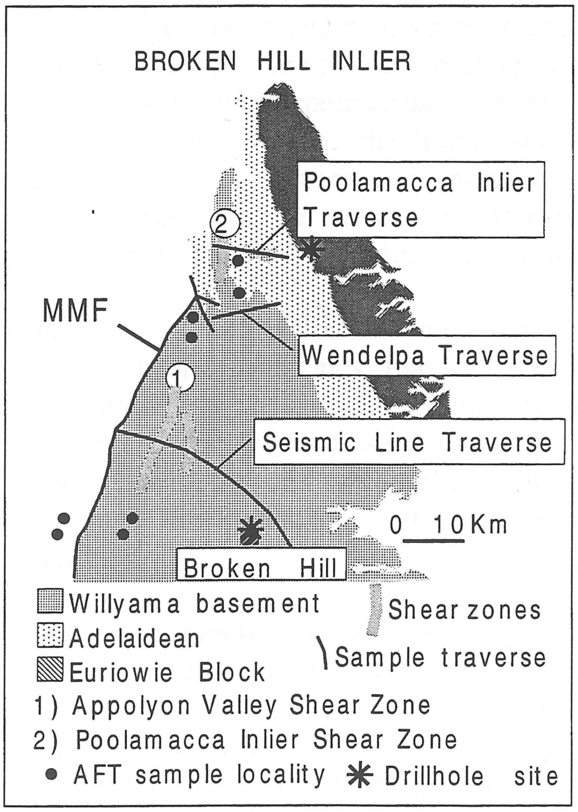

Fig. 1 - Geological sketch map of the Broken Hill Inlier showing major traverse locations where sampling for ^{40}Ar-^{39}Ar and AFT thermochronology was conducted. MMF = Mundi Mundi Fault.

These disturbances are associated with major orogenic events during Proterozoic supercontinent break-up and the amalgamation of Gondwana. Identifying the relative significance of individual tectonothermal events is crucial to elucidate the times of formation and geometry of major features in the metamorphic belt. Discrimination of discrete events requires data related to the relative timing and conditions of metamorphism and plutonism. Further, timing constraints on shear zones can provide insight into the kinematic and exhumation history evolution of a metamorphic belts.

Results from ^{40}Ar-^{39}Ar laser and furnace step heating analyses of separates collected from over 60 outcrop locations (Fig. 1) across the Inlier, reveal plateau and total fusion ages between ~1600Ma-280 Ma (Fig.2). This extensive time span was punctuated by periods of tectonic reactivation typified by crustal heating, exhumation and cooling, and fault reactivation. Major events revealed by the results include the ~1250-1100 Ma Musgravian (Grenville) and the ~500 Ma Delamerian (Pan-African) orogenies (Fig. 2). Relatively strong tectonothermal overprints across the basement have obscured much of the early history of the Willyama Inliers.

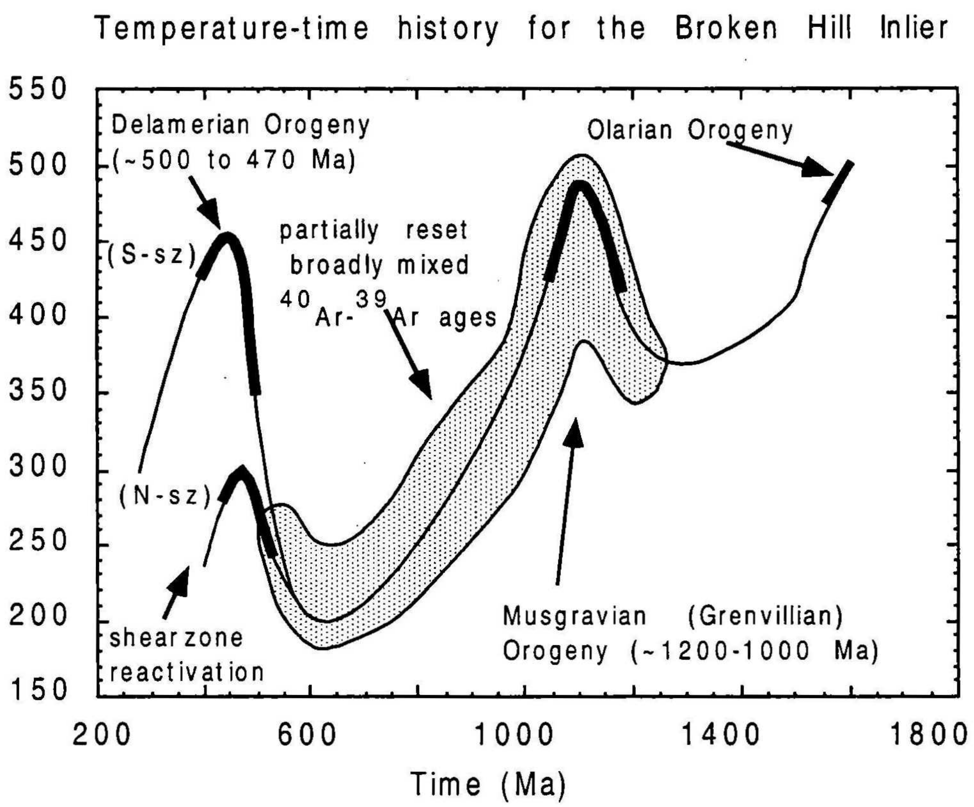

Fig. 2 - A time-temperature cooling path for the Willyama Inlier derived from muscovite, biotite, whole rock, hornblende and K-feldspar ^{40}Ar-^{39}Ar data. (S-sz = southern shear zones, N-sz = northern shear zones).

^{40}Ar-^{39}Ar age spectra from basement samples across the three major traverses (Fig. 1) show a broad mixing of ages from ~1200-500 Ma implying that tectonometamorphic temperatures hadn't reached higher than ~300-400°C (greenschist facies) based on retentivity in muscovite and biotite. K-feldspar data indicate that the basement, outside of shear zones, cooled to <200°C at ~630-610 Ma.

Large crustal scale shear zones that bisect much of the southern parts of the Inlier operated at temperatures higher than the surrounding basement rocks, (reaching ~400-450°C at ~470 Ma) based on Ar retentivity of muscovite. In the northern parts of the Inlier shear zones moved at ~500 Ma. In this area maximum temperatures of formation/reactivation reached ~300°C, based on the estimated closure temperature of white mica-rich whole rock chips. The diachronous cooling of shear zones between the southern and northern parts of the Broken Hill terrane is interpreted to reflect a variation in exhumation/denudation across the Inlier most likely related to relative differences in crustal depth at ~500Ma. Earlier and more rapidly cooled narrow banded shear zones occur in the north whilst the wider, more slower cooling late shear zones occur in the south. Further regional cooling occurred within the shear zones in the northern part of the Inlier, at ~280 Ma, during the Alice Springs Orogeny.

Analyses of AFT data collected from outcrop and deep drill hole samples (Fig. 1) from across the Broken Hill Inlier and in the neighbouring Euriowie Block reveal the low temperature thermal history of the terrane (Mitchell, Hill and Kohn, 1998; Kohn et al, 1998). Numerical forward modelling of measured AFT parameters constrain the magnitude of denudation and timing of relative fault displacement. Periods of Phanerozoic cooling, previously unknown in the Inliers, are identified and linked to tectonic events elsewhere in Australia.

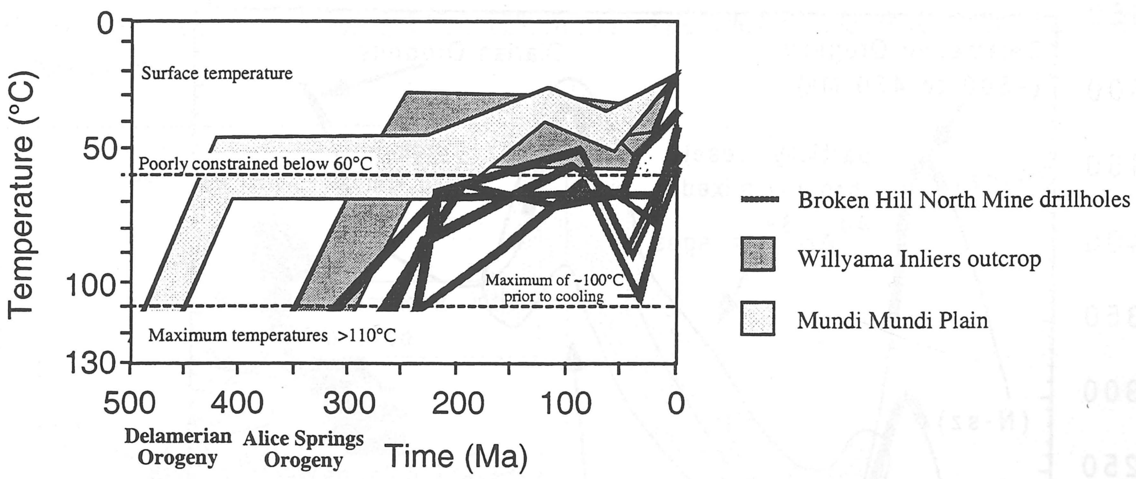

Fig. 3 - Modelled time-temperature cooling envelopes and paths for the Willyama Inlier samples derived from AFT data.

Outcrop samples over much of the Willyama Inlier display similar Phanerozoic thermal histories to those published recently for the adjacent Curnamona Craton and Adelaide Fold Belt, suggesting events of regional extent. Two stages of regional cooling are recognised from AFT data (Fig. 3); the first being associated with the Alice Springs Orogeny (~300-400 Ma) and a second of smaller magnitude occurring during the Late Cretaceous to Tertiary times. A more accurate constraint on the timing and magnitude of the later cooling event comes from two boreholes in the Broken Hill Mine area which indicates ~25-30°C cooling between ~60-20Ma. This cooling phase is possibly associated with denudation in response to intraplate stresses related to the reconfiguration of the Australian Plate and its margins during this time.

An exception to the consistent pattern of AFT data for the Broken Hill Inlier is found in rocks to the west on the Mundi Mundi Plains. The Mundi Mundi Escarpment is predominantly a NE-SW trending feature that divides the Mundi Mundi Plain from the Barrier Ranges to the east (Fig. 1), and approximates the trend of the Mundi Mundi Fault. The Mundi Mundi Fault appears to be of major regional landscape significance, marking the western, upthrown edge of a tilted block. It is an ancient structural feature, possibly dating back to the Proterozoic which has continued to be active up to recent times.

AFT results clearly suggest very different temperature-time paths for rocks on either side of the Mundi Mundi Fault. Samples from west of the fault record initial cooling from palaeotemperatures >~100-110°C during the Early Palaeozoic (Cambrian-Ordovician), suggesting an association with the Delamerian Orogeny (see Fig. 3), whereas samples immediately east of the fault show a significant Late Palaeozoic (Carboniferous) cooling possibly related to the Alice Springs Orogeny. Further cooling of rocks on both sides of the fault is also suggested during the Tertiary but the timing is less well constrained because it occurred from relatively shallow crustal levels. A greater amount of denudation has occurred to the east. Such that at the time of onset of Late Palaeozic related cooling, rocks presently exposed to the west were =40-50°C cooler than those to the east.

Time-temperature cooling paths developed from ^{40}Ar-^{39}Ar and AFT data identify that the Musgravian (~1200-1000 Ma), Delamerian (~500-470 Ma) and Alice Springs (~400-280 Ma) orogenies, to varying degrees, were responsible for the distinct regional episodes of cooling and reheating throughout the Mesoproterozoic to Recent development of the Broken Hill Inlier. These episodes of cooling occurred during known orogenic episodes in Gondwana and Australia and were caused by exhumation and fault reactivation on major structures. In terms of the present day geothermal gradient known from the Broken Hill region (~20°C/km) this represents removal of at least 20 km of section since the Mesoproterozoic.

Acknowledgements
This study has been undertaken as part of the AGCRC project 3043LO (Thermochronological Evolution of Australian Basement Terranes) in conjunction with the Broken Hill Exploration Initiative. The senior author would also like to thank the pastoral holders for the interest shown and willingness to allow access to their land. Work reported here was conducted as part of the Australian Geodynamic Cooperative Research Centre and this abstract is published with the permission of the Director, AGCRC.

REFERENCES

Hill, S.M., and Kohn, B.P., 1998. Morphotectonic evolution of the Mundi Mundi escarpment, Broken Hill Block, NSW. Proceedings of Regolith '98 Conference - New Approaches to an Old Continent, 3rd Australian Regolith Conference (in press).

Kohn, B.P., O'Sullivan, P.B., Mitchell, M.M., Gleadow, A.J.W., and Hill, S.M., 1998. Phanerozoic thermotectonic history of the southwestern Tasman Line-Willyama Inliers region. Extended abstracts of symposium, "Mineral systems and the crust-upper mantle of southeast Australia," Canberra, 20-22 April, 1998. Australian Geological Survey Organisation Record 1998/2, 111-114.

Mitchell, M.M. 1997 The thermal evolution of southeastern south Australia and the western Otway Basin, PhD Thesis, La Trobe University, 457 p.

KALKAROO COPPER-GOLD PROJECT

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EL2055 Kalkaroo is located approximately 90km WNW of Broken Hill and encompasses an area of partially exposed Proterozoic metasediments which crop out through Tertiary and younger sediments. The Kalkaroo project is a joint venture between Newcrest Mining Limited, Placer Exploration and MIM Exploration Pty Limited.

Kalkaroo prospect was discovered in 1992 as a result of rotary mud drilling across linear aeromagnetic highs extending NE along the Waukaloo trend. Placer Exploration and MIM Exploration subsequently completed extensive air core, reverse circulation and diamond drilling over the most intense portion of the magnetic high to define a zone of secondary and primary gold-copper-molybdenum mineralisation at Kalkaroo. Exploration at this stage was reliant on coarse 400 metre line spaced aeromagnetic data. Since 1996, BHEI gravity and aeromagnetic data provided regional geophysical data sets with greater definition with which to focus exploration activities.

Kalkaroo mineralisation occurs within units of the Proterozoic Willyama Supergroup below 50-60 metres of clays and sand of the Eyre Formation. Aeromagnetic data display complex interference patterns attributable to complex folding of the stratigraphy at South Sampsons and Kalkaroo Southeast. Magnetic data and drill hole geology indicate that Kalkaroo mineralisation occurs within units of the Calcsilicate Suite, Bimba Suite and extending into the lower portions of the Pelite Suite. The Brooks Dam Zn-Pb gossan may occur in a similar stratigraphic position (Ashley et al. 1997).

Several granite bodies occur within the project area adjacent to the Kalkaroo, Deep Well and North Mannings prospects. Sparce granite outcrops and air core intercepts of these bodies are leucocratic, unaltered, undeformed and usually contain muscovite. The granite bodies are nonmagnetic with coincident magnetic low and gravity low signatures. Absolute age of these granite bodies is unknown but are interpreted as being at least as old as Mesoproterozoic or as young as Cambrian in age. A broad regional gravity low extending from North Mannings to Benagerie indicates the presence of an inferred granite body at depth.

Primary mineralisation comprises chalcopyrite and pyrite as blebs and lenses within bedding planes and fractures and as cross-cutting chalcopyrite-molybdenum veins. The mineralised zone is up to 100 metres thick and overlies strongly magnetic calc-silicate bearing, albite magnetite metasiltstones. Primary mineralisation has been intersected over 1.2 kilometres of strike. Secondary mineralisation occurs at several levels within the weathered basement (Arkaringa Paleosol) with native copper and chalcocite common. Supergene enrichment extends some distance into to the unweathered basement as chalcocite in carbonate leached zones and as chalcocite replacement of vein and bedding controlled chalcopyrite

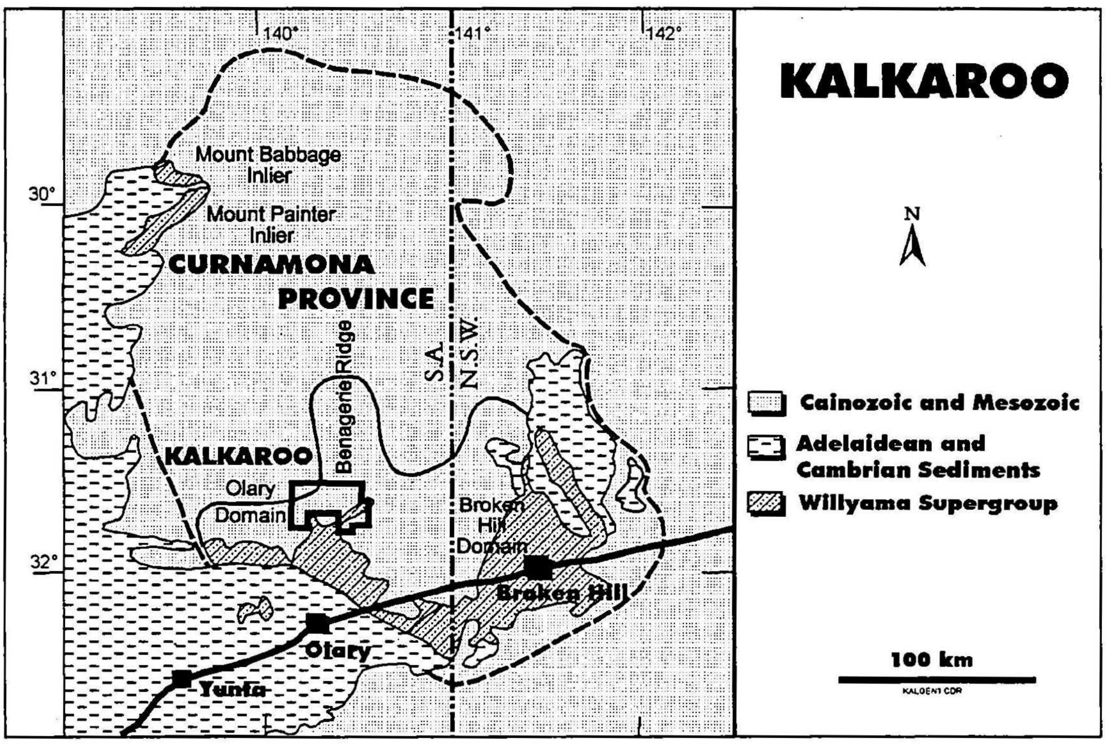
An age determination of the metasediments has been made by the WAISRC SHRIMP II consortium using isotopic analysis of zircon (U-Pb). The sample was collected adjacent to the location of samples analysed by PRISE in 1996. Analysis concluded that the youngest zircon component of the sample has an initial crystallisation age of >1200Ma, consistent with other Paleoproterozoic metasediments in the Olary Domain and interpretation from regional exploration data sets. Cambrian ages arrived at in the PRISE analysis may represent the age of one mineralising phase present at Kalkaroo.

Due to extensive cover throughout the license area, exploration activities by Newcrest have concentrated on air core drilling of magnetic targets. Subsequent follow-up entails diamond drilling with an emphasis on collecting quality oriented data. Newcrest envisages maintaining a presence in the Curamona Region given continuing exploration success at Kalkaroo and surrounding properties.

REFERENCES

Ashley et al, 1997, Geology of the Olary Domain, Curnamona Province, South Australia, MESA Report Book 97/17.

Anderson, 1996, "Kalkaroo Cu-Au Mineralisation, Northern Olary. Delamarian intrusive related?, Resources 96 Convention, Abstracts, 1-3.



REGOLITH CARBONATE ACCUMULATIONS AT BROKEN HILL: SOME ENVIRONMENTAL CONTROLS ON THEIR USE AS A GOLD EXPLORATION SAMPLING MEDIUM

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INTRODUCTION

Regolith carbonate accumulations have been successfully used as a mineral exploration sampling medium in many parts of Australia, however they are not magic! Their geochemical sampling and interpretation requires considerations of their environmental setting and relationships with particular physical and chemical dispersion pathways. As gold dispersion is controlled by local environmental factors, it is important to also recognise other related features that reflect the environmental factors influencing dispersion, such as the morphological facies, landscape setting, chemistry, mineralogy and genesis of the regolith carbonate accumulations hosting gold anomalies.

Where the technique is successful there is a close relationship between the calcium and gold contents of the regolith. This is related to the concentration of gold and diluted abundances of many other elements in regolith carbonate accumulations. Although gold is often present in some iron-rich regolith types (such as ferricretes), an increased abundance of gold in regolith carbonate accumulations corresponds to a dilution of iron relative to the surrounding regolith. Pedogenic carbonate types are preferred hosts for gold ahead of the groundwater types that often form massive, tabular, subsurface lensoidal masses along valley systems. Pedogenic carbonates therefore have the potential to be an excellent sampling medium for gold because they are widespread, easy to collect, readily identified and host gold even within transported cover.

In the Broken Hill region some exploration groups have tried regolith carbonate (calcrete) sampling programs but have had mixed success. Reported limitations include the recognition of "false anomalies", and areas of mineralisation without an overlying regolith carbonate anomaly. Further testing of this exploration technique in the region has found that it is not as straight forward as many previous trials have attempted to find. Rather than sampling "anything that is pale coloured, soft and fizzy when exposed to acid", a discriminant sampling program considering the genetic environmental setting of the regolith carbonate accumulations is required. A brief outline of some important aspects to consider in the Broken Hill region is given here, with further details outlined in Hill *et al.* (in press).

MORPHOLOGICAL FACIES

A range of regolith carbonate morphological facies occur in the Broken Hill region including: nodular, rhizomorphic, hardpan, laminated, boulder, powder, tabular-massive, and septarian accumulation types. Each of these morphological facies form under different environmental conditions and therefore reflect associations with different physical and chemical dispersion pathways. The chemical thresholds for each of these morphological facies will therefore be expected to vary. Direct comparisons of the exploration geochemical results between each of these facies will feature these fundamental genetic differences, which are often far greater than the subtle expression of mineralisation. For example, in many profiles with relatively high total gold contents, most of the gold resides in the nodular facies rather than the adjacent hardpan or powder facies.

CHEMISTRY

Although the close relationship between calcium and gold in regolith carbonate accumulations has been well documented, the close relationship with gold does not necessarily apply to other elements common in regolith carbonates. At low magnesium concentrations, magnesium abundance is broadly associated with gold abundance, largely due to the close association between calcium and magnesium in carbonate minerals. At higher magnesium contents (over 5 wt% Mg) there is a change in the nature of the relationship and magnesium becomes inversely related to gold abundance. The differences in magnesium content of the regolith carbonate accumulations reflect different environmental and chemical settings of the regolith carbonates. Carbonates with high magnesium contents are usually associated with parts of the regolith receiving inputs of saline groundwaters or solutions derived from the weathering of mafic and ultramafic rocks. It seems therefore that the retention of gold is not favoured in regolith carbonate accumulations developing from saline solutions. Regolith carbonate accumulations with higher Ca/Mg ratios are therefore a preferable sampling media for gold.

MINERALOGY

At Broken Hill the regolith carbonate accumulations mainly feature the carbonate minerals: calcite, dolomite, magnesite and ankerite, with calcite and dolomite are the most common. The preference for sampling media with high Ca/Mg ratios is reflected in a preference for accumulations where calcite is more abundant than dolomite. This mineralogical difference can be easily detected in the field as calcite has a stronger reaction with 5 mol. hydrochloric acid. Calcite is usually more abundant than dolomite in the upper parts of regolith profiles. Carbonate mineralogy is an important consideration when comparing or choosing sampling media because of its ability to reflect a series of enviromental variables such as chemistry and hydrology, that are equally important in accounting for the behaviour of gold in the regolith.

LANDSCAPE SETTING

There is a strong catenary relationship with features such as chemistry, mineralogy and morphology for regolith carbonate accumulations. The landscape setting also controls the physical and chemical dispersion pathways associated with the different facies of regolith carbonate accumulations. There is a major lateral mobilisation of many of the chemical components of regolith carbonate accumulations in the landscape. This lateral movement and subsequent accumulation in favourable landscape settings may account for many of the "false anomalies" that have been reported where a surface anomaly does not correspond to a directly underlying mineralisation source. Rather than being seen as "false anomalies" many of these features may be alternatively seen as sites where the physical and chemical dispersion pathways have not been accounted for. This highlights the importance of regolith-landform mapping and framework studies to constrain this lateral dispersion.

BIOLOGICAL CONTROLS

Regolith carbonate accumulations show evidence for major biological controls on their development. Fungal hyphae and algal filaments are seen in hand specimen or after magnification. Rhizomorphic and some nodular carbonate types related to vegetation roots are also common. Areas of abundant regolith carbonate accumulations also feature well developed, species-rich soil microorganism crusts. Typically the pedogenic types of regolith carbonates that have the greatest gold contents feature extensive evidence for biological activity. Further work is needed to test the role of microorganisms and the gold hosted in these materials. It is possible that biological controls and their sensitivity to salinity may account for the observed preferential retention of gold in regolith carbonate accumulations with high Ca/Mg and calcite/dolomite ratios.

GENETIC CONSIDERATIONS

Although pedogenic types are preferred sampling media ahead of groundwater carbonate accumulations, interpretations of the genetic significance of these materials is not always clearly identified in the field. Some groundwater carbonate types may be later exposed by erosion and then experience pedogenic modifications. Pedogenic carbonates may also receive input from groundwater systems, particularly in areas of groundwater discharge or in lower parts of the profile. Composite, polygenetic carbonate accumulations are therefore difficult to account for with a simple genetic interpretation and classification. It is not recommended that sampling media are chosen on the basis of this interpretation alone, but rather are complimented by many of the other considerations described here.

CONCLUSION

Considerable variation in the characteristics of regolith carbonate accumulations occur in the Broken Hill region. The relationships between the variations in the features of the regolith carbonate accumulations to changing environmental conditions also reflects different physical and chemical dispersion pathways. Sampling of regolith carbonate accumulations has the potential to be an important mineral exploration sampling medium in this region, however, consideration of differences in their characteristics is important if these regolith materials are to be sampled and interpreted successfully.

Acknowledgements

This research has been conducted within the Cooperative Research Centre for Landscape Evolution and Mineral Exploration, and is published with the permission of the Director. The NSW Discovery 2000 program is thanked for providing funding for part of this research. Further support and interest was provided by Rio Tinto Exploration, Pasminco Exploration, Normandy Exploration, Acacia Resources and Triako Resources.

REFERENCES

Hill, S.M., McQueen, K.G. & Foster, K. (in press). Regolith carbonates in western and central NSW: characteristics and potential as an exploration sampling medium. *Papers from Regolith 98,* CRC LEME.

RECENT ADVANCES IN THE DEVELOPMENT OF PHYSICAL AND CHEMICAL DISPERSION PATHWAY MODELS IN REGOLITH DOMINATED TERRAIN IN THE BROKEN HILL REGION

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INTRODUCTION

The Broken Hill region is famous for the detailed study of the structure, mineralisation, petrology and geochemistry of its bedrock. However, these features are mostly modified by or concealed beneath a surficial layer of weathered, transported and cemented material, the regolith. Areas where fresh bedrock crop out have been well studied and explored, but considerably less exploration and research effort has taken place in the regolith dominated terrains that extend over much of the region. The chances of undiscovered mineral deposits existing in areas with extensive regolith cover are therefore high. Exploration in the region's regolith dominated terrains by the application of traditional bedrock techniques has been difficult and costly, with limited success. Effective exploration in these areas requires a framework where regolith materials are no longer considered a concealing barrier, but instead are understood within the context of physical and chemical dispersion pathways.

CRC LEME has been involved in a project of regional regolith mapping and characterisation, as well as providing a framework to develop regional models of regolith and landscape evolution. These are essential bases to mineral exploration models that account for physical and chemical dispersion pathways in the region's regolith dominated terrains. The CRC LEME team has involved a number of research scientists and students from AGSO, ANU, CSIRO and the University of Canberra. Student involvement has included three PhD students and five honours students. These students have contributed greatly to the region's regolith-landform knowledge base while they have also been developing their own knowledge and skills as preparation for becoming professional geologists. This presentation outlines some of the advances that have been made as a part of this research program in the region.

REGOLITH MAPPING

The mapping of regolith and associated landform features in the region has so far been carried out and published on the regional scale at 1:500 000 (Gibson & Wilford, 1995; Gibson, 1996). Revised hardcopy and digital editions of these maps are currently being produced. They show broad regolith-landform units giving a valuable regional overview of the main regolith types and their associated landforms. This is of use to mineral explorers in the region wishing to place their tenements within the broad regional regolith-landform context and also giving a general outline of the major areas of bedrock or regolith dominated terrain.

More detailed, although still regional, regolith-landform mapping at 1:100 000 has also been completed (Hill, in press) over the area of the Broken Hill Block in western New South Wales and adjacent areas such as parts of the Euriowie Block. This regolith-landform map is useful for mineral explorers in delineating areas containing specific regolith types that may be used in sampling programs. Regional chemical and physical dispersion pathaways can be delineated from the map, for example from the mapping of major transported regolith types, such as palaeochannels.

At present the regolith in selected areas is being mapped for presentation at 1:25 000 scale. The maps will be detailed enough to emphasise specific regolith materials encountered at the landsurface with further subsurface information represented where available. This information is most adaptable for providing information at the exploration tenement scale, indicating the types of surface sampling materials, such as lag and duricrust types, and detailed physical and chemical dispersion pathways. The final presentation of these maps should compliment the current 1:25,000 geological sheet coverage in New South Wales. In particular they will add detail and information to the 'sea of yellow' that dominates many of these map sheets with only limited bedrock exposure. The first of these maps to be ready for publication should be the Balaclava and Redan 1:25 000 sheets.

REGOLITH STRATIGRAPHY

Previous stratigraphic interpretations of regolith materials in the Broken Hill region have usually been based on broad regional extrapolations and lithostratigraphic correlation. Recent studies have been able to provide more detail to the understanding of the regional regolith stratigraphy, and show the transported and indurated regolith types to have a complex stratigraphic framework.

Poorly cemented sedimentary units have been shown to extend back at least to the Mesozoic. Near Fowlers Gap, Gibson (1996) has used palynology to determine a Cretaceous (Albian-Aptian) age and restricted marine setting for sediments along western edge of the Bancannia Trough, and plant macrofossils to give a probable Late Jurassic-Early Cretaceous age for sediments in the large mesas near the Floods Creek-Fowlers Gap station boundary. At Sandstone Tank on Fowlers Gap Station a rainforest flora assemblage within silcreted quartzose fluvial sediments is similar to Eocene flora described from parts of the Lake Eyre Basin (Greenwood *et al.*, 1997). This flora also reflects a major Cainozoic climate change from humid, mesothermal conditions in the early Palaeogene to the present day aridity. Similar ancient quartzose fluvial sediments have been widely interpreted as being a part of the Eyre Formation along the margins of the Barrier Ranges. This now seems to be a gross oversimplification and in some cases misleading. The stratigraphy of the ancient fluvial systems on the margins of the Barrier Ranges appear instead to be of a wide range of chronological and lithological types, many of which have reworked and incised into earlier units throughout the landscape history (Hill *et al.*, 1997). Depositional extensions of the Murray Basin stratigraphy are now known to be widespread, extending onto the southern margins of the Broken Hill Block. Particularly widespread is a grey, fine silty deposit lithologically similar to the Blanchtown Clay. This is best seen in creek cuttings near Mulculca Station (Hill *et al.*, 1997; Hill & Gibson, 1997), along sections of Pine Creek. It has been intersected by shot holes along the 1996 AGSO seismic lines (G.Gibson *et al.*, 1998).

Indurated regolith types have a range of particularly complex stratigraphic settings. This has been shown to limit their use as morphostratigraphic markers, and other associations with discrete episodes of formation and associated palaeoenvironmental controls (Hill *et al.*, 1996a; b; 1997; 1998; in press). Instead regolith indurations such as silcretes, ferricretes and regolith carbonate accumulations are have formed and continue to be modified in a range of landscape settings that have evolved throughout the landscape history.

MORPHOTECTONIC FRAMEWORK

Contrary to many accounts of Australian landscape evolution, tectonic activity has been of major importance in controlling regolith and landscape evolution in the Broken Hill region. Tectonism appears to have been active throughout the history of landscape development, largely through the reactivation of ancient structures (Hill *et al.*, 1994; Hill *et al.*, 1997; Gibson, 1997). NE-trending structures, such as the Mundi Mundi Fault have been of major landscape significance since at least the Delamarian Orogeny, and during later Palaeozoic and Cainozoic reactivations (Hill & Kohn, 1998; in press). NW-trending structures are have also facilitated morphotectonic activity, particularly along the Kantappa Fault and further north in the Fowlers Gap region and near Tibooburra. The reactivation of these structures has been important in controlling the physical and chemical dispersion processes in the region, such as regolith stripping, sedimentation and groundwater movement (Hill & Kohn, in press).

DURICRUST SAMPLING MEDIA

Ferricretes, silcretes and regolith carbonates all have been shown to be valuable regolith sampling media in the region. Their value however is dependent upon the ability to account for the physical and chemical dispersion pathways related to their particular genetic environments. As morphology, field setting, chemistry and mineralogy all reflect genetic environments, all of these aspects are important considerations when interpreting and comparing regolith geochemistry. Ferricretes, particularly those rich in goethite, are important scavengers of metal trace elements. However the different ferricrete facies such as ferricreted saprolite and sediments, detrital ferricretes and slabby ferricretes all have different geochemical settings and thresholds (Hill *et al.*, 1996; 1997). The sampling of regolith carbonates, such as calcrete, has been very popular in many areas for the exploration for gold deposits. In this region however, the suitability of these materials is closely related to the carbonate mineralogy, chemistry, and landscape setting. Nodular, pedogenic types with low magnesium contents are generally give the best descrimination of gold enrichment in the regolith. Although silcretes have not been widely employed as geochemical sampling media, some promising results have been obtained from the region. Silcretes with pedogenic structures that have higher titanium (anatase) and iron contents generally have higher trace element metal contents, broadly reflecting lateral chemical dispersion pathways converging in many palaeochannel settings. Gypcretes and manganocretes are still being assessed; some early results appear promising, particularly for manganocretes possibly derived from the weathering of spessartine garnets often associated with mineralisation.

PALAEODRAINAGE RECONSTRUCTION

The regional drainage network appears to have been unstable during its evolution. This has resulted in migration of drainage divides, fluvial channel location and form. This has major implications for changes in the physical dispersion patterns in the region, particularly if palaeochannel channel systems are to be sampled (Hill *et al.*, 1997).

CONCLUSION

The landscape and regolith features of the region are the result of an interplay between bedrock lithologies, climate change, tectonics, eustacy over the history of landscape development extending back at least to at least the Mesozoic. These interactions are also responsible for driving the physical and chemical dispersion patterns that may provide the regolith expression of mineralisation.

REFERENCES

Gibson, D.L., 1996. Curnamona Regolith Landforms, 1:500 000 map scale. CRC LEME.

Gibson D.L. 1997. Recent tectonics and landscape evolution in the Broken Hill region. *AGSO Research Newsletter,* 26, 17-20.

- Gibson, D.L., 1998. Regolith and its relationship with landforms in the Broken Hill region, western NSW. *Geological Society of Australia, Special Publication* 20, 80-85.

Gibson, D.L. & Wilford, J.R., 1995. Broken Hill Regolith Landforms, 1:500 000 map scale. CRC LEME, Perth.

Gibson G.M., Drummond B., Fomin T., Owen A., Maidment D., Gibson D., Peljo M. & Wake-Dyster K. 1998. Re-evaluation of crustal structure of the Broken Hill Inlier through structural mapping and seismic profiling. *AGSO Record* 1998/11.

Greenwood, D.R., Rowlett, A.I., Alley, N.F. & Hill, S.M. 1997. Palaeobotanical evidence for the initiation of the drying of the Australian interior. *In* Price, D. & Danson, G. eds. *Quaternary Deserts and Climate Change Program and Abstracts, ICGP 349.* University of Wollongong School of Geosciences.

Hill, S.M., Eggleton, R.A. & Taylor, G.M., 1996. Duricrust inter-relationships and environmental change in the Broken Hill region, southeastern central Australia. *In* Bottrell, S.H. ed. *Fourth International Symposium on the Geochemistry of the Earth's Surface Short Papers,* 188-193.

- Hill, S.M., Eggleton, R.A. & Tayor, G.M., 1997. A regional regolith-landform framework for mineral exploration models in the Broken Hill region. *AusIMM, 1997 Annual Conference Proceedings,* 131-138.

Hill, S.M. & Gibson, D.L. 1997. Broken Hill regolith field excursion. *Broken Hill Exploration Initiative , 1997 Annual Meeting Abstracts, AGSO Record 1997/49,* 16-17.

Hill, S.M. & Kohn, B.P. 1998. Morphotectonic evolution of the Mundi Mundi Escarpment, Broken Hill. *Abstracts, Regolith 98, Kalgoorlie,* 44. CRC LEME

Hill, S.M. & Kohn, B.P. (in press). Morphotectonic evolution of the Mundi Mundi Rangefront, Broken Hill region, western NSW. *Papers from Regolith 98,* CRC LEME.

Hill, S.M., McQueen, K.G. & Foster, K. 1998. Regolith carbonates in eastern Australia: characteristics and potential as an exploration sampling medium. *Abstracts, Regolith 98, Kalgoorlie,* 11. CRC LEME.

Hill, S.M., McQueen, K.G. & Foster, K. (in press). Regolith carbonates in western and central NSW: characteristics and potential as an exploration sampling medium. *Papers from Regolith 98,* CRC LEME.

Hill, S.M., Taylor, G.M. & Eggleton, R.A. 1994. Field Guide and Notes on the regolith and landscape features of the Broken Hill region, western New South Wales. *AGSO Record 1994/57,* 39pp.

- Hill, S.M., Taylor, G.M. & Eggleton, R.A. 1996. Ferricretes of the Broken Hill region, western New South Wales, Australia: chronological and stratigraphical significance. *Revista da Universidade de Aveiro Geosciences 10,* 15-24.

Hill, S.M. (in press). Broken Hill Block 1:100,000 Regolith-Landform Map. CRC LEME.

Kohn, B.P., O'Sullivan, P.B., Mitchell, M., Gleadow, A.J.W. & Hill, S.M. 1998. Phanerozoic thermotectonic history of the southwestern Tasman Line – Willyama Inliers region. Mineral Systems of the Crust - Upper Mantle of Southeast Australia, AGSO Record *1998/2,* 111-114.

Pb-Zn-Ag MINERAL SYSTEMS: AN EXAMPLE FROM BROKEN HILL

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INTRODUCTION

The Broken Hill deposit is the largest known accumulation of Pb in the world. This fact and the complex geological history of this deposit has meant that its origin has been controversial since its discovery in 1883. Ideas on the genesis of the Broken Hill orebodies have oscillated between epigenetic and syngenetic models. Concepts involving hydrothermal replacement of favourable horizons (e.g. Gustafson et al., 1950) held sway up until the mid-1950s when King and Thomson (1953) first suggested that the Broken Hill orebody formed syngenetically. This syngenetic model was generally accepted by 1970, and, although challenged by the "inhalative" model of Haydon and McConachy (1987), was the "accepted wisdom" until the early 1990s, when epigenetic models were again advocated. At present, the origin of the Broken Hill deposit is again controversial, with one camp advocating an early, syngenetic origin (e.g. Parr and Plimer, 1993; Stevens, this volume) and an opposing camp advocating a late, syn-tectonic origin with a strong structural control (e.g. Ehlers et al., 1996).
Burton (this volume) has reviewed the main genetic models for the formation of the Broken Hill deposit. In this paper we present mineral system analysis of the three genetic models we consider most plausible: (1) a syn-genetic, volcanic-related model, (2) a pre-tectonic carbonate-replacement model, and (3) a syn-tectonic carbonate-replacement model. *The intent is not to assess these models critically, but rather to discuss the implications of these genetic models to empirical exploration models for Broken Hill-type (BHT) deposits.*

THE EMPIRICAL APPROACH TO EXPLORATION AND MINERAL SYSTEMS

One of the most significant Australian discoveries of the 1990s, the Cannington deposit, was found using an empirical exploration model based mainly on Broken Hill (Skrzeczynski, 1993). However, empirical exploration models have potential limitations. For instance, these models may incorporate "red herrings"—coincidental criteria unrelated to ore forming processes. Moreover, by the nature of their construction, empirical models find deposits that most closely conform to the deposit(s) upon which they are based: the more the unknown differs from the known, the less the chance of discovery.

The role of genetic models in exploration should be to refine empirical models by filtering out "red herrings" and by incorporating mineralising processes into the models. An effective way of incorporating these considerations into empirical models is by considering ore deposits as part of a larger "mineral system", which Wyborn et al (1994) defined as "all geological factors that control the generation and preservation of mineral deposits". Mineral system analysis is a data-driven approach in which empirical observations on ore deposits and their environments are assessed in terms of mineralising processes to determine "essential ingredients" that define "mappable criteria" for incorporation into quasi-empirical exploration models.

THE SOURCE AND COMPOSITION OF BROKEN HILL ORE FLUIDS

Ore fluids are the most fundamental component of a mineral system. Their compositions are defined largely by their source, and these compositions, in turn largely determine the characteristics of effective trap sites. Despite the complex geologic history of the Broken Hill area, limits can be placed upon the source and composition of Broken Hill ore fluids that are largely independent of the assumed genetic model.

The source of the ore fluid components. Homogeneous $\delta^{34}S$ in the range of 0±5‰ (Parr and Plimer, 1993) imply that Broken Hill sulphur was derived from one of three sources: (1) inorganically reduced Proterozoic seawater sulphate, (2) magmatic-hydrothermal sulphur, or (3) sulphur leached from volcanic rocks. The latter two sources are also consistent with a mantle input (c.f. Parr and Plimer, 1993). Carbon isotope values of ore-related carbonates are more definitive. Consistent $\delta^{13}C$ values of -20 to -22‰ (Dong et al., 1987, Stevens, unpub. data) are definitive of oxidised organic carbon. Existing isotopic data do not allow the origin of water or chloride in the hydrothermal fluid to be established.

Lead isotopes, like sulphur isotopes, are consistent with, but not definitive of, a significant component of mantle lead in the ores (Carr and Sun, 1996). Alternatively, the lead isotope results could indicate a more juvenile crustal source region than other Australian Proterozoic terranes. Regionally, many units in the Broken Hill region have elevated Zn and Pb values relative to average crustal abundances. The only rocks which appear to be leached of base metals are albite-rich rocks in the Lady Brassey and Himalaya Formations. These rocks typically contain less than 10 ppm Cu, Pb and Zn, making them a potential source rock for the Broken Hill orebody (see below). These rocks also have high Fe_2O_3/FeO ratios, which is consistent with a high temperature reaction zone in which seawater sulphate is reduced to hydrothermal sulphide by the oxidation of ferrous iron.

Fluid conditions. Low Fe_2O_3/FeO ratios in the host rocks to the Broken Hill orebody require ore fluids to have been reduced (i.e. $\Sigma H_2S >> \Sigma SO_4$). Based on metamorphic conditions, the ore fluid temperatures must have approached 700°C for a syn-tectonic model (Ehlers et al., 1996). On the other hand, by analogy to other reduced Pb-Zn-Ag deposits, a fluid temperature of 200-400°C is likely for either the early syn-genetic or carbonate-replacement models. Similarly, the fluid pH is likely to have been moderately acidic. Other fluid parameters, such as salinity and $[H_2S]$, cannot be constrained due to the complex history of the Broken Hill Block.

A COMPARISON OF BROKEN HILL MINERAL SYSTEM MODELS AND IMPLICATIONS FOR EMPIRICAL EXPLORATION CRITERIA

In addition to a source of the ore fluid components, a mineral system also includes four other major parts: (1) an energy source, (2) migration pathways, (3) the trap site, and (4) the effluent zone. The following section discusses these parts of the mineral system in terms of the empirical characteristics of BHT deposits presented in Table 1.

Energy source. The relatively high temperatures (>200°C) required by all genetic models indicates that coeval magmatism, elevated geothermal gradients or metamorphism in an essential ingredient to the Broken Hill mineral system (Table 1). Major periods of felsic magmatism occurred in the Broken Hill Block at 1680-1690 Ma (sub-volcanic granitoids sourcing felsic volcanics in the Broken Hill Group) and 1570-1600 Ma (granitoids that occur mainly in the Olary Block; Nutman and Ehlers, 1998). Mafic magmatism also occurred at 1680-1690 Ma. For a syngenetic model, volcanism and subvolcanic magmatism is an essential ingredient of the mineral system; an association of ores with the culmination of magmatic activity, as indicated by a shift from volcanic-dominant to sediment-dominant sequences, is also a desirable characteristic. For an early carbonate replacement model, pre-tectonic (e.g.

1680-1690 Ma) granitoid suites are an essential ingredient; and for a syn-tectonic model, metamorphism (e.g. 1570-1600 Ma) is an essential ingredient.

Migration pathway. For a syn-tectonic mineral system, structural conduits, such as high grade shear zones that focus ore fluids from their source into trap sites, are an essential ingredient of the mineral system. However, for early models, high grade, syn-tectonic shear zones are "red herrings". Rather, early structures, such as syn-sedimentary faults, or permeable stratigraphic units, are desirable ingredients. As early structures can be difficult to define in high grade metamorphic terranes, sedimentological facies or unit thickness changes, which indirectly indicate early structures, are desirable characteristics for mineral system models assuming an early timing of mineralisation, particularly the syngenetic model.

Table 1. Characteristics of the Broken Hill orebodies and their importance in context of mineral system-based models of Broken Hill-type deposits.

Characteristic	Syn-genetic, volcanic-related	Pre-tectonic carbonate replacement	Syn-tectonic carbonate replacement
Regional- and local-scale BHP criteria (summarised from Walters, 1998)			
Most common in lower-middle ensialic(?) Proterozoic mobile belts	Unknown	Unknown	Unknown
Regional progression from quartzo-feldspathic/acid volcanic dominant lower sequences to psammopelitic upper sequences	Desirable	Nil	Nil
Association with "Exhalites" (BIF, chert, quartz-gahnite rock and toumalinite) ± carbonates in oxidised stratigraphic settings, particularly at transition from quartzo-feldspathic to fine-grained clastic rocks.	Desirable	Nil	Nil
Widespread Pb-Zn anomalism and numerous small shows	Desirable	Desirable	Desirable
Rich diversity of other styles of mineralisation	Unknown	Unknown	Unknown
Association with skarn-like mineral assemblage	Variable	Essential	Essential
Association with Mn, P and F anomalism	Unknown	Desirable	Desirable
High grade metamorphism	Nil	Nil	Essential
Association with polyphase folding	Desirable	Desirable	Desirable
Other criteria			
Stratiform occurrence	Essential	Desirable	Desirable
Association with carbonate	Nil	Essential	Essential
Association with high grade mylonite zones	Nil	Nil	Essential
Association with early structures (if recognisable)	Desirable	Desirable	Nil
Association with sedimentary/volcanic facies changes	Desirable	Nil	Nil
Evidence of coeval magmatism or elevated geothermal gradient	Essential	Essential	Essential

Trap site and effluent zone. For the moderate to high temperature ore fluids that formed Broken Hill, the most effective traps are temperature drops caused by mixing with cold fluids such as seawater, or pH neutralisation caused by interaction with rocks such as carbonate. As mineralisation occurs by mixing with seawater at or near the seafloor in syngenetic deposits, a stratiform occurrence of the ores is an essential ingredient for a syngenetic model. If the mineral system model involves the replacement of stratiform carbonate, a stratabound occurrence to the ores is a desirable ingredient, and an association with skarn-like mineral assemblages is an essential ingredient. Manganese-rich minerals and fluorite are common gangue minerals in Zn skarns (Einaudi et al., 1981) and in sedimentary manganese deposits.
Although syngenetic alteration assemblages may recrystallise under high grade metamorphism to form skarn-like assemblages, these assemblages are not essential for a syngenetic mineral system model, particularly if high grade metamorphism did not occur. The association with regional "exhalative" rocks is desirable for syngenetic models as these rocks are products of the spent ore fluid after ore deposition. However, these rocks are a red herring for early or syn-tectonic carbonate replacement mineral system models.

Post-depositional modification. Although folding is not an essential component of a pre-tectonic mineral system that has produced an accumulation of metals, it may be an important factor in upgrading a metal accumulation into an economic ore deposit. Hence, polyphase folding, which may concentrate sulphide accumulations into fold noses or possibly shear zones, is a desirable ingredient in even pre-tectonic mineral system models.

Mineral system size. The final characteristic of a mineral system with exploration implications is its size. Many world class base metal districts are characterised by a single giant deposit surrounded by many much smaller deposits. Examples of such districts include BHT deposits at Broken Hill, Sullivan and Cannington. The size of individual mineral systems may, in part, account for this distribution. Figure 1 illustrates the relationship between the size of a deposit and the size of the associated mineral system using Pb mass balance constraints. It suggests that giant deposits such as Broken Hill require large mineral systems to supply sufficient Pb. Given the constraints used to construct Figure 1 and assuming a 10% extraction efficiency, the size of the Broken Hill mineral system is on the order of 8000 km^3; if a depth of 7 km is assumed for the mineral system, this translates into a surface area in excess of 1000 km^2, or a square over 30 km on a side. The potential size of base metal depletion zones in albite-rich rocks from the Lady Brassey and Himalaya Formations are consistent with these calculations.

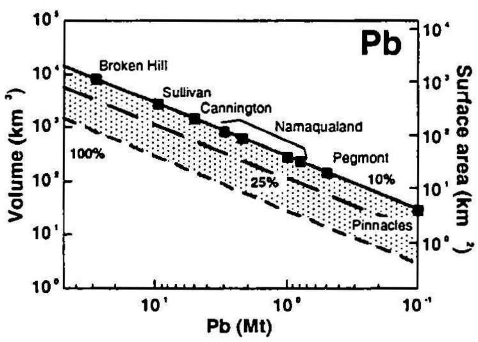

Figure 1. The estimated size of BHT mineral systems based on the contained Pb in selected BHT deposits. The calculations were done assuming a global abundance of Pb (12.5 ppm) and a rock density of 2.8 t/m^3. Curves for 100%, 25% and 10% extraction efficiencies are shown. The sizes of BHT mineral systems are based on a 10% extraction efficiency.

CONCLUSIONS

Analysis of three plausible genetic models for the Broken Hill deposit suggests that empirical exploration models can be refined from an understanding of geologic processes that occur in mineral systems. Suprisingly, many essential and desirable ingredients determined assuming epigenetic (e.g. carbonate replacement) and syngenetic models overlap. For instance, in both instances, the mineralisation should be stratiform and associated with structures. However, major differences between the models exist regarding the significance of high grade shear zones and sedimentary facies changes. Model-independent mass balance calculations indicate that large base metal accumulations such as at Broken Hill require large mineral systems.

REFERENCES

Burton, G.R. this volume.
Carr, G.R. & Sun, S.S. 1996. CODES Spec. Pub. 1, 77-87.
Dong, Y.B., et al. 1987. Trans. Inst Min. Metall. 96, B15-B30.
Ehlers, K., et al. 1996. Geol. Soc. Austr. Abstracts 41, 127.
Einaudi, M.T., et al. 1981. Econ. Geol. 75th Anniv. Vol., 317-391.
Gustafson, J.K., et al. 1950. Geol. Soc. Am. Bull. 61, 1369-1437.
Haydon, R.C. & McConachy, G.W. 1987. Econ. Geol. 82, 826-856.
King, H.F. & Thomson, B.P. 1953. Geology of Australian Ore Deposits, 578-600.
Nutman, A.P. & Ehlers, K. 1998. Precamb. Res. 90, 203-238.

Parr, J.M. & Plimer, I.R. 1993. Geol. Assoc. Canada Spec. Pap. 40, 253-288.
Skrzeczynski, R.H. 1993. AIG Bull. 13, 35-38.
Stevens, B.J. this volume
Walters, S. 1998. CODES Short Course Manual 5, 1.47-1.102.
Wyborn, L.A.I., et al. 1994. Proc. Austr. Inst. Min. Metall. Ann. Conference, 109-115.

HYDROGEOLOGY AND HYDROGEOCHEMISTRY AS AN EXPLORATION TOOL IN THE BROKEN HILL AND SURROUNDING AREA

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As part of the Basins Program of CRC LEME, a hydrogeological/hydrogeochemical component aims to complement other CRC LEME activities, to provide the minerals industry with improved methodologies for exploration in areas covered by thin sediment and regolith cover (generally, <300 m). The Basins Program applies a multi-disciplinary investigative approach to areas where sedimentary sequences onlap onto basement lithologies of high mineral potential, as well as where the concealed basement rocks are believed to be barren. When combined with detailed regolith and sediment characterisation, hydrogeological and hydrogeochemical techniques represent a powerful investigative vector tool for pre-existing, but yet to be explored mineral deposits and the potential to predict the formation and location of authigenic mineralisation. Integrated approaches to understanding dissolved ion chemistry and operative water-rock interactive processes that constrain their behaviour may lead to the development of hydrogeochemical models that may be used by the mineral industry.

The development of a successful hydrogeochemical model relies heavily on the careful integration of chemical data with hydraulic and geological data. Following the development of conceptual hydrogeological flow models, quality groundwater-sampling strategies specifically target representative groundwater from unconsolidated aquifers within regolith, and consolidated and fractured aquifers within sediment and bedrock. Through an analytical program that targets a wide range of general parameters (Dissolved Oxygen, Redox Potential (Eh), pH, electrical conductivity (EC), major elements, numerous trace elements (including specific pathfinder elements) and stable isotopes (Deuterium, Oxygen-18, Carbon-13, Sulphur-34), broad based hydrogeochemical characteristics will be established.

Initial characterisation will utilise a range of univariate, bivariate and multivariate statistical techniques that best define the parameters for synthesis and modelling. Modelling will specifically target a range of hydrogeochemical scenarios, including the evolution of background and anomalous hydrogeochemistry. In all cases, model interpretation will integrate real world data gathered from the complimentary regolith and sediment studies. Significant deliverables include integrated hydrogeochemical models and hydrogeochemical maps that provide the mineral industry with a regional scale tool for exploration prospectively. These may be used to enhance and consolidate existing exploration techniques.

The Broken Hill Block and surrounding Olary Block and Curnamona Province provide excellent territory to undertake such studies. Following the failure to find other significant mineral deposits of the size of the Broken Hill Ag-Pb-Zn deposit, attention is turning to the sediment-covered margins of the block and the surrounding area. Recently, exploration interest in the margins of the Broken Hill Block, Olary Block and Curnamona Province has risen. The regional nature of the hydrogeological/hydrogeochemical investigative tool and the large area of exploration acreage in this area to be explored, provide an excellent basis for collaborative research between CRC-LEME and the areas exploration licence holders.

SOLID GEOLOGY INTERPRETATION & EXPLORATION POTENTIAL OF COVERED AREAS NORTH OF OLARY, SA

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Solid geology interpretation of five 1:100 000 map sheets covers an almost totally concealed area of approx 13 000 sq km containing prospective Palaeoproterozoic and Mesoproterozoic basement in the Curnamona Craton. Interpretation is based on geological data from 550 drill holes to basement plus open file and published reports integrated with a detailed analysis of recent BHEI aeromagnetics surveys.

A broad stratigraphic / structural and lithological interpretation of prospective covered Willyama Supergroup and the Mesoproterozoic Benagerie Volcanics has been produced over the Kalabity, Benagerie, Lake Charles, Coonarbine and Thurlooka Sheets and this is complimentary to the Mulyungarie Sheet reported on earlier by Leyh (1997).

Structural interpretation indicates regionally dominant NW to NNW and locally N trending faults. The Benagerie Ridge is most clearly defined along its shallower eastern margin by major N and NW trending faults, including the Yalkapo Fault, traceable in excess of 100km. Traversing the Benagerie Ridge in the north are the NW trending Lake Gomarla and Coonarbine Faults which appear to be major boundary faults on the Coonarbine Trough, a suspected graben zone of inferred down-faulted Neoproterozoic rocks. Other major NW to NNW faults on the Benagerie Ridge are the Benagerie, Mannings, Emu Dam and Billeroo Creek Faults which may correspond to a continuation of the Mooleulooloo Fault Corridor. The N trending M 10 Fault is another major, but regionally unique structure traceable for more than 60km which appears to have locallized basaltic intrusion and volcanics on the Benagerie and Coonarbine Sheets. Several large circular structures of possible sub-volcanic or granitoid origin occur central to the Benagerie Sheet and these coincide with an area of volcanic complexity cut by the E-W trending Lake Tinko and Mercer Dam Faults. Sharply defined circular aeromagnetic lows outline generally magnetite deficient Hiltaba Suite 1590 Ma or younger granitoids at Triangle Hill and North Mannings Dam on the Kalabity Sheet. The latter occurs in the Mooleulooloo Fault Corridor.

Numerous major complexly refolded F1-3 fold interference structures are outlined under cover by the Upper Albite (Lwt) to Bimba (Lwbmb) contact. These occur mainly on the Kalabity Sheet but extend north onto the Benagerie and Lake Charles Sheets and include the Benagerie Antiform which is associated with at least a dozen recently discovered significant gold and base-metal prospects. Complexly deformed F1 axes are interpreted in many areas and suspected F2-3 axes trend mainly N to NE. Other major structures occur, including the highly attenuated near isoclinal Cartspring Antiform outlined by Lwt / Lwb prospective rocks south of Mercers Dam Prospect and the major regional north plunging Mulyungarie Antiform; this is traceable under deep Cambrian and Adelaidean cover for an additional 30km beyond the Mulyungarie Sheet onto the Lake Charles Sheet west of the SA / NSW border.

Stratigraphic interpretation has succeeded in outlining a total 920km of prospective possible Bimba and adjacent units mostly concealed by relatively shallow cover on the Kalabity, Mulyungarie, Benagerie and Lake Charles Sheets. This total does not include any infolded thin

Bimba (Lwbmb) or Broken Hill Group (Lwb) rocks which may be present internally to some of the complexly deformed strongly magnetic Thackaringa Group (Lwt) terrain. Strong exploration potential exists for stratiform to stratabound and replacement styles of base-metal and gold mineralization in numerous untested areas on the Kalabity, Benagerie and Lake Charles Sheets. An estimated 780km strike length of complexly folded Lwt / Lwbmb / Lwb and lower Lws-p is thought to be present on these sheets. The most obvious potential relates to the Bimba Unit which is known to contain regionally extensive Cu Zn Pb Ag +/- Co Au W mineralization and the immediately underlying strongly magnetic Upper Albite Unit often associated with Cu Au +/- (Ag Mo Co) mineralization.

Indications exist for Cloncurry style haematite alteration metasomatic replacement processes of magnetite rich rocks in association with mineralization at some prospects including Benagerie and Mercers Dam as well as in hole BWMIA-1 further west on the Benagerie Ridge.

Additional exploration potential relates to possible volcanogenic massive sulphides in association with rhyolite / andesite contacts or Roxby Downs Style Cu U Au Ag deposits in so far undiscovered sub-volcanic iron rich, magnetite, hydrothermal-haematite replaced breccia complexes. These may occur in association with a wide range of variably magnetic, probably complex volcanics and intrusives present on the Benagerie Ridge.

Regionally extensive suites of porphyritic to rhyodacitic, basaltic-andesitic-(dacite) +/- magnetic adamellite exist. Interpreted rhyolitic-dacitic-trachytic tuffs breccias and lavas or 'laminated feldsparites' have been intersected in only a few holes. Several of these contain significantly anomalous Cu Zn Pb Ag As Au F in association with pyritic mineralization, magnetite rich rocks and alteration in both basic and acidic volcanics. Solid geology interpretation suggests the various volcanics are widespread on the Benagerie Ridge, on map sheets covered by the project area and further north.

The area covered by the solid geology interpretation is considered highly prospective for a range of possible base metal +/- Au deposits particularly in shallower thinly covered Palaeoproterozoic Willyama Complex in the south and to a lesser extent within accessible areas of shallow to moderately deeply covered Mesoproterozoic; the latter contains a wide range of basic to acidic volcanics and intrusives further north on the Benagerie Ridge.

Whilst large shallow massive lead rich orebodies may have been eliminated, with some reliability, to depths of 200 - 300m below surface by using electrical geophysical methods in the nearby outcropping blocks at many prospects, the same is not necessarily true for massive zinc rich ores. Neither type of body, lead or zinc rich have been eliminated from the majority of the vast soil covered terrain belonging to the Curnamona Province.

The likelihood of a world class mineral deposit being discovered, in the near future, on the Curnamona Craton, is extremely high. This is exemplified by the identification of numerous encouraging and often only partly explored, but at the same time very high quality prospects. These prospects have been discovered by different companies with diverse interests over the last 10 - 15 years. Many of them have only been partially drilled under the soil blanketed areas west and northwest of Broken Hill. Platsearch's Thunderdome Prospect on the Mundi Mundi Plains contains abundant mineralized BIF and spessartine garnet quartzite and represents a classical Broken Hill type lode sequence only rarely found outside the immediate environment of the Broken Hill orebody. Information to date strongly suggests that several holes into this aeromagnetic anomaly have intersected a proximal-to-ore host rock package. Elsewhere on the craton major prospect diamond drilling has focussed on one or more of the immediately adjacent stratigraphic layers from prospect to prospect very much depending on obvious indications from available, usually poor outcrop, geophysics or early rotary drill traverses.

The Benagerie Prospects occur in different adjacent stratigraphic positions in a complexly folded and faulted structure. The structure is clearly outlined under soil cover by the magnetics and gravity data. It is interesting to note that exploration drilling in the 1980's on the same Benagerie Magnetic Complex by Marathon, Pan Aust and Billiton already had encouraging intersections of Cu Au and indications of Zn Ag Pb plus anomalous As, Mo, Co hosted by altered rocks in several of the early holes. From 1991 onwards, Pasminco in a joint venture with Werrie Gold, commenced a series of drilling programs on the same magnetic complex but exploration was mainly for a Pb Ag Zn deposit to replace dwindling reserves at Broken Hill. Their regional drilling programs discovered the Au and Cu Au prospects at Portia and North Portia. Exploration now appears to have turned the full circle, according to recently released published results. The drilling reveals numerous prospects with very encouraging Pb Ag Zn, strong geochemical indications of Mo plus some additional potential for roll front sedimentary uranium in overlying Tertiary steam channels. The latter was the original exploration play in this region during the 60's and 70's. What this demonstrates is that persistent drilling is paying off within the regionally extensive mineralized units traceable under cover on the Curnamona Craton.

At least a dozen such prospects have been more intensively explored since persistent multimillion dollar exploration programmes have moved into the vast tracts of previously under-explored soil cover concealing the majority of the craton. Major regional prospects include Polygonum Pb Ag Zn, Grid 4 / Ardeetoo Cu Au, Thunderdome Pb Ag Zn on the Mundi Mundi Plains in NSW and Kalabity-Telechie Cu Zn (Pb Ag), Hunters Dam Zn Pb Ag, Meningie Well Zn Cu, White Dam Cu Au, Kalkaroo Cu Au, plus the Benagerie Prospects Cu Au, Pb Zn Ag in SA.

Some of these prospects have only been subjected to first pass exploration drilling with widely spaced diamond drill holes but nevertheless with encouraging results. Many more shallow rotary holes have intersected strong mineralization over very substantial widths and in anomalous zones persisting in some cases for tens of kilometres. These prospects are mostly broadly stratigraphically controlled within the Willyama Supergroup and together with Broken Hill may constitute a much wider spectrum of Broken Hill styles. The stratigraphy was originally defined by the Geological Survey of NSW following high quality lithologically consistent regional mapping in the Broken Hill Block. In the Olary Block the geological interpretation has been complimented by mapping through MESA and numerous past graduate research studies conducted by the Universities of New England and Melbourne.

Mineralization styles on the Curnamona Craton have evolved throughout deposition, diagenesis, pro and retrograde metamorphism, complex multistage deformation and accompanying intermittent acid to basic intrusive events. Mineralization in the Willyama Supergroup is most closely associated with specific iron formations or unusually iron rich metasediments, a range of suspected chemical sediments, calcsilicates, amphibolites and certain quartzofeldspathic gneisses. It is often found in associated metasedimentary sequences. Mineralization is recognised in a wide range of variably magnetic hosts, and more specific lode rock packages associated with a corresponding wide range of alteration features. However, many styles of mineralization appear fundamentally related and appear originally stratigraphically controlled because of links established through the empirically derived iron formation / chemical sedimentary model. In addition there is a demonstrable stratigraphic control on regional zoning ranging from Cu +/- Co +/- Mo +/- Au at the base to Pb +.- Ag +/- Zn +/- W +/- Sn towards the top of the Willyama Supergroup. Most of the major prospects listed above are either stratiform or stratabound. The recent study peels back the cover and provides explorers with a first pass 'solid geology' interpretation of the region north of Olary. The interpretation reveals the presence of more than 1000km of strike length for the most prospective rock sequence containing numerous prospects with similar styles of mineralization. There is little doubt that a very large, multiply mineralized metallogenic system was operative for a long period of geological time in this craton. It is the type of system which can harbour several world class deposits and is obviously not just present close to Broken Hill.

Stratigraphically controlled zones potentially host numerous and possibly adjacent stacked zones of Cu Au and Pb Ag Zn mineralization under the vast soil cover of the region. The widespread nature of the zones is defined by a distinctive magnetic contact traceable using the BHEI aeromagnetics. Their enormous potential is confirmed by the frequent presence of the highly prospective Cu Zn Pb Ag W mineralized BIMBA horizon which is as yet only partially drilled at many of the major prospects by past explorers. Straddling the BIMBA horizon is a lower often strongly magnetic Cu Au +/- Ag Mo Co bearing unit called the Upper Albite (Himalaya Fm) plus a higher Pb Ag Zn bearing unit called the Lower Pelite Suite. The latter is a probable Upper Broken Hill Group equivalent and constitutes an attractive target zone for classical Broken Hill (or Cannington type) deposits.

Metallogenic observations and prospect drilling show that potential exists for discovery of a much wider range of commodities and styles of mineralization than that found at Broken Hill. Numerous exploration models can be employed on the craton, the main categories include (1) stratiform and stratabound iron formation and metasomatic breccia associated Cu Au (Osborne / Selwyn / Ernest Henry or 'Cloncurry' styles). (2) stratiform and stratabound iron formation and calcsilicate associated 'sedex' Pb Ag Zn +/- Cu (Broken Hill, Cannington Styles etc). (3) stratiform and stratabound sediment hosted Pb Ag Zn (McArthur River, Mt Isa styles) and (4) granite breccia-complex associated Cu U Au Ag REE (Roxby Downs Style).

DISCOVERY OF THE WHITE DAM Au-Cu MINERALISATION

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The White Dam gold-copper prospect is located approximately 25km northeast of Olary township within the South Australian portion of the Proterozoic Curnamona Craton. The deposit has no historical precursor and was gradually discovered under thin cover by conventional geochemistry and drilling during 1989 to 1997.

TARGET MODEL

The widespread minor occurrences of uranium, zinc-lead and copper in the semi-exposed "Olary Block" attracted persistent exploration during the seventies and eighties. The primary target models were sedimentary uranium in Tertiary channels draining the Block and base metals within the sulphidic Bimba Unit that is broadly correlated with the stratigraphic package at Broken Hill. Aberfoyle Resources Limited initially explored the Drew Hill area for "Bimba" zinc-lead targets with the primary search tools of gossan search, mapping and ground EM.

Aberfoyle was joined by Normandy Mining Limited in 1988 to continue the base metal search with an additional focus on gold exploration. Drilling at the Mary Mine prospect demonstrated potential for ore-grade Au-Cu mineralisation associated with silica-magnetite units. A working model was developed based on the Kilo-Moto deposits in central Africa where silica-magnetite, albitite and carbonaceous schists, similar to the Olarian lithologies, reportedly hosted hardrock production of about 7 million tonnes averaging 20g/t gold.

RECONNAISSANCE PROGRAM

An airborne magnetic survey and a reconnaissance soil survey were undertaken in 1989 to initiate exploration of the 300 sq km area of poor outcrop on the western margin of the Mundi Mundi Plain. The geochemical survey concentrated on gold as a pathfinder to Bimba base metal sulphides as well as hydrothermal gold-copper targets. An orientation soil survey at Mary Mine determined the best sampling procedure was aqua regia digest/carbon rod finish (DL 1ppb Au) on the minus 200 micron fraction of 3kg field samples. Using airphotos for location control, the samples were collected on a 1km grid with local adjustments to achieve optimal base-of-slope sites.

The geochemical results peaked at 53pbb Au with a statistical threshold at 15ppb. Two contiguous results of 14 and 19 ppb Au induced follow-up sampling at White Dam on a nominal 400m x 400m pattern. This delineated a 1.5km x 2km anomalous area with an 84ppb Au peak. However, rock chip sampling of scarce outcrop reported a maximum of only 0.3g/t Au from malachite-stained ferruginous gneiss in the northern part of the area. As a supporting magnetic anomaly was adjacent but insufficiently coincident, follow-up was postponed in lieu of targets with better surface indications and conducive to EM definition.

TARGET DEFINITION

During 1994-5, MIM Exploration Pty Ltd recognised the regional potential for gold-copper mineralisation associated with Cloncurry-style alteration in well-exposed prospects south of

the Drew Hill area. An agreement was reached for MIM to enter and manage the Drew Hill JV.
Initial work targeted magnetic anomalies and White Dam, where grid-based -80 mesh soil sampling at 100m line spacing outlined a coherent northeast striking gold-copper anomaly of dimensions 800m x 100m. Values have an asymmetric distribution with the 500ppb Au peak at the western end adjoining a sheet drainage system. The prior 84ppb reconnaissance peak proved to be a small outlier, adjacent to and west of the main zone, and was repeated by a 48ppb grid sample.

DRILL TESTING
During December 1996, five RC percussion holes were drilled on two sections across the defined soil anomaly. The first and most southwesterly hole, WD1, reported 46m @ 1.18g/t Au and 0.18%Cu from 2m (later amended by fire assay to 44m @ 1.21g/t Au from 4m). None of the other holes reported over 1g/t Au.

The catastrophic floods in the following February delayed follow-up drilling until May 1997. Six RC percussion holes tested the strike extensions to WD1. One hundred metres to the west, hole WD14 intersected 42m @ 3.22g/t Au and 0.23%Cu from 4m (later adjusted to 42m @ 2.8g/t Au from 4m). Two other holes reported anomalous intersections.

Further RC percussion and HQ core drilling continued to evaluate areas away from the surface soil anomaly, intersecting both oxide and sulphide gold mineralisation. This drilling confirmed a substantial body of stratabound gold-copper mineralisation within banded biotite-rich leucocratic gneiss. Hole WD71, about 300m west of hole WD1, averages 72m @ 2.61g/t Au and 0.37% Cu from 14m, including 14m @ 7.19g/t Au from 65m.

TACTICAL REVIEW
The White Dam deposit was discovered by drilling a conventional soil anomaly. However, the soil geochemistry does not delineate the main body of mineralisation but is coincident with the weakly mineralised tail that subcrops on the gentle slope to unmineralised albitite outcrop of a few metres relief. A drill sump uncovered malachite-stained quartz assaying 4g/t Au under a few centimetres of soil within the anomalous area. Elsewhere, as little cover as one metre of aeolian or alluvial sand masks significant bedrock mineralisation to conventional geochemistry. The best mineralisation was eventually established to be under and west of the site of the 84ppb outlier. This outlier has a bedrock connection with a mineralised pinnacle such that it would have reported less than 1ppb Au if collected 25m in any direction.
Despite the fragility of the detailed geochemical signature at White Dam due to the varying cover conditions, the reconnaissance sampling had delineated a broad area of distinctly anomalous if low-magnitude results that induced follow-up and drilling.

Considering the high peak amplitude of the detailed soil anomaly at White Dam and unworked veins containing up to one ounce gold exposed elsewhere in the Olary Block, it is interesting to reflect on the geomorphologic and prospecting histories of the region. Why does White Dam not have a better dispersion signature?

White Dam remains a prospect, albeit with considerable surrounding exploration potential. Geochemical surveying and drilling continues. Although the known mineralisation has no magnetic component, very detailed magnetics continues to be a key tool for prospecting and establishing the structural environment.

The association of gold with chalcopyrite, molybdenite and pyrite in stockworks and the regional alignment of deposits indicate a common origin with the Kalkaroo and Portia discoveries. However differences are evident in the gold-copper ratio, host lithology, stratigraphic position and local structural setting.

STRATEGIC LESSONS

The White Dam discovery highlights: -

Persistence is warranted with mineralised terranes and broad anomalies particularly where new target models are evolving. Continuing project familiarity is an important factor. Initially modest drill results require a review of the target signature and environment as well as the prospect model.

Models are tools that require reworking and integration with other data in creating opportunities. There should be continual iteration between empirical target information and genetic models. Anomalies are not to be ignored at the expense of less robust concepts if explorers are convinced they are "at the right address".

The exploration industry continues to be too reliant on historical lead-ins and magnetic signatures for target selection. Geochemistry still has a substantial role to play in Australian exploration particularly as a lead-in within thinly covered terrains. However careful and smart applications are required as many opportunities will have escaped the reconnaissance net.

Acknowledgments

MIM Exploration Pty Limited acknowledges the contribution of many employees, past and present, of MIM, Aberfoyle and Normandy in achieving the above results. Steve Toteff and Peter Binks receive particular recognition for their inimitable efforts in advancing Curnamona exploration. Aberfoyle Resources Limited and Normandy Mining Limited participated in the preparation of this abstract.

POTOSI-STYLE GEOLOGY AND MINERALISATION - ALTERNATIVE EXPLORATION TARGETS WITHIN THE BROKEN HILL BLOCK

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DISCOVERY

After the discovery of the Broken Hill orebody in 1883, intense exploration activity continued along the line of lode. Several old workings were found as outcropping gossans to the NE of the major body. At Round Hill, Silver Peak, Silver Hill (also known as Copper Blow) and Potosi mines, an estimated 4000t of hand sorted, high grade lead-rich ore was recovered before activity ceased around 1930. Subsequent periodic exploration in the area intersected several significant high grade lead-zinc lodes until the open cut potential of the Potosi mineralisation was recognised in 1990.

From late 1989, Pasminco Mine Lease Geologists targeted possible extensions to old workings. Significant drilling results followed by a favourable mise-a-la-masse (MALM) response reinforced near-surface mineralisation potential. Follow-up diamond drilling between 1992 and May 1994 identified an estimated 1.0Mt open cut Inferred Resource to a depth of 200m (Pasminco Mining, unpublished data, 1993). This deposit is currently being mined as Pasminco Broken Hill Mine's Potosi Open Cut.

The exploration history and mineralisation of the Potosi deposit has been described in Morland and Leevers (1998).

GEOLOGY

The Potosi deposit occurs within the upper part of the Broken Hill Group of the Early to Middle Proterozoic Willyama Supergroup, on the opposite limb of the Hanging Wall Synform to that in which the Broken Hill orebody is positioned (Larsen, 1994) (Figure 1). The package of metasediments in this region lies between the NE striking Globe Vauxhall and Western Shear zones, to the E and W respectively, which dip 60-70° to the SE. The retrograde, strongly sericitic Potosi Shear is interpreted to be a sub-parallel striking splay of the Western Shear.

Lithological units exposed in the Open Cut include Potosi Gneiss, of the lower part of the Hores Gneiss (Unit 4.7), the massive meta-pelite (Unit 4.6) with local BIF development at the top of the Freyers Metasediments separating it from underlying, more thickly-bedded psammitic metasediments (Unit 4.5). The Unit 4.5 metasediments are predominantly comprised of bedded psammites with lesser pelites and psammopelites.

The Broken Hill main lode deposit and smaller Silver Peak and Round Hill mines sit within the 4.7 unit, while the Silver Hill and old Potosi workings followed Potosi Shear hosted lead-rich veins. The Potosi Open Cut mines sulphides from within the Potosi Shear and unsheared, silicified 4.5 metasediments. Regionally, the 4.5 hosted mineralisation extends 5.5 km NE along strike from the Tin Street mineralisation to Barrier Main Lode, paralleling the regional structure (Figure 1). Mineralisation in 4.5 has a predominant shallow plunge to the NE.

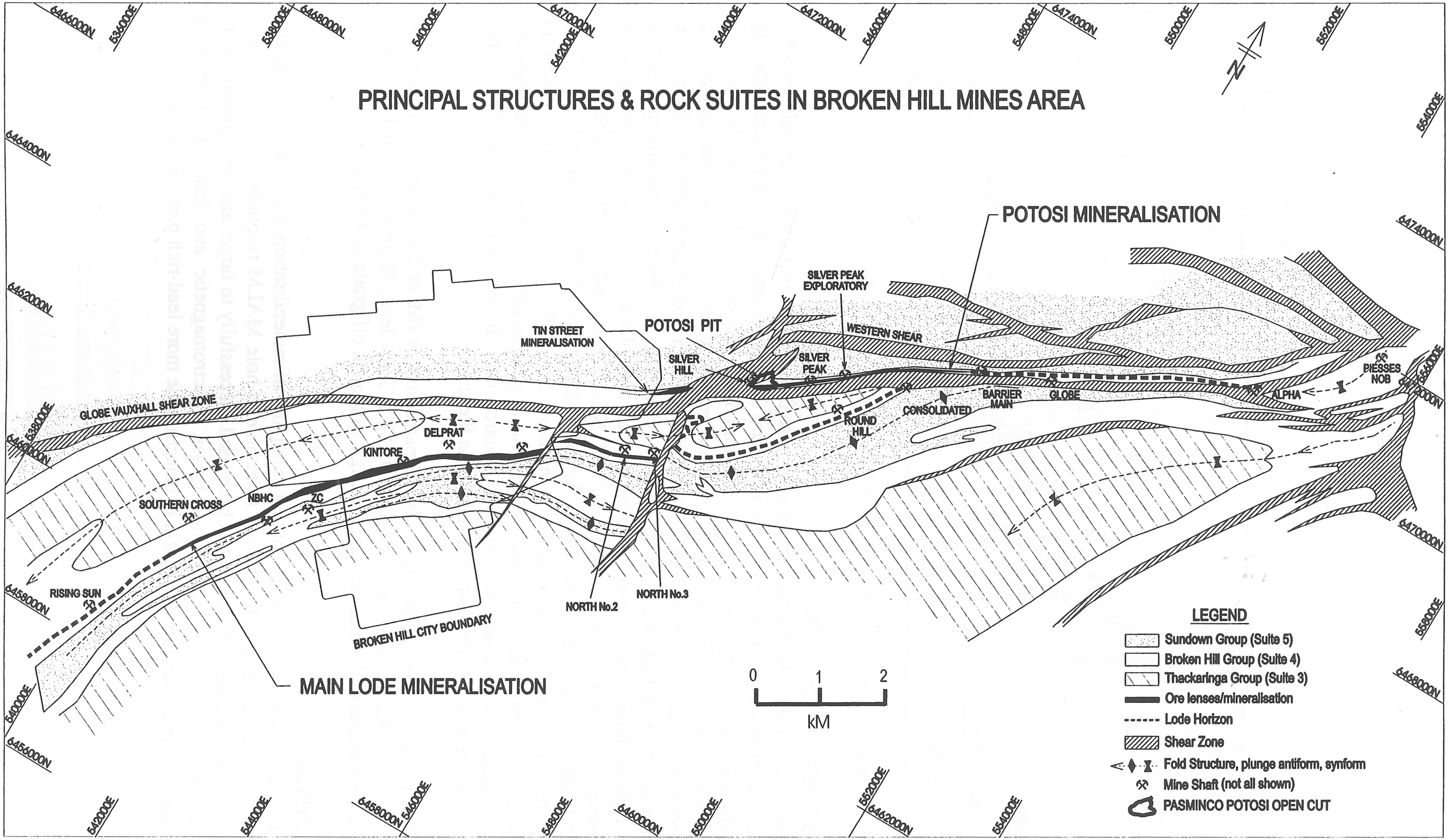

Figure 1 Schematic plan of surface geology with projection of Main Lode and Potosi Mineralisation and location of Potosi Open Cut Mine

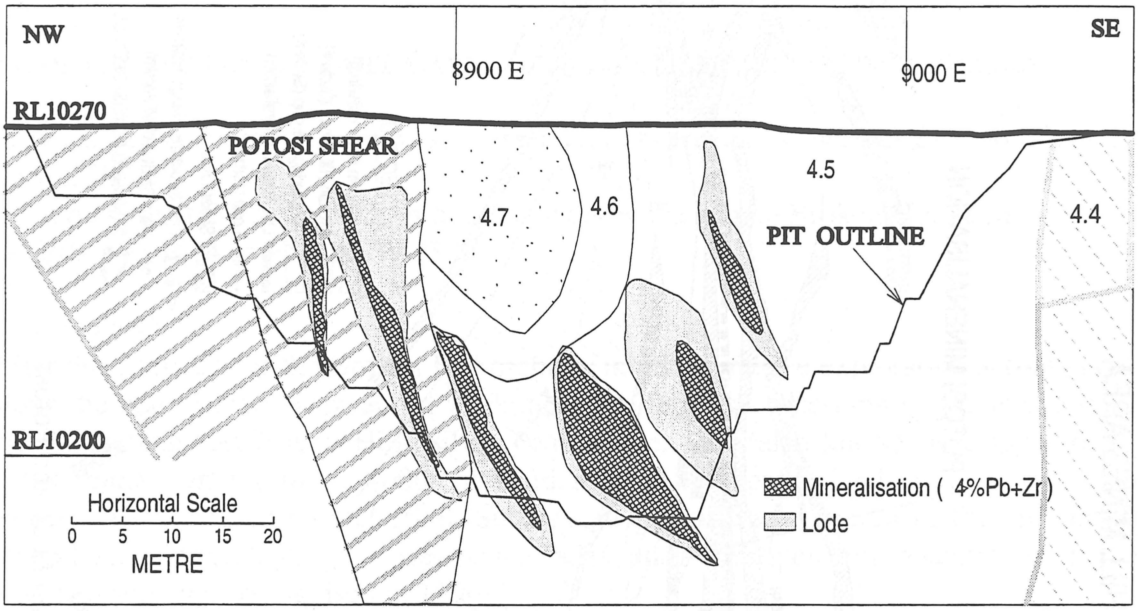

Figure 2 Cross section through Potosi Open Cut Mine at 10895N (+ 15m)

POTOSI MINERALISATION
Mineralisation within the Potosi Open Cut is hosted in two distinct litho-structural domains, the 4.5 psammite unit and the Potosi Shear (Figure 2). The psammite hosted mineralisation is comprised of sub-massive to massive medium-coarse grained, black, iron-rich sphalerite (marmatite), with lesser interstitial fine-medium grained galena and minor chalcopyrite and pyrrhotite. Mineralisation is typically enveloped within a blue-quartz alteration halo, with variable disseminated galena, pyrrhotite, pyrite, chalcopyrite, sphalerite, gahnite and garnet. The sulphide bodies are oriented sub-parallel to the fold axial surface and plunge of a mesoscopic synform, approximately 063°/15° NE, dipping 60° E. Potosi Shear hosted mineralisation, is oriented sub-parallel to the main shear fabric (037°/75°E, plunging 15° NE), and occurs as veins and sub-massive to massive bodies. It is mineralogically similar to sulphides in the psammite unit, and occurs also as galena-rich veins further west from the shear contact. Thin, commonly sheared, quartz lode bounds sulphide in places, but mineralisation appears to be re-mobilised within the shear.

The Reserve for the Potosi Open Cut was estimated to be 0.7Mt at 2.0% lead, 26 g/t silver and 9.2% zinc. The Resource is estimated to be 0.6Mt at 2.2% lead, 29 g/t silver and 10.4% zinc. Both are estimated within the current pit design with a cut off grade of 4% lead + zinc.

GEOPHYSICS
Surface MALM has shown the extent and continuity of mineralisation. Continuity of vein and stringer mineralisation may be inferred from hole to hole MALM responses. More recently, drillhole magnetometric resistivity has been used successfully to target and semiquantitatively model the lead-poor, zinc-rich Potosi lenses. Electromagnetic and induced polarisation methods have been variably successful in detecting the more lead-rich parts of the lodes.

IMPLICATIONS FOR EXPLORATION

Historically, exploration has targeted Broken Hill-type mineralisation, in dimension and style, within the Hores Gneiss (4.7) unit of the Broken Hill stratigraphic sequence. However, the geological position of the Potosi mineralisation provides us with alternative models for future exploration in the Willyama Supergroup, and raises the following points:

1) It has provided a new stratigraphic target for mineralisation within the psammites of the upper 4.5 Freyers Metasediments unit which has largely been overlooked in regional exploration;

2) The proximity of the orebody to the Western, Potosi and Globe Vauxhall Shear Zones and the interpreted structural role in sulphide mineralisation provides potential for similar structurally-controlled targets in the region;

3) There is the coincidence of mineralisation sub-parallel to the minor synclinal fold axial surface and plunge which parallels the strike of the regional fabric;

4) Re-mobilised mineralisation within the Potosi Shear indicates the potential for structural upgrading of primary mineralisation to produce an economic deposit.

The Potosi deposit raises the sceptre of structural versus stratigraphic constraint on mineralisation, or a combination of both controls. With a broadened focus on exploration strategies, the potential exists to discover additional Potosi-style deposits in the Broken Hill region.

REFERENCES

Larsen, D.F. 1994. The Potosi orebody - a newly discovered base metal deposit at Broken Hill, New South Wales. *Geological Society of Australia Abstracts 37*, 238.

Morland, R. & Leevers, P.R. 1998. Potosi zinc-lead-silver deposit, Broken Hill. *Geology of Australian and Papua New Guinea Mineral Deposits*, 615-618.

Acknowledgments

The authors acknowledge the cartographic work of Frann Sette for this abstract.

EXPERIMENTAL STUDIES IN THE SYSTEM PbS-FeS-ZnS±Ag_2S: IMPLICATIONS FOR THE BROKEN HILL OREBODY, NSW.

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The sulphides of Broken Hill N.S.W contain a number of unusual features, such as metal (Zn-Pb) zoning that is inverted with respect to "typical" exhalative deposits (Stanton, 1967) and the presence of Pb-rich sulphide dykes (droppers) extending out from the main lode into shears that cross-cut post ore dykes. Given that the region has undergone granulite facies metamorphism, it is not beyond the realm of possibilities that the sulphides at Broken Hill may have undergone partial/total melting during peak metamorphism.

Avyetisan and Gnatyshenko (1956) determined the 1 atm. eutectic temperature in the system PbS-FeS-ZnS to be 820°C. In a 1 atm. experimental study of the system Fe-Pb-S, Brett and Kullerud (1967) showed the presence of a melt phase at relatively low temperatures (<850°C) and suggested that the addition of ZnS (as demonstrated by Avyetisan and Gnatyshenko, 1956) may produce melts at even lower temperatures, "whereby partial melting of galena and sphalerite would produce a Pb-rich sulphide liquid, which might separate into veins and off shoots, resulting in Pb-rich ores....this could occur in high-grade districts such as Broken Hill".

Lawrence (1967) used sulphide textures in Broken Hill sulphides as evidence for the presence of "neomagmas" and suggested that sulphide melting could occur at temperatures as low as 700°C, but provided no supporting evidence for this assertion. Given that pressure severely increases melting temperatures for most metals, silicates and sulphides, the effects of pressure on the eutectic temperature must be ascertained before we can determined if partial melting of these ores was possible. If partial melting of sulphides is possible under peak Broken Hill metamorphic conditions, then many of the unusual characteristics of the Broken Hill ores may be more easily explained. Therefore, an experimental study of melting in the system PbS-FeS-ZnS±Ag2S was undertaken to determine the eutectic temperature in this system as a function of temperature and pressure.

Experiments were performed over a range of temperatures at one atmosphere and at 5, 10 and 27 kbars. Spec pure PbS, FeS and ZnS were mixed and pressed into pellets which for 1 atm. experiments were sealed in evacuated silica-glass tubes, heated to temperature and rapidly quenched into water, after which they were polished for microscopic study. High pressure experiments were performed by placing sulphide pellets in graphite sleaves which were sealed in Pt and run for 4-8 hours at the pressure and temperature of interest in piston-cylinder apparatus, and then rapidly quenched, and polished. Unmelted experiments (Fig.1) were readily distinguished from those that melted (Fig. 2) by the characteristic graphic texture produced when molten sulphides are quenched.

For the system PbS-FeS-ZnS the eutectic temperature and composition was found to be 800±2°C and 63%PbS, 31%FeS, 7%ZnS respectively, at 1 atm. Figure 3 summarises all of the experimental results. The eutectic temperature at 27 kbars was found to be 960°±10°C with a composition enriched in ZnS relative to the 1 atm. eutectic. These results allow interpolation of the eutectic temperature at any pressure, with an increase of approximately 6°C/kbar. Thus, at 5 kbars the eutectic temperature for the pure system is 830°C, however the addition of 1 wt.% Ag2S depresses the eutectic temperature to 770±5°C at 1 atm. and 805±5°C at 5 kbars (Fig. 3).

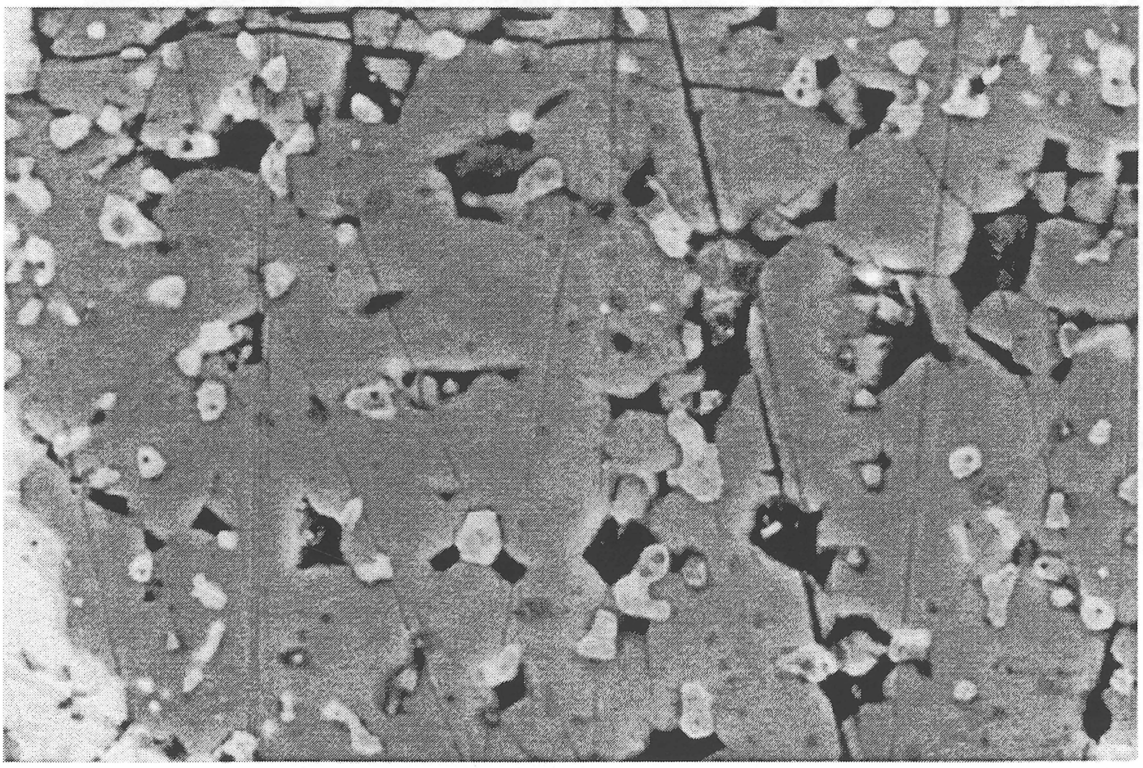

Figure 1. Unmelted sulphide pellet annealed at 27 kbars and 780°C. Width of field equals 140 mm.

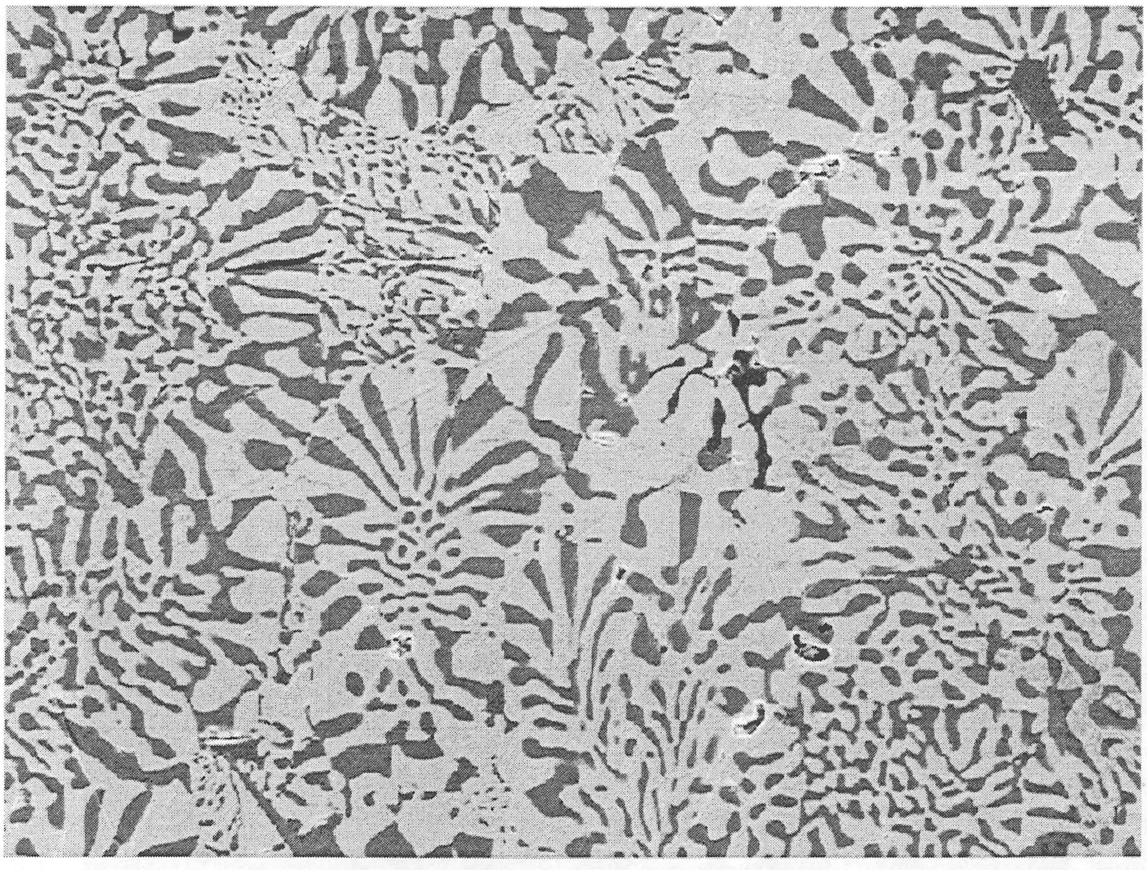

Figure 2. Graphic sulphide texture quenched from 27 kbars and 1020°C. Width of field equals 80 mm

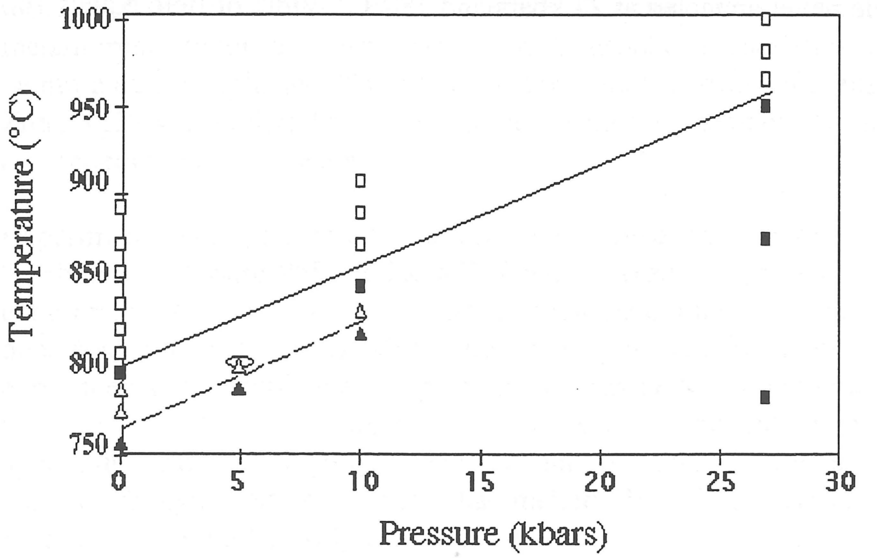

Figure 3. Experimental results for the pure system PbS-FeS-ZnS (square symbols) and those doped with 1% Ag2S (triangles). The solidus curve is indicated by a solid and a dashed line respectively. Experiments which showed no sign of melting are represented by solid symbols, and those in which melting occurred are shown by open symbols. The ellipse represents peak metamorphic conditions for Broken Hill (Phillips, 1980)

The conditions of peak metamorphism for the central and southern areas of Broken Hill Block lie above the solidus of the PbS-FeS-ZnS+1%Ag2S system, strongly suggesting that partial melting of the sulfide orebody occurred. If the sulphides of the broken Hill orebody were partially molten during metamorphism, then information on the current metal zoning of the deposit sheds no light on its genesis. Consequently, mineral exploration programs targeting exhalative deposits in high-grade metamorphic terranes should not adhere too closely to current stratigraphically concordant mineralisation models.

REFERENCES

Avyetisan, K. and Gnatyshenko, G.I. 1956. Thermal and metalographic study of the lead sulfide-zinc sulfide-iron sulfide system. *Izvest. Akad. Nauk. Kazak. S.S.R. Ser. Gorn. Dela., Stroimaterialov i Met.* **6**, 11-25.

Brett, R., and Kullerud, G. 1967. The Fe-Pb-S System. *Economic Geology* **62**, 354-367.

Lawrence, L.J. 1967. Sulfide neomagmas and highly metamorphosed sulfide deposits. *Mineralium Deposita* **2**, 5-10.

Phillips, G.N. 1980. Water activity changes across an amphibolite-granulite transition, Broken Hill Australia. *Contrib. Mineral. Petrol.* **75**,377-386.

Stanton, R.L. 1967. Petrochemicqal studies of the ore environment at Broken Hill, N.S.W.:3-banded iron formations and sulfide ore bodies: Constitutional and genetic ties. *Trans. Inst. Min. Metall. Sec. B Appl. Earth Sci.* **85**, 132-141.

Acknowledgements

This work could not have been carried out without the fantastic advise and assistance of Bill Hibberson, senior technical officer, RSES, ANU. We would also like to thank Alan Nutman, David Ellis, Hugh O'Neill and David Green for valuable suggestions and support during the course of this work.

UNRAVELLING THE KOONENBERRY BELT

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The Koonenberry Belt wraps around and defines the eastern margin of the Curnamona Craton. The exposed older rocks of the Koonenberry Belt form a segment of the Late Cambrian Delamerian Fold Belt and are Late Proterozoic and Cambrian sediments and volcanics that were deposited on the eastern margin of continental Australia following the Rodinian breakup. The Mootwingee Stage of the Delamerian event is stratigraphically recorded here by an extensively exposed unconformity surface between tight to isoclinally folded, thrusted and vertically cleaved pre-Delamerian units and a moderately dipping Upper Cambrian to Ordovician sequence. Late Cambrian Mindyallan stage trilobites are preserved just above the unconformity at Kayrunnera and this provides a minimum age for the Delamerian folding event in western New South Wales. The rock units deformed in the Delamerian orogeny are of biotite or lower metamorphic grade (reaching lower amphibolite facies locally) and show generally low plunging tight to isoclinal upright folds with wavelengths ranging up to several kilometres. A single vertical slaty cleavage is ubiquitous. This dominant early cleavage preserves a constant NW-SE regional trend but rotates to a N-S and then a NE-SW trend in the Scopes Range area to the south. This rotation is believed to be due to a Carboniferous or younger event that reactivated a Rodinian crustal transform. The mechanics of this rotation may be determined by strike slip motion on a network of vertical curved faults. Secondary and later cleavages, often associated with steeper plunging folds, are locally observed in pre-Delamerian pelitic units but are difficult to verify in predominantly arenaceous sequences. These younger cleavages probably preserve post-Delamerian Palaeozoic tectonic events that have overprinted on the older rocks.

The major portion of the pre-Delamerian sedimentary sequence (the former Wonominta Beds) has been subdivided into three informal units: the Kara beds, Teltawongee beds and the Ponto beds. The Kara beds occupy the core of a regional anticlinorium in the central part of the Koonenberry Belt and can be divided into lower and upper sections separated by the Mount Arrowsmith Volcanics. The lower section is made up predominantly of carbonaceous shales (slates) and siltstones with occasional thin blankets of clean cross-bedded quartz sandstones (quartzites) and rare dolomitic lenses. There is an overall lithological similarity to parts of the Adelaidean Torrowangee Group and the lack of fossils and bioturbation supports this view. The Mount Arrowsmith Volcanics consist of basaltic pillow lavas and tuffs that can be traced on the ground and by their magnetic signature from their best development at Mount Arrowsmith along strike to the south-east to Nuntherungie Creek. A shorter largely unexposed segment is interpreted to be displaced to the west of the Turkaro Range and a third segment is exposed to the south-west of Mount Wright. Extensive geochemical work has confirmed the transitional alkaline character of the magmatism and a zircon date of 586 Ma indicates a late Precambrian age for this unit. The extrusion may be related to local extension of the continental margin. The upper part of the Kara beds is a quartz-rich sequence of laminated, ripple marked and cross-bedded sandstones and siltstones and lesser shales (slates). Dolomitic shales and minor dolomites are common in the uppermost levels of the Kara beds and correlated equivalents of these west of Mount Arrowsmith, some being

KOONENBERRY BELT
STRATIGRAPHIC COLUMN

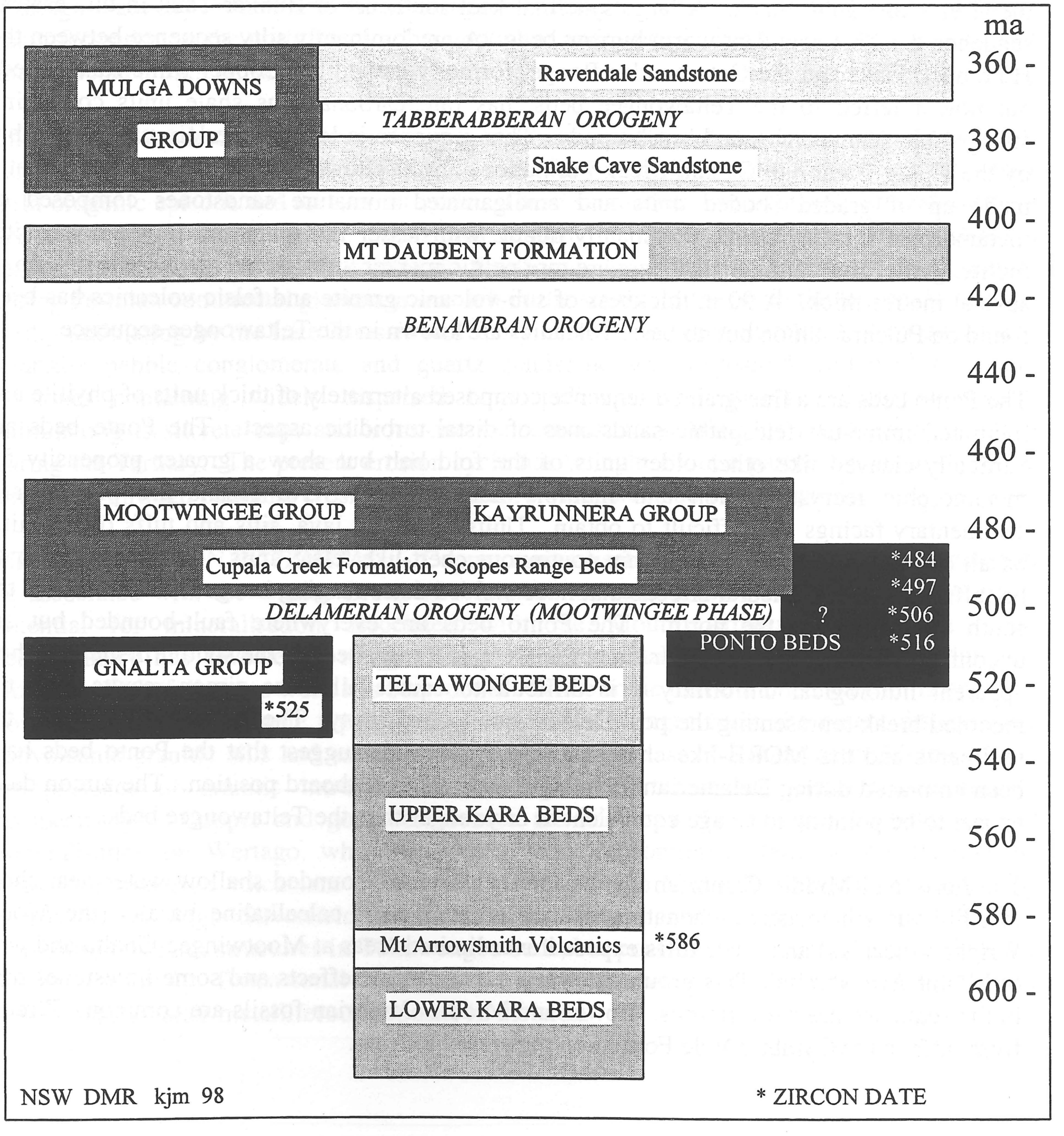
LATE TERTIARY to PRESENT (Alluvium, colluvium, sand dunes etc.)

OLIGOCENE (Silcrete, ferricrete and deep weathering profile) Cordillo surface

LATE JURASSIC to CRETACEOUS (Basal quartz pebble conglomerate, quartz sandstone, siltstone/claystone with polished dropped boulders of Devonian quartzite) Rolling Downs Group

PERMIAN (Glaciated surface, sandstones with glacial erratics)

KANIMBLAN OROGENY



shallow water oolitic units, have been shown to contain shelly fragments suggesting an early Cambrian age for the upper part of the Kara sequence. Because of the suspected presence of numerous thrust faults within the predominantly west facing sequence, the thickness of the Kara beds cannot be estimated at this stage.

The incoming of the first immature turbiditic sandstone bed at the top of the west-facing Kara sequence near Teltawongee Tank, Nundora, marks the commencement of the Teltawongee beds, a monotonous graded-bedded immature sandstone sequence of considerable but unknown thickness, and showing an overall lithological similarity with the Kanmantoo Group in South Australia. No fossils have been found in the small section of Teltawongee beds near Nundora. A more extensive thrust-bounded synclinorial belt of Teltawongee beds stretches from Cobham to Wertago and contains sponge spicule-bearing slates near Wonnaminta homestead. The Teltawongee beds form the major bedrock unit east of the Koonenberry Fault where they stretch at least 40 km across strike before disappearing beneath sediments of the Great Australian Basin. A large synclinal keel southeast of Bunker Tank in this eastern sequence contains abundant worm burrow beds. A predominantly silty sequence between the Hummock Fault and the Coturaundee Range, formerly named the Copper Mine Range Beds but now referred to the Teltawongee beds, has rare carbonaceous shale units containing sponge spicules, sponges and brachiopods. This sequence is locally overlain unconformably by the Upper Cambrian Cupala Creek Formation. The Teltawongee beds are predominantly made up of graded bedded units and amalgamated immature sandstones composed of metamorphic mineral clasts, dominantly quartz with lesser feldspars and minor muscovite, biotite, garnet and tourmaline. There are rare pelitic marker units, some grey, some red, up to several metres thick. A 90 m thickness of sub-volcanic granite and felsic volcanics has been found on Pulchra station but no basic volcanics are known in the Teltawongee sequence.

The Ponto beds are a fine-grained sequence composed alternately of thick units of phyllite and indurated immature feldspathic sandstones of distal turbiditic aspect. The Ponto beds are vertically cleaved like other older units of the fold belt but show a greater propensity for metamorphic recrystallisation and multiple deformation. No fossils are present and sedimentary facings are difficult to obtain. Units of pillow lava, sills and tuffs of tholeiitic basalt can be mapped along with thin continuous chert-like felsic units. The latter appear to be tuffs containing euhedral zircons that have yielded dates ranging in age from 516 ma in the south to 484 ma in the north. The Ponto beds are everywhere fault-bounded but are unconformably overlain by Upper Cambrian Scopes Range Beds in the south. In view of their apparent lithological uniformity it is difficult to equate all these zircon results with the recorded break representing the post-Delamerian unconformity. The more distal aspect of the sediments and the MORB-like character of the tholeiites suggest that the Ponto beds have been emplaced during Delamerian thrusting from a more outboard position. The zircon dates appear to be pointing to an age equivalent to or younger than the Teltawongee beds.

The Early and Middle Cambrian Gnalta Group is a fault-bounded shallow water near-shore fossiliferous siliciclastic-carbonate sequence with units of calcalkaline basalts (the Mount Wright Volcanics) and felsic tuffs exposed over limited areas at Mootwingee-Gnalta and west of Mount Arrowsmith. This group show few metamorphic effects and some limestones high in the sequence are petroliferous. Lower and Middle Cambrian fossils are common. Zircons from tuffs in the Cymbric Vale Formation registered 525 ma.

Following uplift and erosion instigated by the Delamerian fold-thrust event a major erosion surface was formed in the area. Polymictic conglomerates containing a wide range of cobbles eroded from the newly formed Delamerian mountains are preserved at Bilpa, Cupala Creek and Nuntherungie. A sequence of siliciclastic sandstones and siltstones, apparently derived from the south-west, overlie this conglomerate (Scopes Range Beds in the south, Mootwingee Group and Cupala Creek Formation, Kayrunnera Group in the north). The character of this sequence changes from fluvial in the south to marine shelf in the north. The Kayrunnera Group east of Koonenberry Mountain, a finer grained thick shale sequence with some calcareous beds, contains a trilobite fauna that indicates that the sequence might approach the Ordovician boundary. A pronounced WNW-ESE steep cleavage in the in the Kayrunnera Group may signify an important folding and orogenic event in the early Palaeozoic.

In the latest Silurian and Early Devonian the Mt Daubeny Formation, a red-bed facies of conglomerates, sandstones and minor siltstones, was deposited in intramontane basins at Wertago-Daubeny in the north and Churinga in the south. Crustal foundering associated with basin formation in the north has lead to important andesitic, dacitic and rhyolitic magmatism and associated mineralisation.

Thick quartz sandstones blanketed the region in the middle and late Devonian. These units can be referred to the Snake Cave Sandstone and Ravendale Sandstone and are separated by a mild orogenic episode and an erosion cycle. These sandstones were partially eroded during a period of uplift, thrusting and extensional faulting in the Carboniferous when extensive movement occurred on the Koonenberry Fault and its branches. Landscape modification during Permian continental glaciation was felt in the south. In the north the landscape became gently undulating by the Late Jurassic and Early Cretaceous when distally derived quartz and quartzite pebble conglomerate and quartz sandstone was deposited, followed by marly siltstones containing widely dispersed large polished drop stones. Deep weathering culminating is silcrete caps and ironstone veneers and local siliceous lag deposits occurred during the Tertiary. The present erosion cycle has brought about a partial rejuvenation of the landscape through bad-land erosion of the deeply weathered sub-silcrete profile.

MINERALISATION POTENTIAL: Copper mineralisation and barite deposits are known to be associated with the Gnalta Group and fault zones cutting these rocks. While there is a potential for mineralisation associated with the Mount Arrowsmith Volcanics, soil geochemistry has revealed a range of interesting anomalies in the Kara metasediments. However, little follow up work has been done. While some iron-enriched slate units open the possibility for Nairne-pyrite type deposits in the Teltawongee beds, the recent discovery of subvolcanic granitic sills and associated tuffaceous units east of Koonenberry Mountain and the presence of granitic intrusions further to the northeast add other possibilities to prospectivity. Copper and gold occurrences are known within the Ponto beds. Copper mineralisation on Wertago, while reactivated into Carboniferous fault structures, may be sourced in andesitic volcanism within the Early Devonian Mount Daubeny Formation. The nearby Nuntherungie Silverfield has highly argentiferous galena in siderite veins hosted in Carboniferous fault structures in Teltawongee beds, but possibly sourced in a large underlying magnetic anomaly. Extensional faulting in the Carboniferous has enabled the development of many of the smaller metalliferous deposits in the area.

EXPLORATION FOR FE-OXIDE COPPER-GOLD ORE SYSTEMS WITHIN THE BENAGERIE RIDGE MAGNETIC COMPLEX

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The Olary Region is arguably the hottest copper-gold exploration address within Australia. Pasminco, in conjunction with its joint venture partner Lynch Mining, maintain a strategic tenement holding over a number of discrete magnetic features developed along the Benagerie Ridge. The most significant of these, the Benagerie Ridge Magnetic Complex (BRMC) is spatially associated with extensive Cu-Au-Mo mineralisation. Exploration success at Benagerie is attributed to the utilisation of regional datasets followed by aggressive drilling of target areas.

Following the discovery of the Portia gold mineralisation, reprocessing and analysis of Pasminco Exploration and Broken Hill Exploration Initiative (BHEI) regional magnetic and gravity data sets suggested the presence of large discrete magnetite dominant hydrothermal alteration complexes. The Portia mineralisation was interpreted to represent secondary gold mineralisation situated peripheral to the largest of these complexes the BRMC.

Recent regional studies by Pasminco have cast doubt over the integrity of the existing regional stratigraphic model. Evidence suggests complex fold and thrust geometries have resulted in a broad scale repetition of lithologies with extensive, polyphase transgressive alteration systems. Interpretation of magnetic data has enabled the definition of discrete tectonic and metasomatic blocks, granitoid suites and a north-west trending fault bounded corridor which appears to display a fundamental control on granitoid emplacement and the localisation of the alteration and ore systems.

Exploration drilling within the BRMC under the blanket of Tertiary cover has further reinforced the presence of large alteration systems developed principally within the Pelite Suite but interpreted to overprint and transgress a distinct lithological sequence. Diamond drilling, firstly at the North Portia Prospect and subsequently at the Shylock Prospect, has indicated the presence of an identifiable sequence over a thickness of some 200m. Characteristics of the sequence suggest an original evaporitic parentage prior to the alteration overprint. This altered sequence hosts Cu-Au-Mo mineralisation as currently defined within the BRMC. An exploration philosophy based upon an Fe-Oxide hosted Cu-Au-U model was considered most applicable which is similar to the models developed for Olympic Dam and Ernest Henry.

At the Portia Prospect the mapped distribution of mineralisation is coincident with the axis of a strong gravity low. A progressive expansion of gravity coverage over the BRMC revealed a variable pattern of discrete linear and circular gravity lows and highs intimately associated with a variable magnetic architecture. This pattern was interpreted to be the product of a complex relationship between feldspathic alteration and the presence or absence of iron oxide and sulphide phases. The gravity lows are interpreted to represent zones of deep weathering resulting from the breakdown of feldspathic alteration in the presence of acidic ground water sourced from the sulphide enriched bedrock.

Secondary mineralisation such as that observed at Portia and North Portia is interpreted to be the product of supergene processes associated with the breakdown of primary Cu-Au mineralisation located within the gravity lows. The combined use of gravity and airborne magnetic data has provided a powerful tool for mapping alteration and delineating both secondary and primary mineralisation systems beneath the extensive Tertiary cover rocks.

Exploration programmes conducted to date have been very successful in the delineation of significant secondary mineralisation at Portia and, subsequently, highly significant primary mineralisation at North Portia and Shylock. The North Portia prospect continues to yield intriguing and, most significantly, consistent ore grade Cu-Au-Mo mineralisation, whilst the Shylock Prospect has demonstrated anomalous Au mineralisation over three strike kilometres, including a spectacular 23m @ 79.3g/t Au. Of the new prospects identified Lorenzo, 18m @ 3.7g/t Au, Morocco, 14m @ 7.9% Pb, and Jessica, 2m @ 5.1% Cu, appear the most promising at this stage.

ZIRCON AGES FROM METASEDIMENTS, GRANITES AND MAFIC INTRUSIONS: REAPPRAISAL OF THE WILLYAMA SUPERGROUP

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Figure 1 shows a synthesis of the Willyama Supergroup based on SHRIMP zircon geochronology carried out under the auspices of the AGCRC/BHEI/AGSO. Some of the source data supporting this synthesis are shown in Figures 2 and 3. Other relevant information is presented in references given below and on published geological maps produced by the Geological Survey of New South Wales.

Key points are as follows:

• The Broken Hill and Thackaringa Groups (or at least some of the rocks assigned to them) were deposited between 1730-1700 Ma. Between ca. 1700-1670 Ma they were intruded by numerous mafic dykes and granites.

• The Sundown and Paragon Groups are interpreted to have been deposited between 1700-1600 Ma, and are not intruded by numerous mafic dykes.

• An older package of rocks (>1800 Ma) may be present locally in the Redan Geophysical Zone.

• Granitoid and mafic intrusions range in age from ca. 1700 Ma to ca. 1550 Ma. In addition there is growing evidence for amphibolite facies metamorphism as late as ca. 1200 Ma (Hartley, Venn and Nutman - Ar-Ar and U-Pb zircon isotopic data). This points to repeated thermal events in the region.

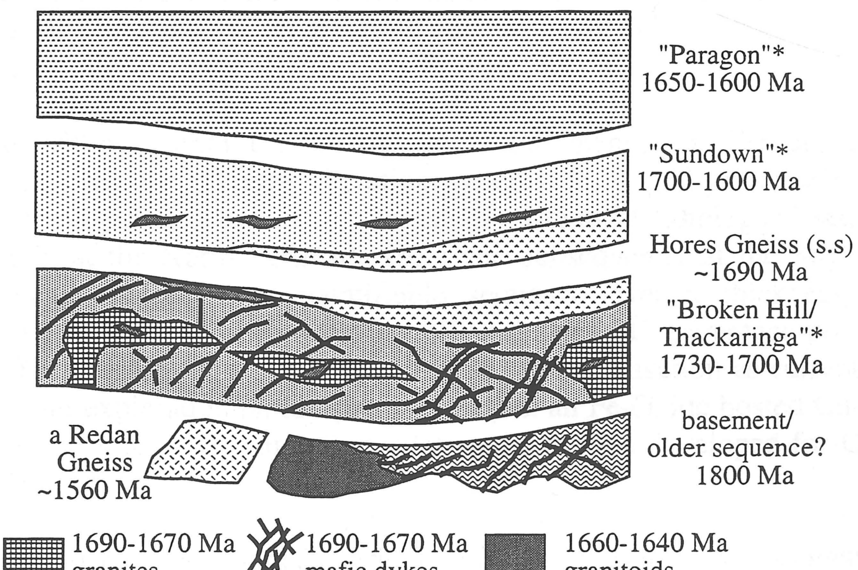

Figure 1. Zirconological synthesis for the Willyama Supergroup, Broken Hill block.
*Signifies that at least some rocks assigned to a particular Group have the age constraints indicated. This does not imply that all rocks assigned to that Group on the basis of lithological mapping have the same age. Gaps have been left between the Groups. This is because the zirconology at present provides no constraints on whether the contacts between Groups are hiatii, unconformities or tectonic breaks.

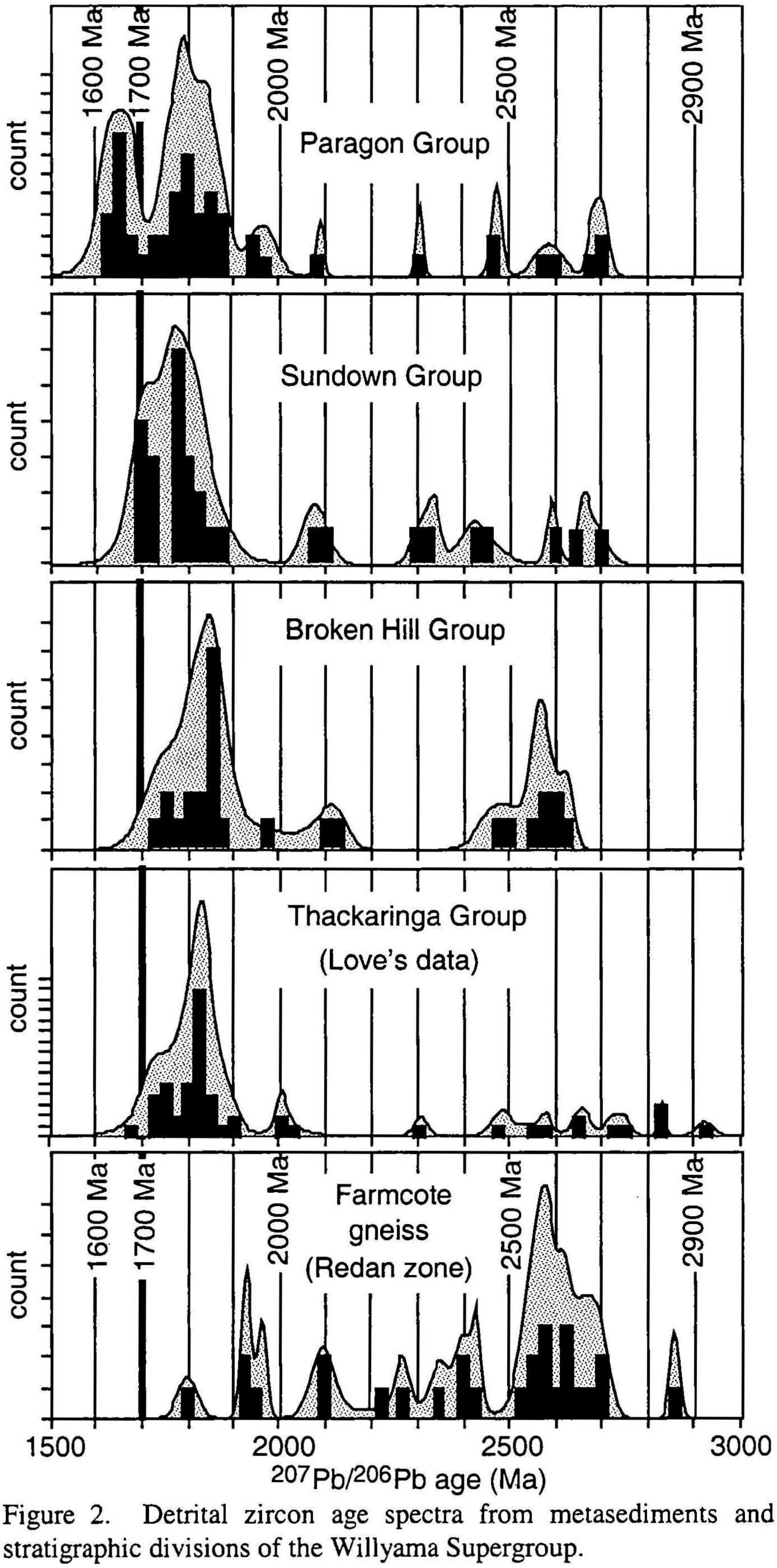

Figure 2. Detrital zircon age spectra from metasediments and gneisses from different stratigraphic divisions of the Willyama Supergroup.

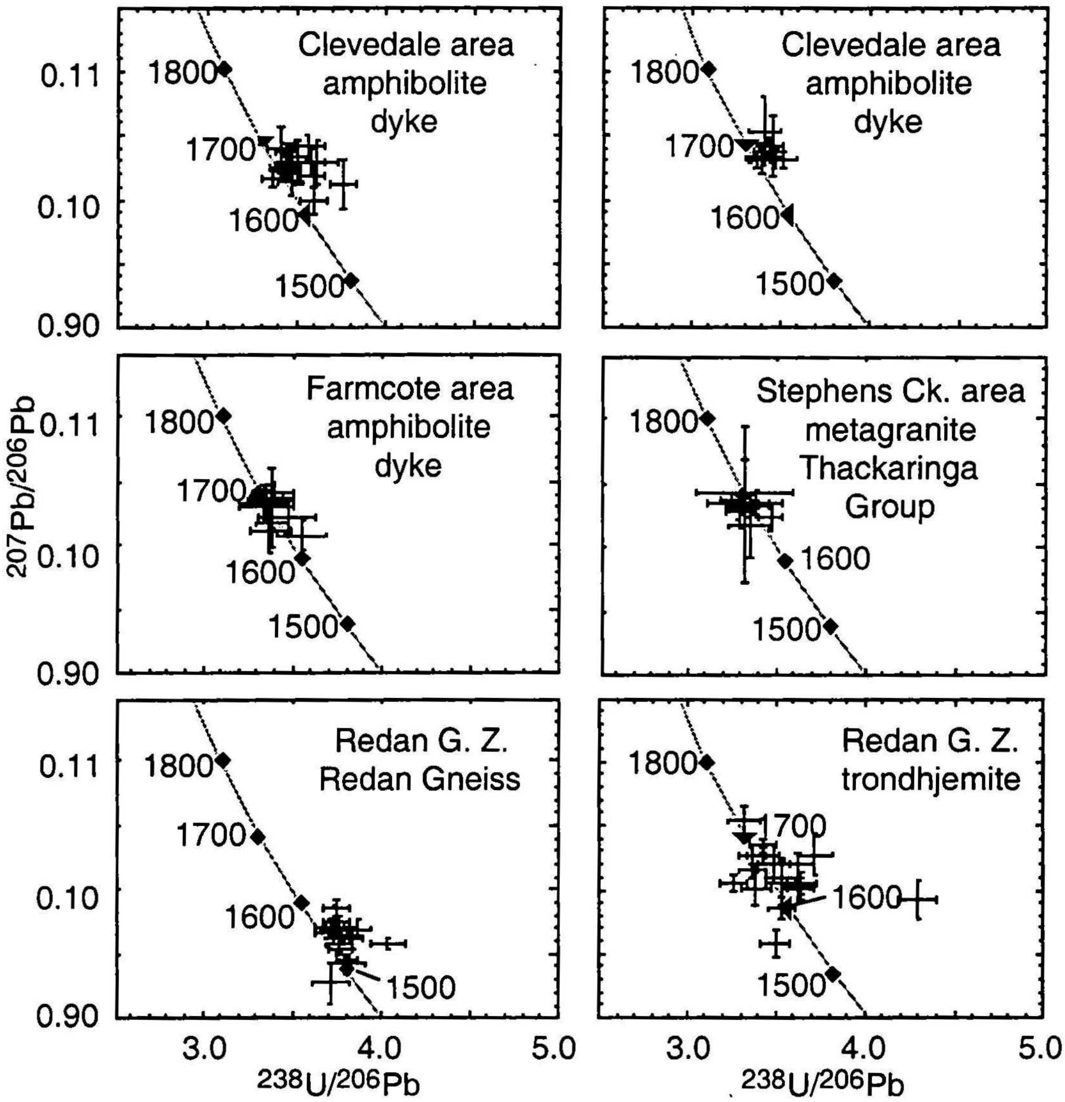

Figure 3. Tera-Wasserburg 238U/206Pb - 207Pb/206Pb plots for representative rocks of granitic and gabbroic composition assigned to the Willyama Supergroup, plus a trondhjemite from the Redan Geophysical Zone.

REFERENCES

Donaghy, A.G., Ehlers, K., Gibson, G.M., Maidmont, D.W., Nutman, A.P. & Venn, C.J. 1997. Dating of multiple Proterozoic thermal events by SHRIMP Uranium/Lead geochronology at Broken Hill, New South Wales, Australia. *Seventh Annual V.M. Goldschmidt Conference Abstracts*. Lunar and Planetary Institute, Houston, p. 60.

Love, S. 1992. Possible ages and origins for some rocks of the mid-Proterozoic Willyama Supergroup, New South Wales. *Unpublished B.Sc. (Hons) thesis*, Geology Department, Australian National University, Australia.

Nutman, A.P. & Ehlers, K. 1998. Evidence for multiple Palaeoproterozoic thermal events and magmatism adjacent to the Broken Hill Pb-Zn-Ag orebody, Australia. *Precambrian Research 90*, 203-238.

Page, R. & Laing, 1992. Felsic metavolcanic rocks related to the Broken Hill Pb-Zn-Ag orebody, Australia. Geology, depositional age, and timing of high-grade metamorphism. *Economic Geology 87*, 2138-2168.

Stevens, B.P.J., Brown, R.E., Stroud, W.J. & Willis, I.L. 1988. The Willyama Supergroup in the Broken Hill and Euriowie Blocks, New South Wales. *Precambrian Research 40*, 297-327.

GEOCHRONOLOGY OF METASEDIMENTARY AND METAVOLCANIC SUCCESSIONS IN THE OLARY DOMAIN AND COMPARISONS TO BROKEN HILL

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INTRODUCTION

The Olary Domain in eastern South Australia includes a sequence(s) of metamorphosed, dominantly quartzofeldspathic arenaceous and pelitic sediments, calcsilicate-bearing rocks, and minor volcanic or sub-volcanic rocks. Together with pre-tectonic A-type granites, this terrain forms part of the Palaeoproterozoic Willyama Supergroup which extends eastwards to Broken Hill. It has long been an important endeavour to correlate the Olary Domain sequence with the Broken Hill sequence (Clarke et al., 1986; Stevens et al. 1990; Cook and Ashley, 1992; Laing, 1996).

Deformation, high grades of metamorphism, paucity of suitable dating material, poor outcrop, and commonly fault-bound major geological contacts are factors that have so far inhibited an unambiguous geochronological picture emerging for the Olary Domain, particularly in regard to the age(s) of its metasedimentary sequences. Hence the lithostratigraphic correlations across the various inliers within the Olary Domain, and stratigraphic connection between Willyama Supergroup rocks in the Olary Domain and Willyama Supergroup rocks near Broken Hill have remained conjectural. Furthermore, there is potentially great interest in establishing a geochronological framework, and hence a better quantified basin history, for the Olary Domain because such knowledge would provide a more substantial basis to compare this terrain's evolution and metallogeny with that of other highly mineralised Palaeoproterozoic terrains such as Mount Isa Inlier and eastern Gawler Craton.

This study – within the Broken Hill Exploration Initiative (BHEI) – is designed to fulfil some of the above objectives. We report new geochronological and isotopic results that improve understanding of the age, correlation, and genesis of the Willyama Supergroup in the Olary Domain. Our investigations began in May 1998 and are still in progress.

EARLIER GEOCHRONOLOGICAL WORK

Previous geochronological efforts in Willyama Supergroup rocks within the Olary Domain have established the broad Palaeoproterozoic age framework initiated by a widespread A-type felsic magmatic event close to 1700 Ma old. This event (evident from U-Pb zircon work of Cook et al., 1994; Ashley et al., 1996) is considered an early phase of an intracratonic rift setting history (e.g. Ameroo Hill 1703±6 Ma; Abminga 1699±10 Ma). The lithostratigraphic framework for the Olary Domain (Clarke et al., 1986) packages these supracrustal sediments, volcanics, and high-level intrusive rocks in the lower 'quartzofeldspathic suite'. Complex detrital zircon age patterns in two albitised metasediments from the 'quartzofeldspathic suite' ('middle schist' or 'upper albite' units) range from late Archaean through to early Palaeoproterozoic, with the youngest populations providing maximum depositional ages of 1770-1785 Ma. From one of these sediments, Cook et al. (1994) reported a detrital zircon with an age of ~1630 Ma, but the stratigraphic significance of this much younger maximum age is unclear, especially as I-type intrusive granitoids such as Poodla Hill (1629±12 Ma) and Antro (1641±11 Ma) would appear to provide similar minimum ages for this Palaeoproterozoic sedimentation (Cook et al., 1994; Ashley et al., 1997). Younger granitoids (e.g. Crocker Well, Triangle Hill) in the Olary Domain are considered to be S-type (Ashley et al., 1997) and have U-Pb zircon ages of 1580-1590 Ma (Ludwig and Cooper, 1984; Cook et al., 1994).

Lithological and age correlations are made between the 'quartzofeldspathic suite' and the ~1700 Ma Thackaringa Group at Broken Hill (e.g. Donaghy et al., 1998). Clearly, parts or all of lithostratigraphic packages younger than the 'quartzofeldspathic suite' (such as 'calcsilicate suite', 'Bimba suite', and 'pelite suite') could be correlatives of the ~1690 Ma-Broken Hill Group (e.g. Cook and Ashley, 1992). However, no geochronological link has yet been established. Specifically, since there have been no depositional ages published in the upper parts of the Olary Domain lithostratigraphy ('calcsilicate, Bimba and pelite suites'), correlation with the ~1690 Ma Broken Hill Group (and/or younger Sundown and Paragon Groups) in the vicinity of Broken Hill has been speculative and without timing control.

NEW GEOCHRONOLOGICAL RESULTS

The approach we are currently adopting is to measure depositional and zircon provenance ages on a number of lithologies in the Olary sequence, and to blend this age and stratigraphic knowledge with their Sm-Nd isotopic evolution. We are doing this for selected metasediments and metavolcanics, with 'age traverses' across six stratigraphic sections. These sections are: Mulga Bore region, Cathedral Rock region, Mount Howden/Bimba mine region, southern part of east Weekeroo Inlier, northern part of east Weekeroo Inlier, and central Weekeroo Inlier.

(a) Meta-igneous rocks. Our initial SHRIMP U-Pb zircon ages (quoted at 95% confidence level) for metagranitoid and volcaniclastic rocks in the 'lower albite' unit of the 'quartzofeldspathic suite' substantially confirm results on comparable rocks by Ashley et al. (1996). For example, the oldest rocks exposed in our Mulga Bore traverse give a concordant U-Pb zircon age of 1711±2 Ma (SW Drew Hill felsic intrusion). Felsic volcaniclastic units in the north and south of the eastern Weekeroo Inlier have virtually identical crystallisation ages (1713±2 Ma, 1710±3 Ma). The essentially synchronous nature of this magmatic event (considered to be at different stratigraphic levels within the 'quartzofeldspathic suite') and the inferred short depositional time intervals involved for this sedimentary package, are further emphasised by another similar age (1712±2 Ma) from a felsic volcaniclastic unit at the top of the 'quartzofeldspathic suite' (Mulga Bore traverse). Preliminary zircon ages on a younger felsic volcanic within the 'calcsilicate suite' are inseparable from the above ages. If these zircon crystallisation ages are accepted as meaningful depositional ages, it suggests that both the 'calcsilicate suite' and underlying 'quartzofeldspathic suite' were deposited within a few million years. Our recent geochronological studies in the Redan Zone at Broken Hill suggest a magmatic event(s) of similar age in that area. Such magmatism at ~1710 Ma is coeval in time with a major rifting/magmatic episode dated in northern Australia (McArthur Basin and Lawn Hill Platform – Page and Sweet, 1998).

Sm-Nd data. The A-type granitoid from Drew Hill (1711±2 Ma) has very high contents of light rare earth elements with 350 ppm Nd. It has initial eNd value +0.6 at 1711 Ma and TDM model age of 2130 Ma. This is consistent with data from two A-type felsic gneisses (Ameroo Hill and Abminga) reported by Ashley et al. (1996). These rocks have higher eNd values, and have TDM model ages which are 200 million years or more younger than 1600 Ma regional granitoids in the Olary (Ashley et al., 1996) and ~1700 Ma felsic gneisses in Broken Hill. The latter commonly have initial eNd values -4 to -5 at 1700 Ma, and TDM model ages of 2400-2600 Ma. These values include the Broken Hill Farmcote gneiss and leucogranite, but do not include Hores Gneiss which has higher eNd value (-2) and younger model age (2300 Ma). Among the 1710 Ma Olary volcanic rocks, there are also samples which have intermediate eNd values (-2) and model ages. These Nd isotope data will be integrated with geochemistry in the evaluation of petrogenesis.

Fanning (1995) reported Sm-Nd data for five Kalkaroo metasediments hosting Cu-Au mineralisation. They have TDM model ages 2345-2512 Ma and initial eNd values -2.8 to -4.1 at 1700 Ma and -18.8 to -13.7 at 500 Ma. These data cover the same eNd range as most other 1600-1700 Ma rocks of Olary and Broken Hill Domains. In contrast, Turner et al. (1993) reported Cambrian sediments in the Normanville and Kanmantoo Groups of South Australia with younger TDM model ages (1.9-2.2 Ga) and higher eNd values (-9.4 to -13.4) at 500 Ma. Thus, the Nd isotopic data for the Kalkaroo sediments are quite consistent with their late-Palaeoproterozoic stratigraphic age. However, whether Cu-Au mineralisation hosted in the Kalkaroo metasediments was formed or remobilised in late-Precambrian to Cambrian (Fanning, 1995) or late-Palaeoproterozoic is a separate issue which is currently being investigated.

(b) Meta-sedimentary rocks. Detrital U-Pb zircon ages indicate a sediment's provenance domain(s). As well, the youngest clastic zircon component in a detrital suite provides the sediment's maximum depositional age. We are endeavouring to blend such provenance information with the above ~1710 Ma volcanic crystallisation ages across the six stratigraphic sections being studied. For this purpose, it is clearly necessary to avoid new zircon growth at ca. 1600 Ma – a product of the regional metamorphic event.

The clastic rocks so far measured in the Mulga Bore-Cathedral Rock and Mount Howden traverses include strongly albitised medium-grained psammites, psammopelites, and pelites. Detrital zircon age patterns are complex, indicating source terrain(s) composed of late Archaean and earlier Palaeoproterozoic rocks. Some early Archaean zircons (3700-3600 Ma) are found. The dominant Palaeoproterozoic zircon ages suggest strongly domainal provenance, from terrains around 1920 Ma, 1860 Ma, 1780 Ma, and 1730 Ma old. This provenance signature is common to most of the eight sedimentary rocks in the sequences so far analysed. It suggests a maximum depositional age of around 1730 Ma. However, data from two of the 'quartzofeldspathic suite' sediments show a minor component suggesting a younger maximum depositional age of closer to 1710-1715 Ma. If the presence of this so far very minor 1710-1715 Ma detrital suite is verified elsewhere in the 'quartzofeldspathic suite', this sequence's age will become tightly controlled, as its maximum (1710-1715 Ma) and minimum (~1710 Ma) ages would be effectively coincident.

The ~1780 Ma detrital age component which we observe for all sediments so far studied – from 'quartzofeldspathic suite' to 'pelite suite' – was evident in the data of Cook et al. (1994) from the 'upper albite unit'. On the basis of this, Ashley et al. (1997) suggested a source region dominated by ~1780 Ma felsic igneous rocks. Many of the above zircon ages are compatible with Gawler Craton provenance, but presumably wider derivation from specific ~1780-Ma felsic igneous terrains (Fanning et al., 1988) such as the Tidnamurkuna Volcanics (Peake and Denison Inliers) cannot be excluded.

At this early stage of the study, there are some interesting enigmas within the zircon age provenance patterns from the lower part of the Olary sequence. Some would find it surprising that there is such a dearth of 1710-Ma detrital zircons in the sediments. Clastic and epiclastic sediments, which are supposedly conformable with 'quartz-eye volcanics' in the dated ~1710 Ma 'quartzofeldspathic suite', either totally lack or contain very little zircon of this age. Instead they are dominated by older Palaeoproterozoic to late Archaean detritus. Could the ~1730 Ma maximum ages be closer to the actual depositional age of some of these sediments, or is it that the 1710-Ma volcanics were not an exposed source at the time that contemporary clastic sediments were being deposited? Could some or all of the ~1710 Ma felsic magmatic rocks be shallow-level sills emplaced into such a sequence? As discussed by Ashley et al. (1997), the latter is an unlikely scenario given the volcanic textural features of many of the 1710 Ma igneous rocks, but the lack or paucity of 1710 Ma debris in the clastic sediments, and prevalence and uniformity of the older provenance age patterns in most of our new data, make it worth asking these questions.

No depositional or provenance ages have yet been measured on any part of the 'Bimba suite' – the thin, base-metal prospective pyritic sequence of carbonaceous schists, calcsilicates, marbles, and ironstones that gradationally overlies the 'calcsilicate suite'. Because it is widespread and of such economic interest (correlated in general terms with the Ettlewood Calcsilicate Member, base of Broken Hill Group) the age of deposition of the 'Bimba suite' is certainly a desirable objective given its postulated stratigraphic and metallogenic correlation with part of the Broken Hill Group. We expect to report U-Pb zircon data on these sediments in the near future.

Rocks of the 'pelite suite' overlie the 'Bimba suite' sediments. Our detrital zircon ages for 'pelite suite' metasediments in the Mulga Bore traverse are ~1770 Ma and older – effectively a mimic of the 'quartzofeldspathic suite' detrital ages. In the Mount Howden area, however, 'pelite suite' rocks up sequence from the Bimba mine include much younger detrital zircons. They reveal not only the same complex provenance as seen in the older 'quartzofeldspathic suite', but also an additional younger component defined by a coherent array of detrital zircon at 1648±6 Ma. This zircon suite is possibly from a reworked tuff. This part of the 'pelite suite' was thus deposited no earlier than 1648±6 Ma ago. If this result is substantiated in our other traverses, it would indicate that there is a structural discontinuity, or a significant unconformity, or at least a ~50 million year depositional break, between the 'pelite suite' and older rocks. The clear distinction in provenance between 'pelite suite' rocks at Mulga Bore and Mount Howden also suggests there might be more than the one 'pelite suite'. This will be further tested, particularly in relation to 'pelite suite' equivalents in the Kalkaroo region.

The fact that part of the 'pelite suite' in the Olary Domain is no older than 1648±6 Ma invites possible correlation with the Sundown or Paragon Groups near Broken Hill. The Olary sequence between 'pelite suite' and 'quartzofeldspathic suite' will have been deposited in the interval 1710 to 1650 Ma, and hence may contain direct correlatives of the ~1690-Ma Broken Hill Group. This possibility, and the wider geochronological connections that now emerge between these 1650-1700 Ma sequences and contemporary sequences such as the Mount Isa Group and McArthur Group in northern Australia, provide an age framework against which more advanced basin analysis and metallogenic models can be considered.

ACKNOWLEDGMENTS We thank Chris Foudoulis, Tas Armstrong, and Steve Ridgeway who continue to be an enormous help in achieving the above outcomes. RWP and S-sS publish with the approval of the Executive Director, AGSO, and CHHC publishes with approval of Director, Mineral Resources Group, PIRSA.

REFERENCES

Ashley, P.M., Cook, N.D.J. and Fanning, C.M., 1996. Geochemistry and age of metamorphosed felsic igneous rocks with A-type affinities in the Willyama Supergroup, Olary Block, South Australia, and implications for mineral exploration. Lithos, 38, 167-184.

Ashley, P.M., Lawie, D.C., Conor, C.H.H. and Plimer, I.R., 1997. Geology of the Olary Domain, Curnamona Province, South Australia. Department of Mines and Energy South Australia, Report Book 97/17, 51 pp.

Clarke, G.L., Burg, J.P. and Wilson, C.J.L., 1986. Stratigraphic and structural constraints on the Proterozoic tectonic history of the Olary Block, South Australia. Precambrian Research, 34, 107-137.

Cook, N.D.J. and Ashley, P.M., 1992. Meta-evaporite sequence, exhalative chemical sediments and associated rocks in the Proterozoic Willyama Supergroup, South Australia: implications for metallogenesis. Precambrian Research, 56, 211-226.

Cook, N.D.J., Fanning, C.M. and Ashley, P.M., 1994. New geochronological results from the Willyama Supergroup, Olary Block, South Australia. In: Australian Research on Ore Genesis Symposium. Proceedings Australian Mineral Foundation, Adelaide, pp.19.1-19.5.

Donaghy, A. Hall, M., Gibson, G. and Nutman, A., 1998. The age of deposition and first deformation of the Palaeoproterozoic Willyama Supergroup, Broken Hill, Australia. Geological Society of Australia, Abstracts No. 49, p.118. 14th Australian Geological Convention, Townsville, July 1998.

Fanning, C.M., Flint, R.B., Parker, A.J., Ludwig, K.R. and Blissett, A.H., 1988. Refined Proterozoic evolution of the Gawler Craton, South Australia, through U-Pb zircon geochronology. Precambrian Research, 40/41: 363-386.

Fanning, C.M., 1995. Sm-Nd isotopic analysis and SHRIMP U-Pb zircon dating, Kalkaroo Prospect. PRISE Reports 94-290 & A94-300 (unpublished).

Laing, W.P., 1996. Stratigraphic subdivision of the Willyama Supergroup - Olary Domain, South Australia. MESA Journal 2, pp. 39-49.

Ludwig, K.R. and Cooper, J.A., 1984. Geochronology of Precambrian granites and associated U-Ti-Th mineralization, northern Olary province, South Australia. Contributions to Mineralogy & Petrology, 86, 298-308.

Page, R.W. and Laing, W.P., 1992. Felsic metavolcanic rocks related to the Broken Hill Pb-Zn-Ag orebody, Australia: geology, depositional age, and timing of high-grade metamorphism. Economic Geology, 87, 2138-2168.

Page, R.W. and Sweet, I.P., 1998. Geochronology of basin phases in the western Mt Isa Inlier, and correlation with the McArthur Basin. Australian Journal of Earth Sciences, 45, 219-232.

Stevens, B.P.J., Barnes, R.G. and Forbes, B.G., 1990. Willyama Block - regional geology and minor mineralisation. In: F.E. Hughes (ed.), Geology of the Mineral Deposits of Australia and Papua New Guinea. Australasian Institute Mining and Metallurgy, Melbourne, pp. 1065-1072.

Turner, S., Foden, J., Sandiford, M. and Bruce, D., 1993. Sm-Nd isotopic evidence for the provenance of sediments from the Adelaide Fold Belt and southeastern Australia with implications for episodic crustal addition. Geochim. Cosmochim. Acta 57, 1837-1856.

OVERVIEW OF THE CURNAMONA PROVINCE AND ITS TECTONIC SETTING

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The Curnamona Province is a well-defined near-circular area of Palaeoproterozoic to Mesoproterozoic crust straddling the SA-NSW border and surrounded by Neoproterozoic to Palaeozoic mobile belts. Palaeozoic deformation variably affects the marginal zones, but the centre is cratonic. According to the popular SWEAT hypothesis, Australia was juxtaposed against western Laurentia as part of the supercontinent Rodinia, which split at ~0.7 Ga to form Gondwana and Laurasia.

The oldest preserved rocks are the late Palaeoproterozoic Willyama Supergroup, including the Pb-Zn-Ag orebodies at Broken Hill. Total known thickness is not great compared to rifts and passive margin wedges; the lower part is a little older than 1.7 Ga, but its base is not seen and the nature of its basement is uncertain. Evidence points to an epicontinental basin with restricted access to the ocean: there are no ophiolites, there is evidence of evaporitic conditions in the lower Willyama Supergroup, and turbidites occur only in the upper part. The succession was complexly deformed and metamorphosed in the Olarian Orogeny (~1.6 Ga).

The tectonic context of the Curnamona Province is poorly understood. Boundary relationships with the generally older Gawler Craton to the west are largely obscured by Neoproterozoic sediments of the Stuart Shelf and Adelaide Geosyncline. The Gawler Craton has a core of late Archaean metasedimentary, metavolcanic and granitic rocks flanked to the east by mid-Palaeoproterozoic sediments, tectonised in the late Palaeoproterozoic. Late Archaean to late Palaeoproterozoic detrital zircons in the Willyama Supergroup suggest the eastern Gawler Craton as a source region.

The SWEAT hypothesis involves assembly of Rodinia by amalgamation of various continental fragments during Grenvillean (1.1 ± 0.1 Ga) orogenesis. Grenville-age mobile belts run from E Laurentia around East Antarctica to join the Albany-Fraser Belt and the Musgrave Block. Grenville-age orogeny has also been suggested in northeastern Queensland. On the other hand, the Willyama Supergroup and the Maronan Supergroup of northwest Queensland, and their orogenic histories, have often been compared, and a continuous orogenic belt, the Diamantina Orogen, has been proposed extending between Cloncurry and Broken Hill. However, if Rodinia was assembled during Grenvillean orogenesis, northern Australia bearing the Cloncurry-Mt Isa region and southern Australia containing the Curnamona Province were not amalgamated until the Musgravian Orogeny. This paradox remains unresolved.

The southern part of the Curnamona Province is divided into the Broken Hill and Olary Domains, reflecting fundamental differences in geological history. In the northwestern part, the Mount Painter and Mount Babbage Inliers are infolded with very thick Neoproterozoic Adelaide Geosyncline cover. The remainder of the Curnamona Province lacks continuous exposure. North of the Olary Domain, the Benagerie Ridge comprises Willyama Supergroup equivalents (but at low metamorphic grade) and little-deformed Mesoproterozoic felsic and mafic volcanics and sediments, known only from drillcore.

Willyama Supergroup is divided into the Thackaringa, Broken Hill, Sundown and Paragon Groups. There is uncertainty as to how these correlate between the two domains, especially in the upper Willyama. The Thackaringa Group is characterised by parallel-laminated, plagioclase-rich metasediments, albite generally dominating over quartz. Initially considered volcanogenic, these contain only detrital zircon populations. More recent literature suggests diagenetic alteration of Na-rich zeolites precipitated under evaporitic conditions. Associated local facies include pelitic schist, and lenticular banded iron formation and bedded barite. In the Olary Domain, the Group contains widespread lenticular quartz-rich rhyolites with round quartz "eyes" and occasional feldspar phenocrysts, coeval with associated with high-level A-type granite intrusives and yielding ages in the range 1.70-1.73 Ga.

Syndepositional mafic and felsic igneous activity characterises the Broken Hill Group of the Broken Hill Domain, often interpreted as representing a rift environment. The base is marked by laminated calc-silicate. The orebodies have been suggested as submarine exhalatives within this rift, and have undergone all the metamorphism and deformation. In the Olary Domain, outside the rift, the Broken Hill Group is represented by thin calc-silicate and the basemetal-anomalous Bimba Sulphide Member. The Hores Gneiss at the top of the Group is a concordant marker in the Broken Hill Domain but lacks an equivalent at Olary. The age (1.69 Ga) is consistent with its interpreted volcanic origin and stratigraphic position above the >1.70 Ga Thackaringa Group volcanics in the Olary Domain. Geochemically similar gneisses of granitic aspect in the Thackaringa Group may be equivalent subvolcanic intrusives.

The upper Willyama Supergroup is dominated by fine to medium-grained clastic metasediments; the Sundown Group generally lacks graphite but contains calc-silicate nodules, and the overlying Paragon Group is characterised by graphitic sediments.

The basin architecture is poorly understood, with no consensus on its overall polarity, where its foreland was, whether it was intracontinental or faced onto an open ocean, and what initiated the Olarian deformation and metamorphism. The great structural complexity of the terrain makes syndepositional structures difficult to interpret. If major tectonic repetitions near Broken Hill are proven, there may be less disparity in thickness between two domains.

Outside the Curnamona Province, the late Palaeoproterozoic to early Mesoproterozoic record is fragmentary. The shape and extent of the Province is determined by Neoproterozoic to early Palaeozoic tectonics, and equivalents of the Willyama Supergroup are likely to have extended beyond its present limits. On eastern Eyre Peninsula, openly folded but little metamorphosed siliciclastic and volcanogenic sediments have intercalated felsic volcanics which, at ~1.74 Ga, are a little older than oldest dated rocks at Olary. On northern Yorke Peninsula, deeper water, more distal sediments interbedded with mafic and felsic volcanics, dated at ~1.74 Ga, are variably metamorphosed, deformed, and hydrothermally altered, being host to copper mineralisation at Wallaroo-Moonta. In the Mount Lofty Ranges, sheared and retrogressed high-grade metamorphics occur as thrust sheets beneath Adelaidean cover. Limited geochronology suggests Olarian metamorphism, implying Willyama Supergroup precursors.

In the Mount Painter Inlier, Mesoproterozoic quartzitic metasediments and felsic volcanics and intrusives possibly overlie an older Palaeoproterozoic core that has been compared to the Willyama Supergroup. However, stratigraphic and structural relationships are still not clear, and no rocks from Mount Painter have so far yielded Palaeoproterozoic ages.

The Olarian Orogeny has mostly been interpreted in terms of three main deformation phases and associated metamorphic episodes. D1 has been commonly accepted as involving nappe-style folding with substantial overturned limbs and the production of regional bedding-parallel foliation. There is, however, little agreement on the vergence of the nappes and associated thrusts, and it is not clear what the overall transport direction was, or indeed if it was uniform throughout the province. In the Olary Domain at least, there is evidence for SE over NW transport, though recumbent synclinal closures are rarely preserved and many may be cut out by thrusts. D2 folds are developed more locally at Olary but, in the Broken Hill Domain, the major NE to N-trending folds that have deformed both upright and inverted strata have traditionally be referred to D2. They may, however, be coextensive with and of similar orientation to D3 structures in the Olary Domain, where D3 folds and shear zones trend NE to E-W, and formed under retrograde conditions. If so, then temperatures remained elevated at Broken Hill where this folding is associated with high-grade metamorphism. There is a general fall in metamorphic grade form granulite facies in the south to lower amphibolite in the north. The Olary Domain is mostly upper amphibolite, but grade decreases northward to the extent that siltstones on the Benagerie Ridge are only gently tilted and weakly cleaved. Syntectonic granite intrusives include 1.63 Ga I-types and 1.59 Ga regional S-types.

The tectonic setting of the orogeny is difficult to establish. The high-temperature metamorphism and lack of ocean-floor rocks or subduction complexes suggest an intraplate environment. NW-directed D1 nappes at Olary and the decrease in intensity to the north suggest a foreland to the NW. If so, then the high grade of ?Palaeoproterozoic rocks in the Mount Painter Inlier is anomalous but, this metamorphism may be largely Delamerian.

During the early Mesoproterozoic, much of the Curnamona Province was uplifted and unroofed. Deposition of pebbly sandstone and felsic and mafic volcanism followed erosion north of the Olary Domain, while the post-tectonic Mundi Mundi Granite was intruded in the Broken Hill Domain. In the Mount Painter Inlier, the extremely thick Freeling Heights Quartzite was deposited and overlain by felsic volcanics and intruded by comagmatic high-level 1.57-1.55 Ga granitoids. Deformation of the Mesoproterozoic rocks is enigmatic: the Freeling Heights Quartzite is structurally concordant with the overlying Adelaidean cover, yet Mesoproterozoic granitoids are highly sheared along the NE trending Paralana Fault and in E-W trending mylonite zones in the Mount Babbage Inlier. Though partly Delamerian, these structures probably had Proterozoic precursors, as either shears similar to D3 retrograde shears in the Willyama Supergroup, or younger structures related to the Musgravian Orogeny.

After long hiatus, sedimentation in the Adelaide Geosyncline began at ~0.83 Ga (early Willouran) with the Arkaroola Subgroup (Flinders Ranges) and equivalent Poolamacca Group N of Broken Hill. Sedimentation of five major rift cycles can be recognised in the Adelaide Geosyncline. The first was marked by intrusion of the NW-trending Gairdner Dyke Swarm (NE Gawler Craton) and Little Broken Hill Gabbro (NSW), and extrusion of the Beda, Wooltana and Wilangee Volcanics that overlie basal Adelaidean transgressive sediments.

The second rift cycle (late Willouran) is represented by the evaporitic, mixed clastic-carbonate Curdimurka Subgroup, largely disrupted by diapirism, with minor mafic lavas, felsic tuff dated at 0.80 Ga low in the Subgroup, and dolerite intrusives. This rift trends mostly NW through the central Flinders Ranges into the Willouran Ranges, but the Mount Painter-Olary and Adelaide regions were on the NE and SW shoulders respectively, where no Curdimurka Subgroup was deposited.

The third rift cycle (Torrensian age) saw a shift to a N-S rift axis, with a W margin along the Torrens Hinge Zone. The NW-trending Macdonald Fault may have been an eastern rift margin; the Broken Hill area was not affected. Sedimentation of the Burra Group commenced with fluvial sands and gravels with local minor mafic volcanics. The bimodal Boucaut Volcanics S of Olary, dated at 0.78 Ga, underlie the basal sandstone, possibly representing initiation of the third rift phase. The remainder of the Burra Group comprises siltstone, dolomite, sedimentary magnesite and feldspathic sandstone occurring as 6-7 transgressive-regressive sequences, with some minor disconformities.

The fourth rift cycle (Sturtian age) accompanied glaciation. Major sites of rifting surround the Curnamona Province and may be largely responsible for determining the shape of this crustal remnant: Baratta Trough to the SW, Yudnamutana Trough to the NW and Torrowangee Trough to the E. The Redan-Anabama Fault was a transform perpendicular to the NW-trending rifts. The Sturtian rift phase was probably closely followed by continental separation (the breakup of Rodinia). The Umberatana Group (SA) and Torrowangee Group (NSW), of Sturtian to early Marinoan age, record the rift- to sag-phase transition. Marinoan glacials accumulated during the sag phase. Lesser extensional faulting continued, producing local sub-basins and uplifts; deep canyons were cut in the latest Neoproterozoic.

At the end of the Neoproterozoic a hiatus in sedimentation, without deformation, was followed by Early Cambrian transgression, with overall upward-deepening carbonate-dominated successions (Hawker Group in the N and Normanville Group in the S). Tuff (0.526 Ga) and mafic flows at the top of the Normanville Group herald the final major extensional episode which formed the NE-trending Kanmantoo Trough, in which many kilometres of marine clastic sediments of the Kanmantoo Group were extremely rapidly deposited. Coeval redbeds in the N contain tuffs dated at 0.52 Ga.

The Delamerian Orogeny (~0.50 Ga) represents the first compressive deformation of the Adelaide Geosyncline and its basement. Deformation first impinged from the SE with tectonic transport to the NW against the SE corner of the Gawler Craton, and then propagated northward. In the Olary region, the Adelaidean cover and its basement were affected by an earlier N to NW-trending fold set and a later ENE-trending set. The latter folds are dominant in the eastern arm of the Nackara Arc and may be largely controlled by the predominant Olarian D3 grain in the basement. The Delamerian Orogeny may involve collision with a microcontinent or island arc to the SE, leading to maximum crustal shortening across the southern Mount Lofty Ranges. However, the position of the Rodinia-breakup continental margin and the relationship to the Tasman mobile belt is still highly uncertain. At the E margin of the Curnamona Province, the Mid-Palaeozoic Bancannia Trough obscures its relationship to the Koonenberry belt containing folded ?Neoproterozoic, Cambrian, Ordovician and Devonian rocks.
After the Paleozoic, the Curnamona Province and its surrounding mobile belts were subject to continued erosion and deep weathering, and are presently exposed because of Cainozoic uplift as Australia came under compression, moving northward after its breakup from Antarctica. It is principally the Paleozoic mobile belts that were uplifted because Paleozoic reverse faults were appropriately for reactivation, and uplift is still under way. The central cratonic part of the Curnamona Province, little deformed by the Olarian Orogeny and undeformed by the Delamerian, today remains submerged beneath the Lake Frome lowlands.

BROKEN HILL-TYPE MINERAL DEPOSITS: IMPLICATIONS FOR FUTURE EXPLORATION AND RESEARCH

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Implications for further exploration assume that present explorers have already made good use of the more detailed aeromagnetic and gravity data; at least for direct targeting of anomalies. Therefore future emphasis will be on further geological interpretation.

To assess the impact of both the BHEI and some concurrent AGCRC contributions we may reflect on the following four questions:

What are the important new key observations and what level of confidence can be put on these?

How does that change our understanding of the geology and hence where we look for mineral deposits in this region?

How may important ore controls be recognised in standard data?

Can a field test be devised to detect the presence or absence of key criteria necessary for ore formation?

At the time of writing this abstract I can only make preliminary comment on a few points based on two earlier meetings this year (April and July) which specifically looked at Broken Hill Research as well as some published data from the AGCRC.

The combination of mapping by Donaghy and geochronology by Nutman suggest to me the real possibility of a cratonised Thackaringa crust prior to a "Sundown Basin Rifting" event (probably around 1675 Ma). This would put the Broken Hill ore system at a package boundary which is recognisable in standard data. It also begs the question of what is the true nature of the Broken Hill Group.

Future research may determine if that sequence boundary is an unconformity or tectonic surface and if ore was emplaced in the brittle upper crust or at ductile mid crustal levels.

As most BHT exploration already follows the favourable horizon concept the impact of these "new observations" is marginal to exploration, at least close to Broken Hill.

The new regional structural interpretation of Gibson emphasises faults based in large measure on the new seismic data. The implied net sinistral shear offset of the Broken Hill Antiform (to a position west of the Yanco Glen Synform) gives a clear but only local target focus.

The more fundamental question about the boundary between the Olary and Broken Hill block (Mundi Mundi fault) and the south-east dipping listric shaped faults south-east of the Stephen Creek shear, remains unclear. The fact that some of the faults (eg Rasp Ridge Shear Zone) were also high grade mylonites, suggest they existed at the time or prior to the recorded high grade metamorphic events (1600 Ma and possibly 1640 Ma) either as thrust or extensional faults.

The suggestion that the original rift geometry (possibly as old as 1675 Ma) is that seen in the seismic section after Mid Proterozoic metamorphism and deformation, Grenvillean thrusting, Rodinian extension and Delamerian thrusting is implausible. Also apparently of little exploration value without a field method for locating the older faults. What is needed is a better reconciliation of the flat detachments? with the steep listric faults, the mapped geology, the basement gravity and the metamorphic grade.

Thermal history data from AGCRC studies (Ehlers and Nutman) needs further evaluation and may, in time, lead to a fundamental shift in where we look for these deposits globally.

Acknowledgements
On behalf of the Industry Advisory Panel of the AGCRC, I thank the BHEI organisers for the opportunity to review this initiative from an exploration perspective. I am also grateful to people at AGSO, Monash, NSWGS and BHP for freely discussing their ideas

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POTENTIAL FOR PORPHYRY COPPER MINERALISATION IN THE BROKEN HILL REGION, NSW

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The Broken Hill Block is renowned for the existence of the world class Broken Hill silver-lead-zinc deposit and some 3,500 minor base metals, precious metals and industrial minerals deposits. It is one of the most intensively explored and mapped Proterozoic domains in Australia, and yet immediately to the south east across the Redan fault there is virtually no information on the basement geology other than that provided by regional geophysical data and five drillholes (compared with 1300 drillholes on the Broken Hill Block). Using this geophysical information PlatSearch has applied for a set of tenements covering some 1,800 square kilometres extending from the Scopes Range area to the north east to the South Australian border to the south west.

Our focus on this region stemmed from interesting drilling results at our Wahratta prospect, combined with the release of detailed aeromagnetic data by AGSO over the Menindee Sheet, and PlatSearch's chronic fixation for soil covered previously unexplored areas with interesting geophysics and within trumpeting distance from known 'elephant country'.

At Wahratta, located approximately 50 kilometres east of Broken Hill, our previous JV partner Rio Tinto completed drill hole DD96WA003 to test a very large discrete magnetic anomaly located on the eastern periphery of the Broken Hill Block. This hole intersected a variously magnetic intrusive complex from 826 to 1103 metres vertical depth.

Petrological study of the core by Rio Tinto's petrologist has shown that the entire intersection is comprised of shoshonitic volcanics, porphyritic intrusive rocks including monzonites, micro-diorite, and quartz syenite. There is pervasive hydrothermal alteration, and K-feldspar alteration around sulphide veins - a classic porphyry copper gold geological environment, probably of Palaeozoic age. All of the rocks are considered to represent an andesitic volcanic province with a wide variety of subvolcanic intrusions. The NSW DMR has obtained suitable zircon samples from the core and is currently having age testing done at ANU.

Our consultant Geonz Associates confirms the above findings and suggests that based on the nature and degree of alteration and fracturing, the hole is probably close to a major hydrothermal centre. Selective assaying of the hole shows weak copper anomalism (up to 370ppm). The highest gold assay is 14 ppb.

An 816 metre diamond drill hole by Mobil on a gravity anomaly approximately 2.5 kms to the west cored Adelaidean sediments all the way, suggesting the presence of a major north south structure between the two holes. This could be the conduit for a hydrothermal system.

Clearly, at these depths, typical porphyry copper mineralisation would not be economic. However, this is a large intrusive complex with plenty of scope for other styles of mineralisation. PlatSearch has completed a gravity survey at Wahratta and the results show three features of interest - a gravity 'low' which is possibly due to an alteration system, a gravity 'high' which is possibly due to a large sulphide/ironstone body, and a north-south trending contact structure which could be a conduit for mineralisation. All three features represent worthwhile targets for further drilling.

Following the results at Wahratta, using available aeromagnetic and gravity data, PlatSearch acquired a set of tenements covering a large area to the south. The aeromagnetic data combined with sparse drilling information indicates that the depth of cover in these areas is much shallower than at Wahratta. As far as can be determined from the limited information, depth to basement appears to vary between 30 and 200 metres over the tenement areas.

Detailed aeromagnetic data are available for part of the area thanks to AGSO and the Broken Hill Exploration Initiative programme. The magnetics show the Wahratta rocks extending south into an extensive zone of complexity to the east of the Redan Fault. This zone is part of a major structural corridor related to the Darling Lineament, bounded on the west by the Redan Fault and to the east by the Bancannia Trough. Within this zone the magnetic and gravity data show evidence of extensive rifting and dislocation of the basement geology. Coloured images do little justice to the magnetic data in this area, as the image stretching tends to be dominated by the intense magnetic patterns to the west over the Willyama Block. Magnetic contours present a much more useful picture. There are several areas and anomaly features that warrant testing in PlatSearch's view.

To the south of Wahratta and east of the Redan fault, there are only 5 recorded drill-holes that have penetrated basement. Summaries of these holes follow.

Hole CP3, Mobil, 1981, total depth 400 metres. At 32 metres the hole entered weathered basement and from 38 to 400 metres an altered mafic rock/sediment sequence. Rocks examined comprise non-porphyritic andesite, pyroxenite and tuffaceous sediments, with generally low intensity of alteration. Of note is the absence of magnetite even though the hole was targeted at a magnetic anomaly. Mobil reported anomalous copper in the weathered profile. The hole was thought to have been located on a basement high. An Alliance Oil drill hole (Kars No2) located approximately 8 kms to the north east of CP3 intersected similar basement rocks beneath 120 metres of Tertiary cover.

Hole ED1, BHP, 1982, total depth 400 metres. The hole targeted a linear magnetic anomaly that appears to be structurally related and coincides with eastern boundary of graben structure parallel to the Redan Fault. The hole intersected a highly variable sequence of lavas, pyroclastics, sediments and intrusive rocks beneath 136 metres of Quaternary and Tertiary cover. Large intervals of the igneous rocks were reported to display pervasive hydrothermal alteration together with intense quartz microveining and fracturing. Pyrite and pyrrhotite were locally abundant as disseminations and thin veinlets. There was high primary K-feldspar contents in the matrix of some of the volcanic and pyroclastic units. The observed alteration was described as actinolite, epidote, calcite accompanied by K-feldspar veins and sericitised quartz-albite veins carrying pyrrhotite, pyrite and trace chalcopyrite. Analysis results indicated no anomalous base metals values. BHP considered that there is a correlation of the volcanic sequences at the ED1 and CP3 holes, but that ED1 was a more proximal volcanic/intrusive environment. PlatSearch has so far been unable to locate the core from ED1.

Hole EHK1, Pasminco, 1995, total depth 129.5 metres. The hole entered basement at 109.6 metres and intersected microdiorite with minor quartz and K-feldspar.

Hole EHK2, Pasminco,1995, total depth 187.5 metres. The hole entered basement at 167 metres and then intersected microdiorite tending to monzonite. Some parts show pervasive K-feldspar flooding and secondary biotite. Fracture filled veinlets filled with quartz and, pyroxene and pyrite are also present.

Hole EHK3, Pasminco, 1995, total depth 306 metres. This hole entered bedrock at 122.5 metres and continued in a mixed suite of andesite, dolerite and microdiorite. The dolerites showed evidence of a calc-alkaline affinity including some highly potassic andesites while the dolerites where interpreted as belonging to a more tholeiitic suite. Weak alteration and minor pyrite and common magnetite were present in most samples.

Following inspection of all available core, Geonz Associates reported that the overall intensity of hydrothermal alteration in both the Mobil and Pasminco cores is low in comparison to Wahratta, indicating that the former are probably more distal from any possible porphyry type centre. In Geonz Associates view there are sufficient indicators from the lithologies and the minor alteration features to support the prospectivity of the region for porphyry copper-gold mineralisation.

There appear to be two NE-SW trending, predominantly igneous, belts of rocks separated by a sedimentary trough. These may represent former structurally controlled island arc type volcanic terrains separated by a major graben feature. The only gravity information in the region is old very wide spaced data, but this is sufficient to show two gravity "high" ridges coincident with these igneous belts.

Of significance, from the point of view of potential for mineralisation, is the emerging evidence for a high calc-alkaline affinities and strong magma differentiation along the northern arc. Granodiorite and diorite intrusives intersected in recent drilling by BHP to the north east of Wahratta occur proximal to the altered shoshonitic rocks at Wahratta in what appears to be a central position.

Along strike to the north east, trachyte, trachyandesite and latite have been intersected by BHP's drilling. It is important to note that petrological studies on samples from both the intrusions and the trachytic lavas have revealed high potassium contents in the form of biotite and K-feldspar. In the equivalent position to the south west mixed lithologies comprising lavas and dolerite/diorite intrusions were cored in the earlier BHP and Pasminco drill holes.

This information is pointing towards a very positive environment for the existence of porphyry related Cu-Au deposits, similar to those in central NSW. Clearly, given the paucity of drilling and the size of the area involved, the area is essentially unexplored.

Being located on the north west margin of the Murray Basin, PlatSearch's tenements are also prospective for heavy mineral sands. Westralian Sands has farmed into PlatSearch's areas, and are earning an 80% interest (in mineral sands only) by undertaking a programme of detailed aeromagnetic surveys and extensive shallow drilling. With Westralian's new data we now have almost continuous detailed aeromagnetic coverage over the full set of tenements. There are several basement features in the new data, including at least one Wahratta "look alike", that will warrant drill testing in PlatSearch's view.

Some samples from Westralian's shallow drilling will be made available to PlatSearch for other analyses and PlatSearch intends to investigate the applicability of calcrete BLEG and/or mobile ion geochemical techniques to assist in the exploration of these areas.

COPPER-GOLD MINERAL SYSTEMS AND REGIONAL ALTERATION, CURNAMONA CRATON

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The Curnamona Province is host to some of Australia's newest copper and gold discoveries, including the Portia, White Dam and Kalkaroo prospects. As an emerging major Cu-Au mineral province, there is a need to re-evaluate the metallogeny of its Cu-Au mineral systems, with the aim of developing datasets that will assist in reducing risk in mineral exploration. We report here some preliminary constraints on the timing and chemical conditions of regionally distributed alteration styles, and their relationship to Cu-Au mineralisation.

REGIONAL ALTERATION

The Paleoproterozoic Willyama Supergroup in the Olary and Broken Hill Blocks is remarkable for its abundance of regional alteration, including widespread pre- or early-tectonic sodic metasomatism, more localised syn-tectonic Na-Ca-Fe alteration, garnet±epidote replacements, and potassic – iron oxide – carbonate alteration (Ashley et al., 1997; Ashley & Plimer, 1998).

Pre- or early-tectonic sodic metasomatism: Significant thicknesses of the Quartzo-feldspathic Suite (QS) and Calcsilicate Suite (CS) in the Olary Block, and Thackaringa Group and lower units in the Broken Hill Block, are sodic plagioclase±magnetite-rich, and probably represent metamorphosed altered sediments and felsic volcanics (e.g. Plimer, 1977; Cook & Ashley, 1992). This sodic alteration overprinted ~1712-1700 Ma A-type felsic volcanics and intrusions (Ashley et al., 1996; Page & Conor, 1998), but predated or was synchronous with the earliest recognised deformational fabric. A repetition of this metasomatic process occurred within ~1650 Ma or younger (Page & Conor, 1998) low grade sediments of the northern Olary Block – Benagerie Ridge, and in 1630-1640 Ma I-type granites. Pelitic sediments, commonly biotite-bearing and in places carbonate-rich and/or carbonaceous, were Na±Fe±S altered (now albitite ±magnetite±biotite± pyrrhotite/pyrite) prior to, or early within, the ~1590 Ma regional deformation and low grade metamorphism. The pre- or early-tectonic sodic alteration of the Benagerie Ridge appears to be largely stratabound, and associated disseminated magnetite (in part metasomatic) may be the source of extensive curvilinear magnetic anomalies below the contact with less altered pelites.

Syntectonic Na-Ca-Fe alteration: Vein networks, massive replacements and calcsilicate-matrix breccias overprint pre- or early-tectonic sodic alteration, and occur widely and preferentially within the CS (Yang & Ashley, 1994). Breccia clasts are mainly albite±titanite altered calcalbitite and rare granite, and the matrix is composed of actinolite-albite ±clinopyroxene±quartz±magnetite±hematite±garnet. Host rocks are intensely albitised within tens to hundreds of metres of breccia bodies, which may reach several hundred metres in areal dimensions. This style of alteration decreases in prominence northwards in the Olary Block – Benagerie Ridge, and has not been reported in the Broken Hill Block. At least two stages are present: syn-$D_{3(?)}$ Na-Ca-Fe alteration localised by NE-plunging $F_{3(?)}$ upright folding and brittle-ductile shearing (e.g. Teliche Valley, Cathedral Rock), and later extreme bleaching to albite±actinolite. The first stage included substages of early clinopyroxene, and later retrograde actinolite. The $D_{3(?)}$ alteration and brecciation postdates ~1630-1640 Ma I-type granites (e.g. Antro granite) but is intruded by granite dykes that are probably affiliated with the ~1590 Ma suite, which is itself minimally altered. Massive garnet-epidote-rich replacements of calcsilicate horizons (garnet-plagioclase Sm-Nd ages of ~1530-1585 Ma: Kent et al., unpublished data), may have formed coevally with syntectonic Na-Ca-Fe alteration from similar and related oxidised brines (Ashley et al., 1997).

Potassic and hematitic alteration: Biotite and red hematitic K- and Na-feldspar alteration are largely confined to the northern Olary Block – Benagerie Ridge. There are, however, notable examples of localised biotite-magnetite alteration in other areas, commonly associated with Cu-Au mineralisation, e.g. Walparuta (SW Olary Block) and Copper Blow (SE Broken Hill Block). Potassic alteration in the Benagerie Ridge occurs with or without Cu-Fe sulfide mineralisation, and consists of red K-feldspar and/or biotite with carbonate±magnetite± amphibole±quartz vein stockworks and replacements, overprinting sodic altered metasediments. Still later albitisation of K-feldspar is evident in some areas. Enhanced magnetic response commonly accompanies K-feldspar- and biotite-bearing alteration. The potassic alteration was synchronous with mainly brittle deformation in northern areas, and ductile-brittle deformation further south, relatively late in the tectonic history (late-D_3?). Biotite- and muscovite-rich retrograde shear zones, some of which were active during the Delamerian orogeny, are probably unrelated to the magnetite- and/or K-feldspar-bearing potassic alteration.

Late-stage chlorite, sericite and carbonate±fluorite: Chloritisation of hydrothermal biotite is widespread throughout the northern Olary region, whereas intense sericitic alteration is mostly restricted to discrete zones of relatively late-stage deformation, post-dating potassic alteration. Minor late veins of carbonate-quartz-chlorite±fluorite±chalcopyrite±barite, in places with high-level vein infill textures, are present on the Benagerie Ridge.

HYDROTHERMAL CONDITIONS

The pre- to early-tectonic sodic alteration is spatially associated at regional scale with ~1712-1700 felsic volcanics and subvolcanic(?) intrusions, and may represent unfocussed down- and/or lateral-flow zones in relatively low temperature regional convective hydrothermal systems. Iron formations and baritic rocks of exhalative origin (Lottermoser & Ashley, 1996), and possibly some stratabound minor Cu in the QS, are possible products of these systems. The sources of the fluids responsible for 'early' sodic alteration are being determined using stable isotopic methods, and could include contributions from saline lake waters, seawater, magmatic waters or connate brines with input from evaporites (Cook & Ashley, 1992; Ashley et al., 1996, 1997; Ashley & Plimer, 1998).

Syntectonic Na-Ca-Fe alteration formed initially anhydrous assemblages including clinopyroxene at high temperatures, followed by a hydrous stage represented by amphibole. Hypersaline, hematite-stable fluids at 450-600°C were involved in development of at least the early assemblage (Yang & Ashley, 1994; Ashley & Plimer, 1998). These alteration zones may represent parts of fossil fluid reservoirs deep within syntectonic hydrothermal systems, or fluid flow paths linking source regions to higher crustal levels, following peak metamorphism. The lack of sulfides associated with the Na-Ca-Fe alteration is probably related to low sulfur contents of the fluids and/or high temperature, rather than low metal contents.

Potassic alteration occurred at generally lower temperature and pressure than for syntectonic Na-Ca-Fe metasomatism, and involved CO_2-bearing, near-neutral pH fluids, at redox varying from magnetite-pyrrhotite to magnetite-hematite stability. It is likely that this alteration represents fluid-rock interaction in an upflow and/or cooling hydrothermal regime, at higher crustal levels and/or later than the Na-Ca-Fe alteration. The precise relationship between these two alteration styles, and with magmatism and Cu-Au mineralisation, are key questions under investigation.

CU-AU DEPOSITS

A large number of minor Cu prospects as well a several major Cu-Au (-Mo) prospects in the Olary region are situated within a few hundred metres of the interface between ≤1650 Ma pelitic±carbonate±carbonaceous metasediments of the Pelite Suite and underlying calcsilicate-rich metasediments of the Bimba Suite, CS and ~1712-1700 Ma felsic volcanics and metasediments of the QS. Although apparently stratabound, the larger epigenetic Cu-Au systems contain locally fracture- or shear-controlled mineralisation that is transgressive to compositional layering. Chalcopyrite-pyrite±molybdenite form stockworks, breccia matrices, replacements along compositional layering and disseminations generally associated with potassic alteration and hydrothermal carbonate. Albite, magnetite, pyrrhotite, actinolite, hematite, barite and chlorite are locally present in sulfide-associated assemblages at various stages in the paragenetic sequences. Pre-existing iron formations and ironstones host epigenetic Cu-Au in a few cases (Lottermoser & Ashley, 1996). Copper mineralisation anomalous in Co±As, especially in calcsilicate-rich parts of the stratigraphy (e.g. Bimba Suite), may represent epigenetic overprinting of pre-tectonic sulfide mineralisation (Ashley et al., 1997). Bierlein et al. (1996) suggested that epigenetic Cu-Au-quartz and Pb-Zn±Cu-carbonate vein deposits were emplaced at 450-480 Ma. These deposits differ from the ?Paleo- or Mesoproterozoic Cu-Au- (Mo) deposits associated with potassic – iron oxide – carbonate alteration discussed herein.

Anomalous molybdenum is characteristic of several of the larger mineralised Cu-Au systems: the shared metal inventory is suggestive of common genetic processes. Two groups are apparent in the table below, with Au/Cu ($x10^4$) ratios >1 and <1.

Gold and copper grades*, Curnamona Craton

Prospect	Au, g/t	Cu, %	Mo	Representative Drill Hole Intersections	Au/Cu $x10^4$
White Dam	2.8	0.2	signif	20 m	14
	7.2	1.7	signif	14 m	4.2
N. Portia	1.21	1.06	235 ppm	76 m	1.1
	0.56	0.72	838 ppm	72 m	0.78
Walparuta	0.3	0.31		28 m	1.0
Mundi Mundi	6.2	7.2	trace	1.8 m	0.86
Kalkaroo	0.14	0.28	signif	30 Mt resource	0.5
Copper Blow	0.8	4.0	trace	10.8 m	0.02
	4.2	5.7	trace	2.7 m	0.73
Waukaloo		>0.3	trace	35.1 m	

*data from media and open file reports

White Dam is distinguished by high Au/Cu ratios and very low iron oxide content. Copper Blow mineralisation typically has lower Au/Cu than most of the Olary – Benagerie Ridge deposits, and is hosted by epigenetic magnetite-biotite-rich ironstones that formed synchronously with post-peak metamorphic shearing. These two deposits may represent end-members within a spectrum of Cu-Au systems in the region.

COMPARISON WITH CU-AU SYSTEMS ELSEWHERE

Alteration styles, assemblages and sequences in the Olary - Benagerie Ridge region show remarkable similarities with those of Cu-Au districts in the Eastern Succession of the Mt Isa Inlier and Moonta-Wallaroo district of the Gawler Craton (Conor, 1996). The transition spatially and temporally from Na-Ca-Fe to potassic alteration with associated Cu-Au is particularly significant for exploration. Copper-gold-iron deposits of the Curnamona Craton are viewed as members of a broad class of structurally controlled Proterozoic Cu-Au-Fe deposits including those of the Cloncurry, Stuart Shelf, Tennant Creek and Kiruna districts. Ore-stage conditions at Olympic Dam are characterised by lower pH fluids (sericite-chlorite alteration) and higher redox (abundant hematite) than in Olary Cu-Au systems. However there are similarities between paragenetically late carbonate-barite-fluorite veining at Olympic Dam and in the Benagerie Ridge. The metal inventory (Cu-Au-Mo) and alteration are superficially similar to those of porphyry Cu-Au systems (e.g. Sillitoe, 1993), but carbonate is not characteristic of potassic alteration in porphyry systems and the Olary mineralisation does not occur within porphyritic intrusions, although a link with ~1590 Ma granites has been suggested (Wyborn et al., 1998).

REFERENCES

Ashley, P.M. and Plimer, I.R., 1998. Proterozoic Olary Domain, South Australia: Regional and local scale alteration and mineralisation. *Geol. Soc. Aust. Abstracts* 49, 14.

Ashley, P.M., Cook, N.D.J., Fanning, C.M., 1996. Geochemistry and age of metamorphosed felsic igneous rocks with A-type affinities in the Willyama Supergroup, Olary Block, South Australia, and implications for mineral exploration. *Lithos* 38, 167-184.

Ashley, P.M., Lawie, D.C., Conor, C.H.H. and Plimer, I.R., 1997. Geology of the Olary Domain, Curnamona Province, South Australia, and Field Guide to 1997 Excursion Stops. *Mines & Energy SA*, Report Book 97/17.

Bierlein, F.P., Foster, D.A. & Plimer, I.R., 1996. Tectonothermal implications of laser ArAr ages of sulfide-bearing veins and their host rocks in the Willyama Supergroup, South Australia: Evidence for syn-tectonic to late-stage mobilisation. *Min. Pet.* 58, 1-22.

Conor, C.H.H., 1996. Curnamona, Moonta and Cloncurry: Common styles of alteration and mineralisation linked by the Diamantina Orogen. In: Preiss, W.V. (compiler), Resources '96 Convention Abstracts, *Mines & Energy South Australia*, 40-42.

Cook, N.D.J., and Ashley, P.M., 1992. Meta-evaporite sequence, exhalative chemical sediments and associated rocks in the Proterozoic Willyama Supergroup, South Australia: Implications for metallogenesis. *Precambrian Research* 56, 211-226.

Lottermoser, B.G. and Ashley, P.M., 1996. Geochemistry and exploration significance of ironstones and barite-rich rocks in the Proterozoic Willyama Supergroup, Olary Block, South Australia. *Journal of Geochemical Exploration* 57, 57-73.

Page, R.W. and Conor, C.H.H., 1998. Uranium-lead zircon dating in the Olary Block. AGSO Record, Abstracts of the 1998 BHEI Meeting, Broken Hill (this volume).

Plimer, I.R., 1977. The origin of the albite-rich rocks enclosing the cobaltian pyrite deposit at Thackaringa, NSW, Australia. *Mineralium Deposita* 12, 175-187.

Sillitoe, R.H., 1993. Gold-rich porphyry copper deposits: Geological model and exploration implications. In: Mineral Deposit Modelling, *GAC Special Paper* 40, 465-478.

Wyborn, L.A., Budd, A., Stevens, B.J., Conor, C.H.H., Ashley, P.M. and Bastrakova, I., 1998. Granites of the Broken Hill - Olary region and their metallogenic potential. AGSO Record, Abstracts of the 1998 BHEI Meeting, Broken Hill (this volume).

Yang, K. and Ashley, P.M., 1994. Stratabound breccias in the Willyama Supergroup, Olary

Block, South Australia. *AMF*, Proceedings, Australian Research on Ore Genesis Symposium, Adelaide, December 1994, 16.1-16.5.

THE ORIGINS OF BROKEN HILL ROCK TYPES AND THEIR RELEVANCE TO MINERALISATION

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Interpretation of the origin of rock types is profoundly influenced by interpretation of the stratigraphic sequence and relative ages of the rocks. For four years or more the NSW Geological Survey stratigraphic interpretation of the Willyama Supergroup (Willis et al. 1983, Stevens et al. 1988) has been under seige from structural and metamorphic geologists who refused to believe that a stratigraphic sequence could be identified after the high grade metamorphism and multiple deformation. Some of these researchers (Nutman et al. 1997), and others, have produced a valuable collection of SHRIMP zircon U-Pb dates, supporting the overall NSWGS stratigraphic interpretation. It is now quite clear that the NSWGS stratigraphic interpretation is valid, at least from Cues Formation to the top of the Paragon Group. Doubt has been cast on the existence of the Lady Brassey Formation and the Alma Gneiss in the Thackaringa-Triple Chance area (Donaghy et al. 1998), and some rock types which were interpreted as parts of the original stratigraphy may in fact have been syn-sedimentary intrusions. There is also continuing doubt about the relationship of the Redan geophysical zone, to the remainder of the Broken Hill Block. There have been attempts to infer major unconformities or pre-folding thrusts between the Thackaringa, Broken Hill, Sundown and Paragon Groups (Nutman et al. 1997), but the proponents have failed to produce convincing evidence or to consider the consequences of such interpretations on regional geology. It is possible that the whole Willyama Supergroup was deposited between 1710 and 1680 Ma. Given the possible effects of high grade metamorphism and fluids on the integrity of zircon U-Pb systems, this is a very narrow range with much scope for erroneous interpretation of results.

Following is my assessment of the most likely origins for each of the rock types, then some discussion about their relevance to mineralisation.

Metasediments The origin of the siliciclastic metasediments is not in doubt, but there could be more than one interpretation of depositional environment.

Basic Gneisses The chemistry of the amphibolites and basic granulites is consistent with Fe-Ti rich fractionation of tholeiitic basalt (Stevens and Capnerhurst 1998). They are present throughout the sequence up to the top of the Broken Hill Group, are extremely rare in the Sundown Group and are absent from the Paragon Group. They have been dated at 1680-1690 Ma (Nutman et al. 1997), except one at about 1620 Ma (A.Nutman pers. comm). Many have massive textures consistent with an origin as dolerite. One outcrop in the Mt Robe area shows dendritic amphibole, suggestive of replacement of quench-textured pyroxene. Despite a thorough search, no pillow structures have been found. The most likely origin for these massive-textured basic gneisses is syn-sedimentary sills and dykes. Other basic gneisses are moderately to well-layered; some of these may have had a tuffaceous origin. A small number of basic gneisses may be post-1690, pre-1600 Ma intrusions.

'Potosi-Type' Gneiss in Hores Gneiss Abundant volcanic quartz phenocrysts and feldspar laths in the lowest metamorphic grade area, establish a connection with volcanism (Page & Laing 1992, Stevens et al. 1998). Detrital zircons of 1690-1700 Ma (Nutman et al. 1997) in the overlying Sundown Group metasediments, the same age as those in the 'Potosi-type'

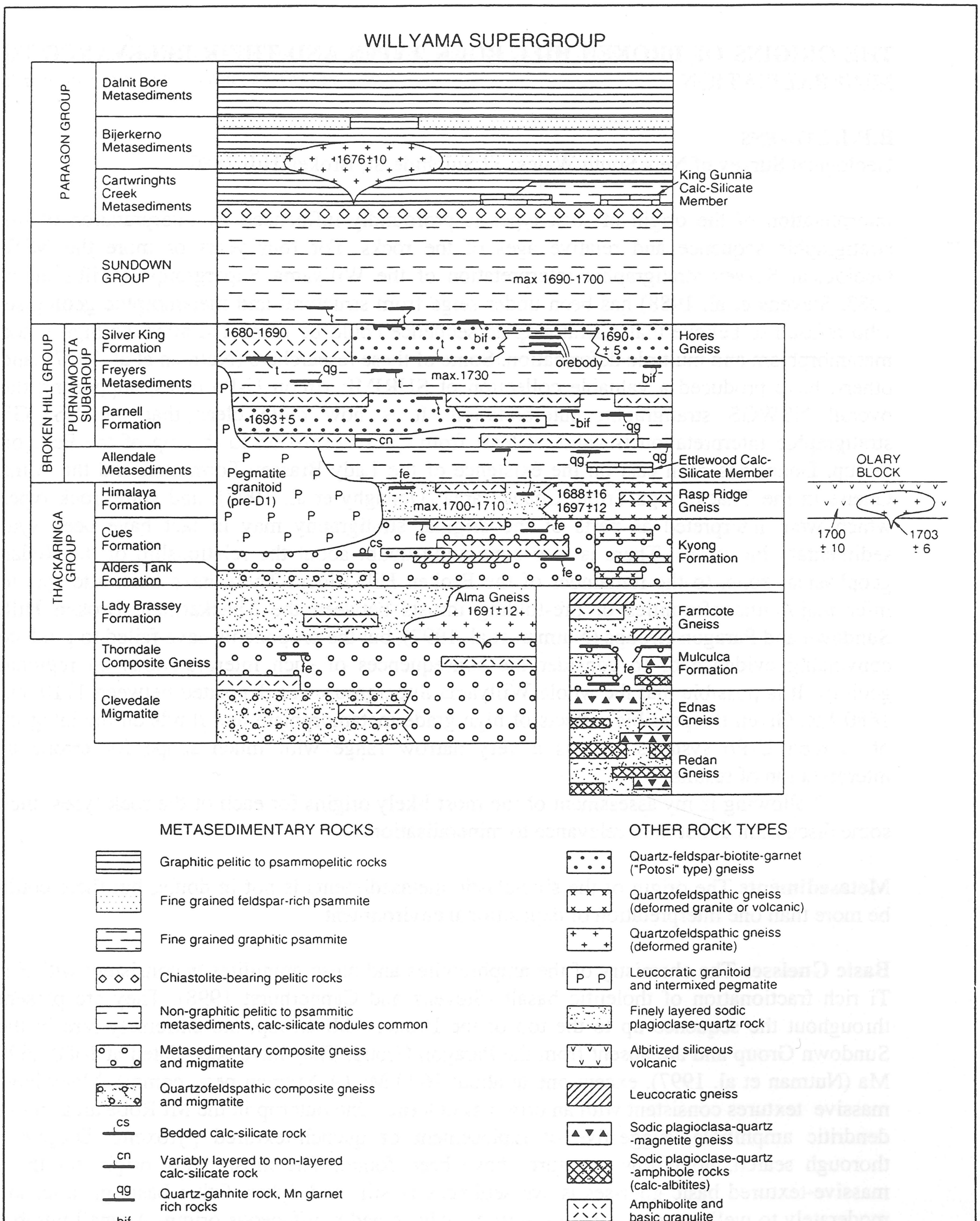

Figure 1: Simplified rock relationship diagram for the Willyama Supergroup, showing zircon U-Pb dates (Ma) accepted by the author, as depositional ages or detrital ages (youngest detrital age in metasediments shown as maximum age for that unit). Dates from Page and Laing (1992), Nutman et al. (1997), Nutman and Ehlers (1998).

gneiss (1690±5 Ma), show that magmatic rocks of this age were exposed to erosion soon after deposition. The great lateral extent of Hores Gneiss (2000-3500 km^2), its continuity, low aspect ratio, conformability, consistent stratigraphic position and incorporated wet sediment clasts, are all consistent with an extrusive or volcanic sediment origin. Its composition is not that of a pristine acid lava, but appears to require the addition of sediment (Stevens et al. 1998). The gneiss originated as volcaniclastic sediment, ignimbrite with incorporated sediment, and/or lava, probably burrowing, with incorporated sediment. Suspected amygdules near Yanco Glen suggest a lava or ignimbrite for part of this unit. Nutman and Ehlers (1998) used the younger of 1690±38, 1665±12 and 1651±12 Ma zircon U-Pb dates from Hores Gneiss in the Southern Cross-Nine Mile area to suggest a later, granitic origin. Field evidence shows that these rocks were not granites; they are in the Hores Gneiss stratigraphic position, and they contain calc-silicate-bearing metamorphosed concretions which preserve volcanic quartz phenocrysts (somewhat recrystallised). Explanations for the ambiguous U-Pb results may include partial Pb loss during metamorphism, resetting by adjacent intrusive leucogranite (now leucogneiss) and pegmatite, and alteration by fluids.

'Potosi-Type' Gneiss in Parnell Formation Much of the same argument applies to this gneiss in Parnell Formation. However volcanic quartz phenocrysts have not yet been identified, and the composition of the gneiss in the lowest metamorphic grade area is somewhat different from that of Hores Gneiss. The common but puzzling gradation between the 'Potosi-type' gneiss and amphibolite, producing the rock known as 'Potobolite' may have resulted from a reaction between wet volcaniclastic sediment and intrusive dolerite. The gneiss was dated at 1693±5 Ma (Page & Laing 1992), consistent with a volcanic or volcaniclastic sediment stratigraphically below Hores Gneiss.

Alma Gneiss In several places, the quartzo-feldspathic gneiss which constitutes the Alma Gneiss, contains abundant feldspar megacrysts and augen, and resembles a deformed, coarsely porphyritic granite. It has the composition of an almost unaltered granite. Its age (1691±12 Ma, Nutman & Ehlers 1998) is indistinguishable from that of Hores Gneiss. Willis et al. (1983) interpreted the Alma Gneiss as a metamorphosed volcanic, because of its apparent conformability and consistent stratigraphic position. Evidence that the megacrysts are igneous and not metamorphic (Vassallo 1995) supports the interpretation that the gneiss was a granite. It apparently intruded as a thick sill, no more than 2 km below the contemporaneous seafloor.

Rasp Ridge Gneiss This stratigraphic unit also consists primarily of quartzofeldspathic gneiss, but with far fewer feldspar megacrysts. The gneiss is widespread and occupies a consistent stratigraphic position. The composition of most of it corresponds with that of an unaltered granite or acidic lava, but in rare places, garnet-rich phases have compositions resembling those of Hores Gneiss. Scattered quartz-spotted phases containing calcic plagioclase have not yet been satisfactorily explained.The gneiss has been dated at 1688-1697 Ma (Love 1992, Nutman & Ehlers 1998), indistinguishable from Hores Gneiss and Alma Gneiss. This age is slightly younger than the probable age of laterally equivalent albitic metasediments in the Broken Hill Block (youngest detrital zircons 1700-1710 Ma, Donaghy et al. 1998), and metavolcanics and deformed granite in the upper part of Thackaringa Group equivalents in the Olary Block (Ashley et al. 1996). The age difference infers that the Rasp Ridge Gneiss was a granite emplaced about 10 m.y. after the Thackaringa Group, and possibly co-magmatic with Hores Gneiss. If so it was a sill emplaced only about 1 km below the seafloor. However such small age differences may not be valid. The Rasp Ridge Gneiss could have been acidic lavas and/or ignimbrites, or a combination of volcanic and intrusive rocks.

Albite Rocks Layered (bedded) albite-quartz rich rocks constitute most of the Himalaya and Lady Brassey Formations, are found in Cues Formation, Thorndale Composite Gneiss and Clevedale Migmatite. They are too Na-rich to be normal detrital sediments; their compositions could be achieved by zeolitisation of glassy ash in alkaline lakewater, but the characteristics of contained zircons suggest that the rocks were detrital sediments with only minor volcanic component (Love 1992, Donaghy et al. 1998). The zircon grains are small, anhedral and pitted, and have a range of ages. The concentrations of zircon grains are irregular, suggesting sedimentary sorting. The current interpretation is that the albitic rocks were planar-laminated sediments (fine sand, silt, possibly clay), altered as a result of deposition in an evaporative (lake or sabhka) environment. The existence of dolomite rhombs in albitic metasediments in the Olary Block strengthens the evaporite interpretation. Boron isotopes indicate evaporative conditions somewhere in the Willyama Supergroup (Slack et al. 1989) . Albite-quartz-hornblende-magnetite rocks in the Redan area are finely, planar bedded, and similar in composition to calc-albitites of the Olary Block.

Mixed Leucogranitoid/Pegmatite Bodies (map symbol Lq) These appear on maps as large blobs in places such as the Mt Robe Synform and the Paps Synform. However they are approximately stratigraphically controlled (Stevens 1978), probably representing thick sheets. None of the large masses extend stratigraphically above the Hores Gneiss; this applies on upright and on inverted F1 fold limbs. They exhibit a deformation layering and parallel schistosity which is folded. It is interpreted that leucogranitoid sheets were emplaced before D1. The melts most probably crystallised at a pre-folding andalusite-sillimanite isograd. Remnants of this isograd exist near Yanco Glen and east of Mt Robe.

BIF The rocks labelled bif are Mn garnet-magnetite-apatite-quartz rocks. They are confined to the Broken Hill Group, exhibit finely laminar bedding and probable slumped bedding and were either distal exhalites related to formation of exhalative Pb-Zn orebodies, or marine chemical sediments, probably resulting from upwelling of cold Fe-Mn-P rich seawater into warmer, more oxidising seawater.

Calc-Silicate Rocks The Ettlewood Calc-Silicate Member consisted of interlayered dolomitic marl, rarer calcite beds and probable chert. It may have formed in shallow marine evaporitic conditions (Plimer 1994) with silica deposited from mixing with terrestrial groundwater. The King Gunnia Calc-Silicate Member is more homogeneous, with undisturbed planar bedding, probably a deeper shelf dolomite. Calc-silicate ellipsoids in siliciclastic Broken Hill and Sundown Group metasediments were diagenetic carbonate concretions, preserving some early textures and providing evidence of post-depositional fluid history (Stevens 1998). Some contain sulphides and may be a pointer to orebodies. Corruga-type calc-silicate bodies are irregular, tend to occur in or adjacent to basic gneiss or 'Potosi-type' gneiss, and probably represent seafloor or sub-seafloor alteration.

Quartz-Gahnite, Garnet Quartzite These rocks have been considered exhalites, but the distribution pattern of garnet quartzite around the Broken Hill orebody suggests that it was a hydrothermal alteration product, probably a manganiferous quartz-chlorite rock. Thinner, conformable bodies elsewhere could have been exhalative sediments. The quartz-gahnite rocks were either exhalites or were formed within the sediments, by lateral fluid flow along permeable beds. Local low-angle discordances could have resulted from rheological contrasts, or from re-solution of some quartz-gahnite during metamorphism.

Tourmaline Rocks Some tourmalinites in the Broken Hill and Sundown Groups preserve delicate cross-bedding and graded bedding, and show a long deformation history. Their chemistry indicates that they are replacements of siliciclastic sediments (Slack et al. 1993). Boron isotopes indicate that the boron came from a non-marine evaporite source (Slack et al. 1989). The albite rocks of Thackaringa Group, deposited in an evaporitic environment, are a likely source of boron; some contain tourmaline layers.

Relevance to Mineralisation

Broken Hill-type deposits were most likely submarine exhalative in origin. It is shown on mid-ocean ridges that the minimum requirements to form exhalative massive sulphide orebodies are dolerite sills, continent-derived sediments and seawater (ODP Leg 169). Cu and some Zn can be derived from dolerite, while Pb and Zn are derived from continental sediments. Turner et al. (1995, 1996) interpreted that the Sullivan Pb-Zn deposit (Canada) originated as a result of dolerite sills intruding wet sediments just below the seafloor. At Broken Hill many of the basic gneisses were probably dolerite sills intruding wet Broken Hill Group sediments at about 1690 Ma. They provided heat, but perhaps insufficient to drive a large convection cell at 300-350°C. At about the same time (or perhaps just before, since basic gneiss appears to intrude granitic gneiss) substantial granitic sills (Alma and possibly Rasp Ridge Gneisses) intruded at shallow depth. The extra heat provided by the dolerite sills added to the heat from the granite(s) could have powered convection cells. Hores Gneiss resulted from eruptions of a similar scale to the A.D. 186 Taupo eruption in New Zealand. This would have resulted in widespread faulting, quite possibly disrupting convection cells and allowing escape of the ore-forming fluid.

But where did the Pb, Zn and Ag come from? Based on modern ocean floor situations, fluid flow through the upper, poorly-consolidated sediments is very slow, except where there are porous sands. Most fluid flow and leaching takes place below about 500m. At 1690 Ma, this probably means that fluid flow and leaching of metals took place in and below the Parnell Formation (uppermost dolerite sills?) or in and below the Thackaringa Group. Some Thackaringa Group albitic metasediments contain extremely low values of Pb and Zn possibly as a result of leaching by the ore fluid. If the albitic rocks were evaporitic it is likely that they contributed halides to the ore fluid, increasing salinity and efficiency of leaching.

It is possible that all the basic intrusives and extrusives were emplaced during Broken Hill Group time. As on the ocean floor, they could have contributed Mn to the environment, supplying the excess Mn found in many rocks in Broken Hill Group and the abundant Mn found in the Broken Hill orebody.

The orebody is located above, but near the edge of the Rasp Ridge Gneiss. If it was a granite, the heat from this rock would have driven fluids upward. The Rasp Ridge Gneiss is laterally equivalent to the Himalaya Formation. Whether granite or massive volcanic, it is likely to have formed an impermeable barrier to fluids moving laterally through the Himalaya Formation. Fluids may have broken out of Himalaya Formation at the interface with Rasp Ridge Gneiss, and moved upwards to the seafloor.

Acknowledgement This paper is published with the permission of the Director-General NSW Department of Mineral Resources.

REFERENCES

Ashley, Cook & Fanning 1996 Lithos, 38, 167-184.
Donaghy, Hall & Gibson 1998. AGSO Record 1998/2, 55-58.
Love 1992 B.Sc Hons Thesis, ANU.

Nutman & Ehlers 1998. Precambrian Research, 90, 203-238.
Nutman, Gibson et al. 1997. Research School of Earth Sciences, ANU, Annual Report, 127-128.
ODP Leg 169
Page & Laing 1992. Economic Geology, 87, 2138-2168.
Plimer 1994. Economic Geology, 89, 423-437.
Slack, Palmer et al. 1993. Economic Geology, 88, 505-541.
Slack, Palmer & Stevens 1989. Nature, 342, 913-916.
Stevens 1978. Geological Survey of NSW Quarterly Notes, 30, 1-18.
Stevens 1998. Geological Survey of NSW Quarterly Notes, 106, 1-15.
Stevens & Capnerhurst 1998. Geological Society of Australia, abs. 49, p.430.
Stevens et al. 1988. Precambrian Research
Stevens, Wyborn & Jagodzinski 1998. Geological Society of Australia, abs. 49, p431.
Turner, Leitch & Hoy 1995. The Gange, 49 (July 1995), 11-12.
Turner, Leitch et al. 1996. CODES Special Publication 1, 153-163.
Vassallo 1995 B.Sc Hons Thesis, Macquarie University.
Willis et al. 1983. Journal of the Geological Society of Australia, 30, 195-224.

REGOLITH LITHOLOGY IDENTIFICATION USING PORTABLE INFRARED MINERAL ANALYZER (PIMA), AN EXAMPLE FROM PORTIA PROSPECT, BENAGERIE RIDGE, SOUTH AUSTRALIA.

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Infrared (IR) spectroscopy is a rapid, economical and non-destructive physical method universally applicable to analysis of materials that reflects or absorb in the infrared region. Recently developed short wavelength infrared reflectance spectrometry (SWIR) whose wavelength ranges from 1300 nm to 2500 nm is becoming popular because of its portability (e.g. PIMA) and easy collection of spectra. The reflectance of infrared radiation is influenced by the degree of crystalline order (i.e. crystallinity), the amount of water within the mineral particles, and the crystal orientation relative to the IR beam. SWIR analysis is particularly useful for material that contains hydroxyl group.

The weathering profile of the Portia prospect consists of 40 to 60 metres of yellow grey, olive grey and dark grey sediments (YGC, OGC and DG respectively). Underlying is 10 to 15 m of light grey clay (LGC) which passes into weathered saprolite with variably preserved primary rock fabric. Powdered X-ray diffraction results show that the sediments (YGC, OGC and DG) comprise quartz, muscovite, smectite, with lesser amounts of kaolinite. In contrast, LGC is predominantly kaolinite-rich and quartz-, muscovite- and smectite-poor. The saprolite is quartz- and kaolinite-rich, with varying amount of illite/muscovite, smectite and Fe-oxides.

Air-dried samples from three cored profiles of the Portia prospect were analysed using PIMA. An example of the result is shown in Figure 1. The mineral identification was carried out by examining the diagnostic wavelengths in conjunction with the use of the Spectral GeologistTM software. Spectral GeologistTM was used to calculate the reflectance intensities at 2212 nm and 1904 nm which correspond to the relative abundance of kaolinite, illite (Al-OH bond) and smectite (H2O bond) respectively (Crowley and Vergo, 1988). These reflectance intensities of the two parameters were plotted against depth and the results are shown in Figures 2a, 2b, and 2c. Saprock and saprolite with preserved fabric have low (< 0.2) reflectance intensities of both Al-OH and H2O bonds. In contrast, low reflectance intensities in the transported sediments (OGC) represents sandy units with lesser clays. The intersection of the two parameters denotes the transition (unconformity) from DG to LGC. However, these parameters could not completely resolve the transition from LGC (transported?) to the underlying saprolite as both units are kaolinite-rich. Nevertheless, higher ordered crystalline kaolinite has pronounced reflectance intensity at 2164 nm as well as the doublet absorption peaks at 1400 and 1420 nm. On this basis, kaolinite in the LGC has (in general) lesser ordered crystallinity compared to the kaolinite in saprolite. However, this difference in kaolinite crystallinity is not always apparent at the transition due to the presence of a gradual boundary or less crystalline kaolinite in the upper saprolite. Within the saprolite, intersection of the Al-OH and H2O parameters could also occur indicating local smectite-rich saprolite with high H2O reflectance intensity.

REFERENCES

Crowley, J.K. and Vergo, N. 1988. Near-infrared reflectance spectra of mixtures of kaolin-group minerals: use in clay mineral studies. *Clays and Clay Minerals*, v.36, pp. 310-316.

Acknowledgements

The authors would like to thank Pasminco Exploration and CRC LEME for both financial and logistic support for this research project.

Figure 1. Example of SWIR spectral reflectance data arranged in increasing depth.

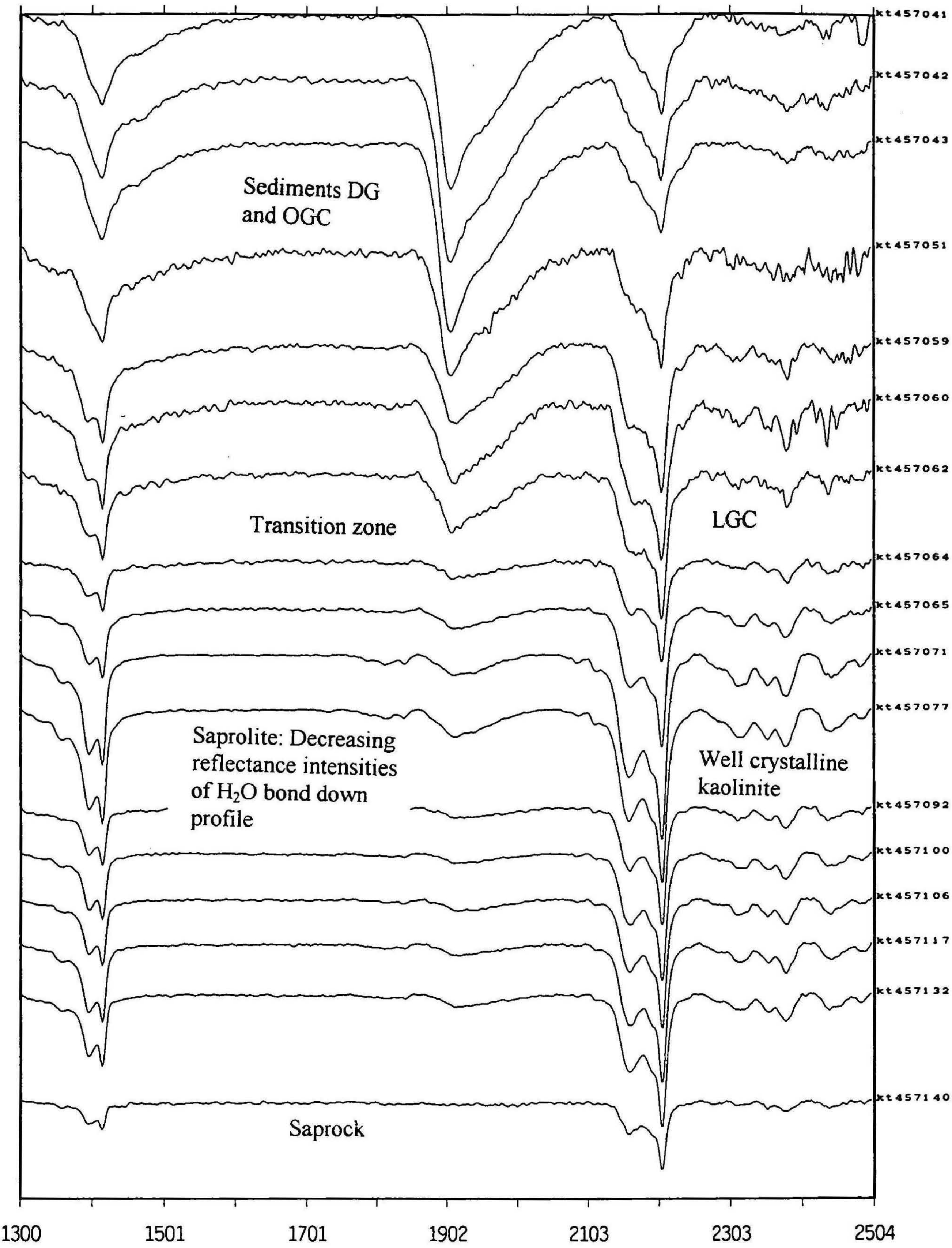


Figure 2a: Relative Reflectance Intensity of P-BEN457

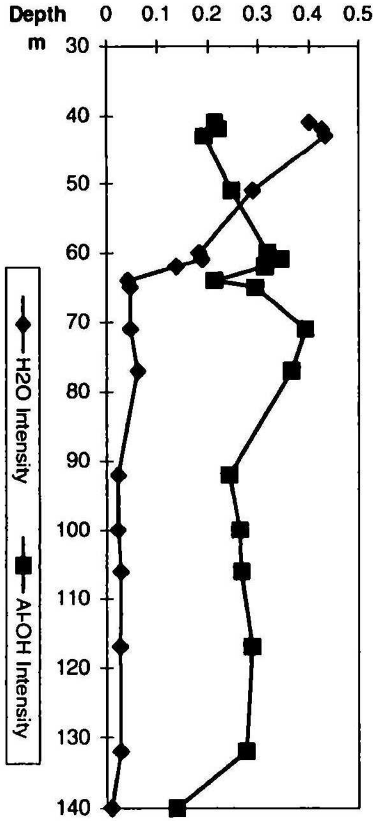


Figure 2b: Relative Reflectance Intensity of P-BEN461

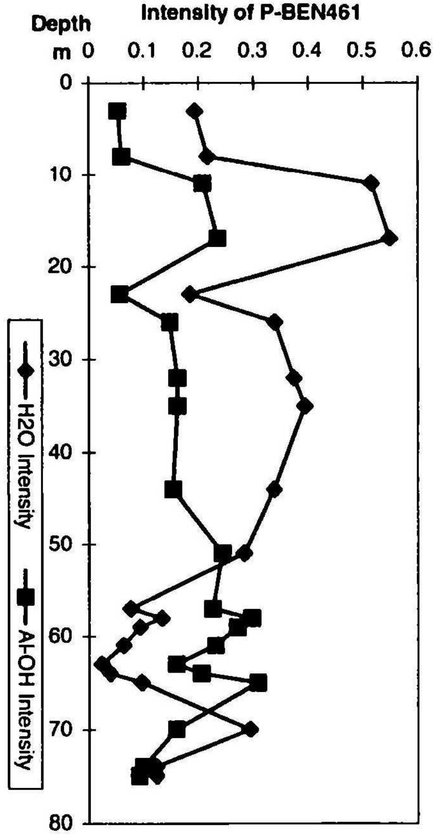
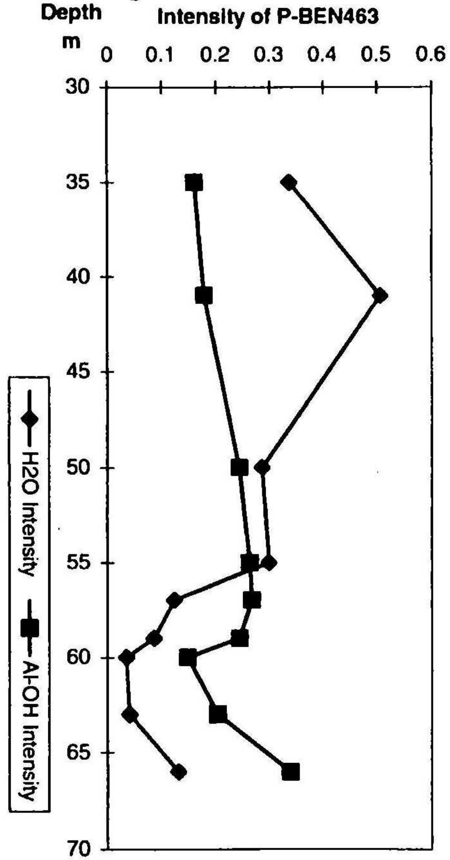


Figure 2c: Relative Reflectance Intensity of P-BEN463



THE AMPHIBOLITE AND METASEDIMENTS OF THE NORTHWEST WEEKEROO INLIER, OLARY PROVINCE

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The northwest Weekeroo Inlier, Olary, consists of Paleoproterozoic, Willyama Supergroup metasediments and amphibolites overlain by Neoproterozoic cover metasediments of the Adelaide Supergroup.

The basement rocks of the area are dominated by structures of the third Olarian event. Macroscopic anticlines and synclines are open to tight, easterly plunging, with a southerly dipping axial-surface. The third generation penetrative schistosity cross-cuts a former schistosity (S1 or S2) which is parallel or oblique to layering. Abundant crenulations and kink bands are likely to belong to the first Delamerian folding event which reactivated many basement structures of the Weekeroo Inlier.

A stratigraphic sequence is recognised whereby pelites ("Mica Schists") overlie psammo-pelites and quartz-albite rocks ("Bedded Schists"). A very broadly conformable sequence of massive, brecciated and layered amphibolite is "stratigraphically positioned" at the top of the Bedded Schists. From a consideration of abundant sedimentary structures, together with facies changes and overall stratigraphic relations, likely depositional models include a very shallow marine shelf, a broad shallow inland lake-alluvial fan toe complex, and a river dominated, regressive deltaic-sabkha situation.

Olarian metamorphic conditions ranged from those characteristic of the upper greenschist facies to those typical of the mid-amphibolite facies. These were followed by strongly retrogressive metamorphism (lower greenschist facies) associated with the cover deformation events of the Delamerian Orogeny. The Olarian metamorphism is manifested by paragenetic relations between actinolite, hornblende, epidote, albite, opaques and sphene in amphibolites, and between fibrolite, chloritoid, almandine, biotite, muscovite, sericite, quartz, minor staurolite and minor chlorite in pelites.

Closely associated with the amphibolite bodies of the Weekeroo Inlier are albitites and cal-albitites. Previously, a metasomatic origin was proposed for these albite rich rocks. Origin as an evaporative sediment with a possible tuffaceous component is now considered more likely.

The Weekeroo amphibolites are chemically similar to ferro-tholeiites of ocean floor-mid oceanic ridge transitional to continental origin.

REFERENCES

Taylor, G. J. 1985. The amphibolite and metasediments of the northwest Weekeroo inlier, Olary Province. Hons thesis. Unpublished.

MINERALOGICAL AND GEOCHEMICAL CHARACTERISTICS OF THE MUNDI MUNDI PLAINS WEATHERED SEDIMENTS: PRELIMINARY INVESTIGATIONS

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The Basins Program of the Cooperative Research Centre for Landscape Evolution and Mineral Exploration (CRC LEME) has just commenced a regional study of the regolith-landform, sedimentological and hydrogeological characteristics of the area surrounding Broken Hill and Olary Blocks. The aim of the program is to provide the minerals industry with improved methodologies for exploration in areas covered by thin sedimentary and regolith cover (generally, < 300m).

The bedrock geology of the Broken Hill Block consists of complexly deformed Lower to Middle Proterozoic metasediments and metavolcanics of the Willyama Supergroup as well as later Proterozoic intrusives and Adelaidean metasediments and metavolcanics. The Mundi Mundi Plains is bounded to the east by the Mundi Mundi scarp, a prominent quasi-linear feature which separates the Cainozoic sediments from Precambrian rocks of the Willyama Complex. The stratigraphy consists of several hundreds of metres (generally 150-350 m) of both transported and residual regolith. The transported regolith is composed of alluvial and colluvial sediments and occupies the top hundred metres of the regolith stratigraphy.

The Mundi Mundi Plains sub-project aims to develop a better understanding of the evolution of the Mundi Mundi Plains sediments through detailed mineralogical and geochemical studies. The determination of mineral paragenetic sequences and geochemistry of sediments will assist in deciphering of distribution patterns of elements in the sedimentary column and possible dispersion mechanisms. The information gained will allow interpretation of the processes of sedimentation (eg, channels, colluvial fans) operating in the basin, sediment provenance, and controls on sediment and system distribution (eg, palaetopography). Through this and additional sedimentological and hydrogeological studies, predictive models for the distribution of sediments, their depositional systems, and the evolution of the sedimentary basin will be developed, with particular attention to physical dispersion models and the development of potential placer and authigenic deposits within the sedimentary sequence.

LANDFORM EVOLUTION AND REGOLITH DEVELOPMENT: REDAN 1:25 000 MAPSHEET, BROKEN HILL, NSW

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Regolith dominated terrain covers a significant area of the Broken Hill Block, causing problems for exploration geologists as it obscures the characteristics of the underlying geology. Current ore reserves at Broken Hill, which once comprised the largest silver-lead-zinc mine in the world, are estimated to be limited to 10 to 15 years present exploitation rates. The future of mining in this area is thus dependent on the discovery of further mineral deposits located under the more common regolith cover rather than already explored bedrock dominated terrain. Consequently, regolith-landform mapping and analytical investigation of site specific materials has been undertaken over the 250 km2 Redan study site, situated 30 km south of Broken Hill. This map will aid in formulating landform evolution and regolith development models, and a framework for mineral exploration in mineral dominated terrains.

High-resolution airborne gamma-ray radiometrics has been used to differentiate between regolith units, using the Potassium (K), Uranium (U) and Thorium (Th) signatures. This technique penetrates vegetation cover and the top 30 to 40 cm of the land surface. Landsat 5 Thematic Mapper multispectral image data (7 bands, 30x30 m pixels) has been used in conjunction with radiometrics and Spot maps to increase topographic information. Augmentation of this image data isolates areas enriched in clay, carbonate and iron oxide minerals when specific bands are used or combined. These minerals comprise a large proportion of the regolith material over the Redan map sheet. Image enhancement techniques (e.g. directed principal component analysis of band ratios pc2, 4/3, 5/7, 7+1, canonical variance analysis) provide increased contrast discrimination of specific scene characteristics. Other techniques used extensively in the study include 1:80 000 and 1:25 000 scale airphoto interpretation and georeferencing of Digital Elevation Models (DEMs). Combining these processes enhances landform features such as the Redan and Mulculca Faults, and provides information on important geomorphic variables, including elevation, slope, aspect, convexity and relief.

A detailed account of the extent and distribution of regolith and landform features of the Redan field site has been documented, and a 1:25 000 scale regolith-landform map produced. Remote sensing techniques have been utilised to discriminate between regolith terrain units. Detailed ground truthing of remote sensed images has been complemented by geochemical and mineralogical analysis of regolith materials, including RAB drill holes and duricrusts such as silcrete.

Investigations into silcrete by Scanning Electron Microscopy (SEM), quantitative X-ray diffraction (XRD), X-ray fluorescence (XRF) and field mapping are yielding important information about genesis mechanisms, cementing agents, source rock and bedrock influences which are crucial when exploring for economic grade deposits which might contain gold, uranium, or base metals. This is especially true when considering that many of the silcretes observed over the redan area are interpreted to have formed in drainage depressions comprising fluvial to alluvial sediments, hence highlighting palaeodrainage systems which might be the locality for accumulations of economic mineralisations.

From the compiled information, a genetic model is being developed to explain the principal regolith units and landform features of this study site, enabling the identification of sampling media which may be suitable for future mineral exploration program.

MAJOR FELSIC IGNEOUS UNITS OF THE BROKEN HILL-OLARY REGION AND THEIR METALLOGENIC POTENTIAL

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This paper presents results from the Broken Hill-Olary region, which were compiled as part of a major review of the metallogenic potential of Australian Proterozoic Granites. A 'mineral systems approach' was used and for each granite suite assessed all public domain information on field relationships, petrology, and geochemistry were compiled in a GIS on the granites, their comagmatic volcanics, their host rocks and any associated alteration systems within 5 kms of the granite boundary. Felsic magmas of the Broken Hill-Olary region are best viewed as part of a wider igneous province that also includes the Gawler Craton and the Mount Painter Inlier (the Gawler-Olary-Broken Hill (GOB) Province). The earliest significant magmatism in the GOB province was the intrusion of the Donnington Suite at ~ 1805-1845 Ma in the Eyre Peninsula (Mortimer et al., 1988). No definite rocks of this age have been recognised in the Broken Hill-Olary region, although some quartzofeldspathic components of the Redan Geophysical Zone (Stevens and Corbett, 1993) may be of this age (Love, 1992). Within the Broken Hill-Olary region, 4 major felsic magmatic events can be identified: ~1710 Ma, ~1690 Ma, ~1630-1640 Ma and ~1590 Ma and these will be the focus of this paper. Insufficient data are available on the Mundi Mundi Granite (Broken Hill Domain) for reliable mineral potential assessment, whilst minor local melts related to high-grade metamorphism are excluded from this paper, as given their small size, they are unlikely to be related to significant mineralisation.

THE ~1710 Ma EVENT (Olary and Broken Hill Domains)

Components: The ~1710 Ma felsic rocks form the only igneous event that can be correlated across the Olary and Broken Hill Domains. They comprise leucocratic quartz-albite gneisses which include granites, volcanics and related epiclastics. In the Olary Domain they occur in the 'lower albite' unit of the quartzofeldpathic suite and the 'upper albite' unit of the calcsilicate suite. Age determinations include the Ameroo Hill metagranitoid at 1703 ± 6 Ma, a felsic metavolcanic near Abminga Station dated at 1699 ± 10 Ma (Ashley et al., 1996) and a similar metavolcanic near Weekeroo station dated at ~1710 Ma. In the Broken Hill Domain, this suite is represented by high Zr and Nb 'leucocratic quartz + plagioclase' rocks of the Thackaringa Group, Ednas Gneiss and Redan Gneiss. In the Thackaringa Group, some of these quartz-albite rocks contain detrital zircons dated from 1700-1710 Ma (Donaghy et al., 1998).

Characteristics: The ~1710 Ma rocks are leucocratic, high in silica and are usually albitic, although there are gradations into types with appreciable K-feldspar. They have high Zr (326-640 ppm), Nb (34-93 ppm), and Y (70 - 285 ppm) contents and have been termed 'A-type' by Ashley et al. (1996). Due to pervasive albitisation most samples have $Na_2O \gg K_2O$ and high $Fe_2O_3/FeO+Fe_2O_3$ ratios. The alteration also affects other feldspar-bearing metasedimentary units within the host sequences, and hence not all quartz + albite rocks are of igneous origin. In the Olary Domain, Ashley et al. (1996) suggested that the timing of the albite alteration was from early diagenesis to peak metamorphism. In contrast, in the Broken Hill Domain this albitic alteration only occurs extensively in rocks stratigraphically older than the Broken Hill Group (it only marginally affects the intrusive ~1690 Ma Rasp Ridge Gneiss), suggesting that the albitic alteration was early and related to diagenetic effects (Stevens, 1995).

Metallogeny and Mineral Potential: No direct economic significance is attached to these ~1710 Ma igneous rocks: similar felsic suites in the Proterozoic of Australia are generally unmineralised. However, in the Olary Domain there is a spatial association with exhalative iron formations and related barite-rich rocks, as well as with epigenetic ironstones. The iron and barium-rich rocks locally host Cu-Au mineralisation: it is equivocal as to whether Cu-Au was deposited syndiagenetically or whether it is due to an epigenetic event (Ashley et al., 1996).

THE ~1690 Ma EVENT (Broken Hill Domain)
Components: The ~1690 Ma event is represented by the Potosi Supersuite which comprises the Alma and Rasp Ridge Gneisses, as well as 'Potosi type' gneisses in the Hores Gneiss and Parnell Formation. Most age determinations obtained are ~1690 Ma including the Hores Gneiss at 1690 ± 5 Ma (Page and Laing, 1992), Alma Gneiss at 1691 ± 12 Ma and Rasp Ridge Gneiss at 1688 ± 18 Ma (Nutman and Ehlers, 1998). Although younger ages from 1665 -1640 Ma have been obtained in the Southern Cross area (Page and Laing, 1992; Nutman and Ehlers, 1998) these samples come from an area where carbonate alteration has been identified (Stevens et al., 1998). As zircons are unstable in the presence of a carbonate hydrothermal fluid (Rizanova et al., 1996), these 1665 -1640 Ma ages are likely to be too young.

Characteristics: The Potosi Supersuite is divided into 3 chemical groups: i) the primary magma, (ii) epiclastic sediments derived from this magma ('Potosi Gneiss'), and (iii) rocks adjacent to the Broken Hill Main Lode (BHML) that have undergone an alteration overprint. The primary magma is characterised by the intrusive Alma and Rasp Ridge Gneisses and rare lavas of the Hores Gneiss and Parnell Formation. These components resemble normal granite compositions and for most elements on Harker diagrams intersect the SiO2 axis near 77 wt.%. The Supersuite is peraluminous, and ASI values decrease with increasing SiO2. The Supersuite is reduced and has low levels of incompatible elements (eg, Zr<400 ppm, Nb< 35 ppm) and represents a totally different magma type to the ~1710 Ma igneous rocks. The primary magma is unfractionated with no evidence of a change in K/Rb or Rb/Sr ratios with increasing SiO2. The closest analogues to the Potosi Supersuite are unmineralised restite-rich S-types of the Lachlan Fold Belt. Compositionally the Potosi Supersuite cannot be sourced by melting sediments of the Broken Hill and Thackaringa Groups or come from gneisses and migmatites of the lower Willyama Supergroup. A possible source is sediments derived by erosion of rocks similar in composition to the 1805-1845 Ma I-type Donnington Suite in the southern GOB.

Most rocks described as 'Potosi Gneiss' do not conform to normal felsic igneous compositions (Stanton, 1976; Stevens et al., 1988). On Harker variation diagrams for most elements they do not intersect the SiO2 axis near 77 wt.%: they also have unusually high Fe contents. The 'Potosi Gneiss' is interpreted as a subaqueous mass flow deposit derived from ignimbrite sheets which flowed into water, with resultant phreatic eruptions removing the minimum melt-dominated ash. The composition was further modified by the incorporation of unconsolidated iron-rich sediments (Stanton 1976; Stevens et al., 1998). District scale chemical variations in the 'Potosi Gneiss' could indicate a stratified water column (Degens and Stoffler, 1976), with a transition from deeper anoxic black shales to oxidised Fe carbonate, Fe silicate/oxide, Mn(Ca) carbonate and Mn oxide zones progressively towards the shoreline (Schissel and Aro, 1992).

A second alteration type occurs in the 'near ore position', where the 'Potosi Gneiss' has significantly higher mean MnO and significantly lower mean Na2O (eg, Main et al.1983). Another difference is that samples in the 'near ore position' have extremely low Fe2O3/FeO+Fe2O3 ratios and many samples plot within the strongly reduced field, inferring that the ore fluids were also strongly reducing. These redox values are lower than for any other quartzofeldspathic units in the Broken Hill-Olary region, and contrast markedly with the strongly oxidised alteration in rocks adjacent to the HYC, Mt Isa and Century Pb-Zn deposits.

Metallogeny and Mineral Potential: It is highly probable that members of the Potosi Supersuite play no direct role in the origin of BHML. Firstly, as the primary magma has not undergone any fractionation and as there is no evidence of exsolution of late stage fluids, the magma is highly unlikely to provide a source for the metals in the deposit. Secondly, although the BHML host rocks are 'skarn-like' it is improbable that this 'skarn' was formed by processes related to granite intrusion. As suggested by Stanton (1983) the BHML 'skarn' is more likely to be a regionally metamorphosed Ca-Fe-Mn-SiO2-rich chemical sediment in which the composition of the minerals precipitated, particularly with respect to Fe, Mn, Ca, P, F and CO3, is controlled by changing eH, pH and CO3 as a response to varying climatic and geological settings (Degens and Stoffers, 1976; Schissel and Rao, 1992) rather than interaction with a magmatic fluid. The 'chemical sediment' model is also complimentary to arguments that the BIF's in the Broken Hill Group are volcanic-related 'exhalites'. The greatest potential for the Potosi Supersuite is that the quartzofeldspathic igneous compositions allow recognition of hydrothermal alteration and fluid pathways, and hence aid in delineating vectors to ore.

THE ~1630-1640 Ma EVENT (Olary Domain)
The 1630-1640 Ma I-type granites are restricted in outcrop and geochemical sampling is very limited. Never-the-less they are an important set of rocks, especially as detrital grains in proximal metasediments may approximate this event. Although they are pervasively altered with Na, Ca, Fe, and K assemblages, no mineralisation is currently recognised with this suite.

THE ~1590 Ma EVENT (Olary Domain)
Components: This is the most extensive suite in the Olary Domain and comprises the so-called 'regional S-type suite'. This granite type has not been recognised in the Broken Hill Domain. Age determinations include the Triangle Hill granite at ~1590 Ma and 1570-1580 Ma for granites of the Crockers Well area (Cook et al., 1994; Ludwig and Cooper, 1984). Inherited zircons are common (Cook et al., 1994), as is typical of peraluminous magmas.
Characteristics: Igneous rocks of the ~1590 Ma event comprise fractionated, magnetite-bearing magmas. Although the rocks are peraluminous and muscovite-bearing, ASI values positively correlate with SiO2, as is more characteristic of I-type magmas. The Rb/Sr ratios exponentially increase to high values of 20, indicating significant fractionation. Although the ~1590 Ma intrusions have intimate relationships with composite gneiss and migmatite, mineralogically and geochemically they are also very similar to the more fractionated, peraluminous muscovite-bearing varieties of the Hiltaba Suite of the Gawler Craton. As well, they are comparable to ~1560 Ma granites in the Mount Painter Inlier.

Metallogeny and Mineral Potential: The ~1590 Ma intrusions are related to U-Th-REE mineralisation. Further work is required to confirm if these ~1590 Ma rocks (or even the 1630-1640 Ma rocks) are magmatically similar to the Hiltaba Suite, which is related to the Olympic Dam Cu-Au-U deposit. In the Olary Domain it is desirable to determine if late plutons visible in gravity and aeromagnetic images as lows, are more felsic fractionated end-members of the primary magma or else are more mafic end-members that have reduced from magnetite- to ilmenite/titanomagnetite-stable assemblages. In the Hiltaba Suite this redox change distinguishes between hematite-stable Cu-Au systems and less oxidised, more Au-rich systems.

ACKNOWLDEGEMENTS

Assistance from Nick Cook, Mark Fanning, Ian Plimer, Kevin Capnerhurst, Roger Skirrow, Dave Huston and David Maidment, as well as the support of 20 industry sponsors for this project is gratefully acknowledged. This paper is published with the permission of the Executive Director, AGSO; the Director-General, NSWDMR; and the Director, Mineral Resources Group, PIRSA.

REFERENCES

Ashley, P.M., Cook, N.D.J. & Fanning, C.M., 1996. Geochemistry and age of metamorphosed felsic igneous rocks with A-type affinities in the Willyama Supergroup, Olary Block, South Australia, and implications for mineral exploration, *Lithos*, 167-184.

Cook, N.D.J., Fanning, C.M. & Ashley, P.M., 1994. New geochronological results from the Willyama Supergroup, Olary Block, South Australia. In: Australian Research on Ore Genesis Symposium Proceedings, Australian Mineral Foundation, Adelaide, 19.1-19.5.

Degens. E.T. & Stoffers, P. 1978. Stratified waters as a key to the past. Nature, 263, 22-27.

Donaghy, A., Hall, M. & Nutman, A. 1998. The age of deposition of the Palaeoproterozoic Willyama Supergroup, Broken Hill. *Geological Society of Australia Abstracts* 49, 118.

Love, S. 1992. Possible ages and origins of some rocks of the Willyama Supergroup, New South Wales. *B.Sc. Honours Thesis, Australian National University (Unpublished).*

Ludwig, K.R. & Cooper, J.A. 1984. Geochronology of Precambrian granites and associated U-Ti-Th mineralization, northern Olary province, South Australia. Contributions to Mineralogy and Petrology, 86, 298-308.

Main, J.V., Mason, D.O. & Tuckwell, K.D. 1983. The characteristics and interpretation of whole rock geochemical data, Willyama Supergroup, New South Wales - trends towards ore. *Australasian Institute of Mining and Metallurgy, Conference Series 12*, 115-131.

Mortimer, G.E., Cooper, J.A. & Oliver, R.L. 1988. The geochronological evolution of Proterozoic granitoids near Port Lincoln in the Gawler Orogenic Domain of South Australia. *Precambrian Research*, 40/41, 387-406.

Nutman, A.P. & Ehlers, K. 1998. Evidence for multiple Palaeoproterozoic thermal events and magmatism adjacent to the Broken Hill Pb-Zn-Ag orebody, Australia. *Precambrian Research*, 90, 203-238.

Page, R.W. & Laing, W.P. 1992. Felsic metavolcanic rocks related to the Broken Hill Pb-Zn-Ag orebody, Australia: geology, depositional age and timing of high grade metamorphism. *Economic Geology*, 87, 2138-2168.

Rizanova, N.G., Levchenkov, O.A., Belous, A.E., Bezmen, N.I., Maslenikov, A.V., Komarov, A.N. & Levskii, L.K. 1996. The dynamics of the interaction of zircon with hydrothermal carbonate fluid. *Geochemistry International*, 34, 226-235.

Schissel, D. & Rao, R. 1992. The major early Proterozoic sedimentary iron and manganese deposits and their tectonic setting. *Economic Geology*, 87, 1367-1374.

Stanton, R.L. 1976. Petrochemical studies of the ore environment at Broken Hill, New South Wales: 4 - environmental synthesis. *Transactions of the Institute of Mining and Metallurgy*, B221-B233.

Stanton, R.L. 1983. Stratiform ores and metamorphic processes - some thoughts arising from Broken Hill. *Australasian Institute of Mining and Metallurgy, Conference Series 12, Broken Hill, July 1983*, 11-28.

Stevens, B.P.J. 1995. A review of Broken Hill Regional Geology. *In:* Mineral Search in the SW Pacific Region. *8th Edgeworth David Day Symposium, Sydney University*, 37-50.

Stevens, B.P.J. & Corbett, G.J. 1993. The Redan Geophysical Zone: Part of the Willyama Supergroup? Broken Hill Australia. *Australian Journal of Earth Sciences*, 40, 319-338.

Stevens, B.P.J., Wyborn, L.A.I. & Jagodzinski, E.A. 1998. The origin of the Hores Gneiss at Broken Hill and its role in mineralisation. *Geological Society of Australia Abstracts* 49, 431.