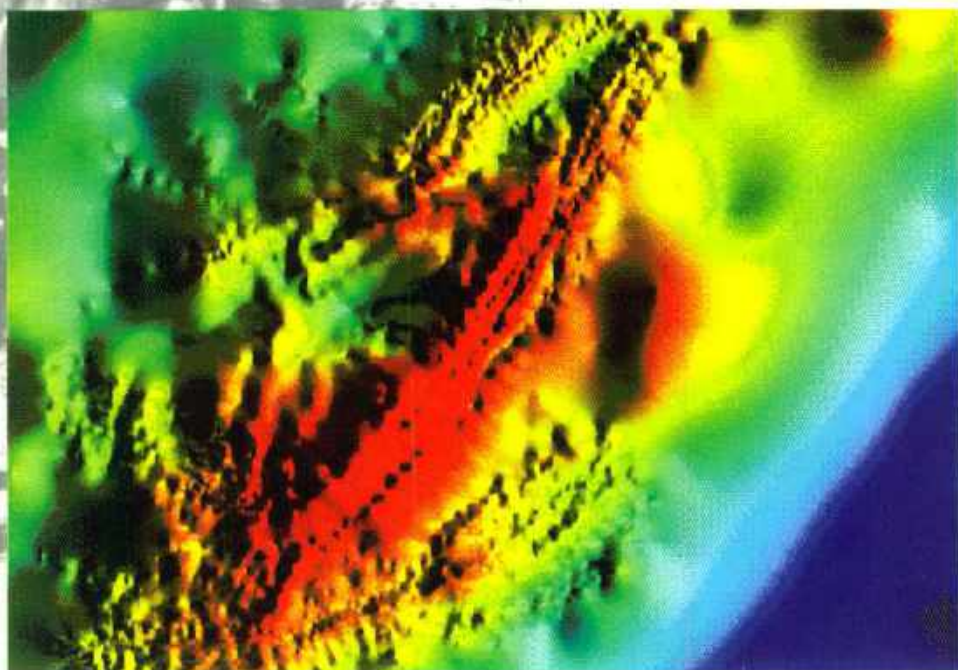
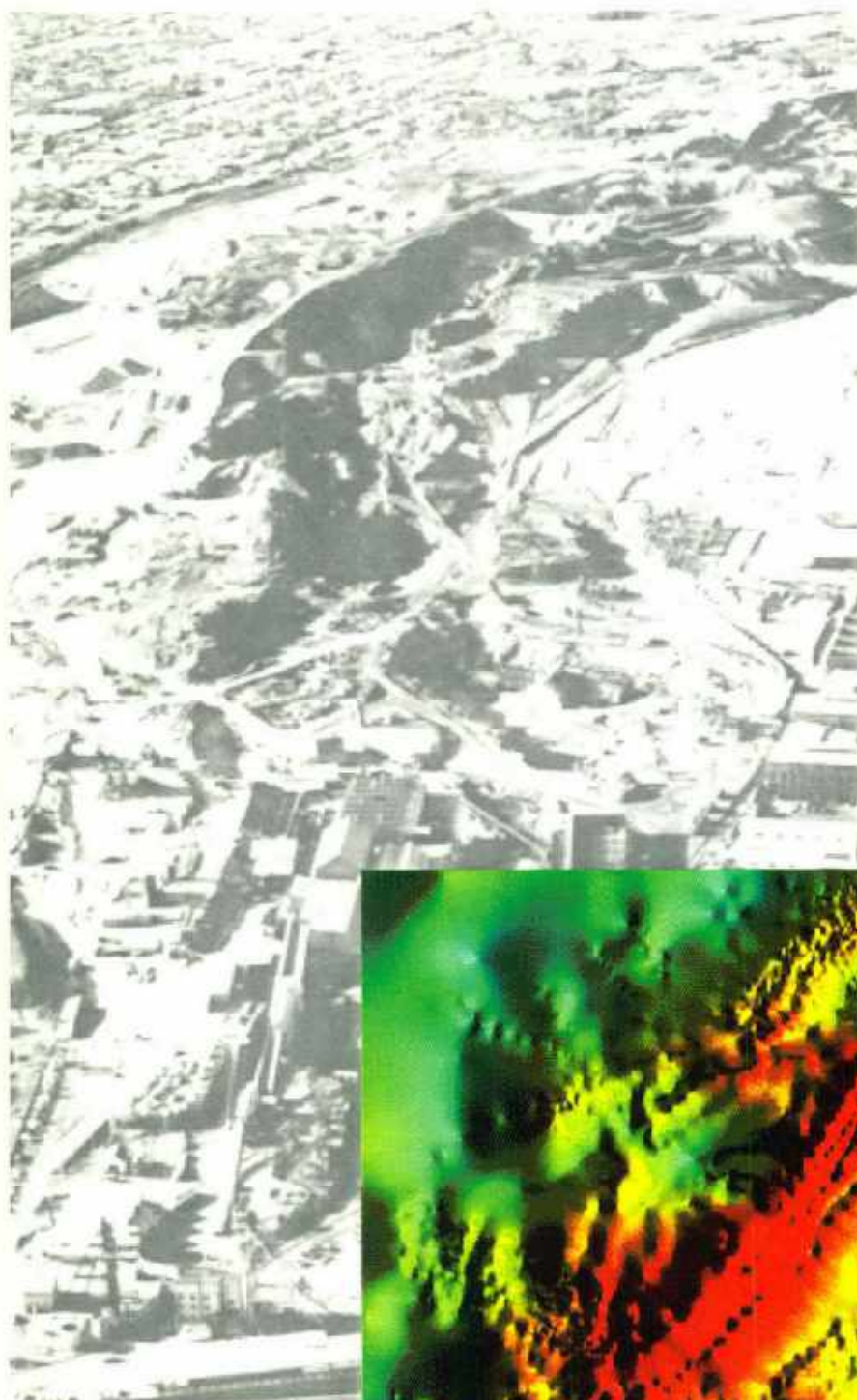


BROKEN HILL EXPLORATION INITIATIVE

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Broken Hill Exploration Initiative:
Abstracts of Papers Presented at the
May 2000 Conference in Broken Hill

AGSO Record: 2000/10

Compiled by M. Peljo

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.

Australian Geological Survey Organisation

Chief Executive Officer: Neil Williams

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FOREWORD

This volume incorporates the Abstracts of papers presented at the May 2000 Broken Hill Exploration Initiative (BHEI) conference in Broken Hill. The BHEI is a joint Commonwealth/State program, carried out under the National Geoscience Mapping Accord, which aims to evaluate a new generation of geoscientific information for the Broken Hill – Olary region in New South Wales and South Australia to provide a framework for continued mineral resource exploration and discovery. The conference series is one of the means for the BHEI stakeholders to share the results of their scientific and exploratory work, and to discuss and plan future work. Comments from participants in previous conferences suggest the BHEI is having a considerable impact on exploration strategies and perceptions of mineral potential in the Curnamona Province.

Technical sessions provided the opportunity to present results on regional geology, metallogenesis, geochemistry, exploration and mineral deposits, and geochronology. The talks ranged in their subjects from re-evaluation of time-honoured exploration methods, to regolith and associated topics, to exciting new approaches to generate new exploration targets. Abstracts are listed alphabetically according to the surname of the first author.

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 Cooperative Research Centres for Landscape Evolution and Mineral Exploration, Australian Geodynamics, and Australian Mineral Exploration Technologies
- Universities of Melbourne, La Trobe, Monash, New England, Tasmania, and the Australian National University
- Mineral exploration and mining companies, and consultancies.

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THE VERDICT TWO YEARS ON: BROKE 'n ILL OR BULLISH?

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INTRODUCTION

The title of this paper equally applies to the Minerals Exploration Industry as to any analysis of the BHEI programme. During the past two years the investment community further fled the mining stocks and the uncertainties of native title took full impact in Australia. The Industry is broke 'n ill so during this downturn we have to remain bullish about research and the production of stimulatory data and ideas. These are the front end of this Industry.

Despite the current policy of user pays particularly aimed at the mining industry, it is in the Governments' interest, through the various agencies and institutions, to capitalise on their own initiatives such as the BHEI by completing the value adding phase in a collaborative and creative manner. So two years further on, will the BHEI be the saviour of the local mining industry of which the public, researchers and miners are all participants and beneficiaries?

THE INDUSTRY'S INABILITY TO DISCOVER

Why is the Industry waning? It is easy to blame land access and lack of investor interest, but our biggest challenge is the Industry's inability to discover and develop at commercial rates especially since 1990. Apart from some brownfields sites and exceptional exceptions, our record of discoveries of blind deposits is very poor. The rash of discoveries in north west Queensland during 1990 was largely driven by magnetic targeting on iron oxide-associated deposits but again at relatively shallow depths. The rash of precompetitive aeromagnetic surveys since that time has not produced a similar plethora of discoveries particularly within the Curnamona Province. Why? Primarily because our models are not good enough to predict whether the province is a one elephant wonder or, if not, where to pinpoint our deeper seeing but localised and expensive tools beneath the extensive Curnamona cover. Empirical exploration is still very reliant on geochemistry and by corollary on a connection of the target deposit with the regolith or at least the base of transported cover. There should be a spectrum of deposits peaking deeper than 100m from the surface, so why are we not finding them? The great hope of non-magnetic targets or indeed deeper magnetic targets is not yet a reality.

The development of deep-seeing multichannel ground geophysics such as MIMEX's MIMDAS system offer much improved tactical tools but this also multiplies the amount of data, 'formational' targets and noise to be sifted as a greater volume of rock is measured in the third dimension.

The industry requires a step change in the 3D understanding of the deeper earth and of the fluid, structural and stratigraphic controls on ore genesis. This will enable better target models and better placement of the 3D remote sensing tools and drill tests. A number of managers are fast recognising this need in the face of becoming the generation that loses the challenge of maintaining the Industry's role and standing in Australian society.

RELEVANCE OF THE CURNAMONA PROVINCE TO EXPLORATION

The overall Industry opinion is the Curnamona Craton remains one of the premier exploration districts within Australia. This is reflected by the continued exploration effort of major explorers and competition for ground in the province.

The 'border fault' still has a bearing on exploration strategies. The primary target of the Broken Hill Block is the Broken Hill style of lead zinc silver deposits. Exploration in the brownfields and well-exposed terrane is mature, at least to shallow depths, based on the criteria of proximity to Potosi Gneiss within garnetiferous lode packages and with expected conductive responses. The potential for economic underground resources is real but frustrated by the challenges of exploring at depth as mentioned above. The envelope to the type deposit has characteristic magnetic and gravity features not readily identified elsewhere. The fear that the Broken Hill Block hosts only one major deposit is a real one.

Although suffering from the poor cousin syndrome, the Olary Block has continually attracted major explorers as a tantalising greenfields terrane with broad stratigraphic and metallogenic parallels to the Broken Hill Block. During the seventies and eighties, exploration focussed on shallow stratabound copper and lead zinc in or near

the Bimba position. This was based on outcropping mineralisation and magnetic targeting for blind stratigraphy analogous to the Suites 4/5 'rift to sag' transition. Sufficient data was collected by the late eighties to move the primary target to iron dominated copper gold deposits of the Ernest Henry-Olympic Dam family with a Kilo-Moto model being one of the earliest analogies drawn by Aberfoyle (Anderson and Toteff, 1990). The usual modest grades of the new style and relative immaturity of shallow Olarian exploration are inducing empirical exploration for open-cut targets that is less reliant on sophisticated 3D models. The focus is the Radium Hill-Portia trend that also hosts the White Dam and Kalkaroo prospects. The Olary Block and the covered flanks to the Broken Hill Block still offer direct magnetic targets with the potential for a repeat of the whirlwind of Cloncurry discoveries. Although new economic deposits are not yet realised, this tactical window will remain open for a few more years and one of the recent prospect discoveries could already be providing a lead-in to a major discovery.

The younger Koonenberry Belt offers greenfields copper and gold potential and has been the focus of recent NSWGS mapping (Mills and Hicks, this volume). The HMS potential on the northwest corner of the Murray Basin is tempered by evidence the Pliocene river mouths were more central to the basin.

Commodity forecasts indicate a short-term increase in base metals prices particularly for zinc then a return to excess supply. This will maintain pressure on mining efficiencies and the discovery of premium resources. The respective pedigree and immaturity of the Broken Hill and Olary Blocks will maintain the exploration interest of large and small miners with zinc and/or copper interests. True exploration maturity will never be reached as the quality of the province will demand improving models and techniques for its exploration.

ASSESSMENT OF THE BHEI TO 1998

The commencement of the BHEI in 1994 coincided with the beginning of a global exploration boom that peaked with a two times increase in expenditure during 1997. Two of the recent discoveries at White Dam and Potosi were initiated prior to and independent of the BHEI, but with the Portia discovery and the release of the new BHEI data, contributed to the six fold increase in Curnamona expenditure over the same period (Haydon, this volume). A measure of the relative BHEI contribution to exploration expenditures is the Olary expenditure increase from 14% of a \$20M South Australian total in 1994 to 20% of a \$53M total in 1997.

After the 1998 BHEI meeting, 37 responses on the meeting and recommendations for programme improvements were received from the 170 attendees. These are summarised as follows:-

- The most frequent requests were for better geological maps, particular in the Olary, for continued stratigraphic studies with essential age dating and for an urgent extension of structural studies. Compilation maps of historical exploration data, geochemistry and alteration were secondary needs.
- Deposit models were an emphasis with the request for research on alternative models and the introduction of BHT experts from elsewhere in the world. The availability of a core library of type ores and systems is an obvious corollary of the positive response to the core displays.
- For geophysical data, a more detailed gravity coverage and concerns with the cost of the AGSO magnetic data were the standouts ahead of requests for more seismic traverses with electrical techniques and rock properties getting a distant mention.
- Strategic concerns were the lack of regular tenement turnover, pointed out by Survey Geologists, and the need for more coordination and less competition between the various research groups in achieving planned research goals.

Most of these requested themes are generic and are already the foundations of the BHEI. Surprisingly, the question of additional seismic and 3D tectonic frameworks received only modest support although many commentators may have had this in mind when referring to structural studies. Granite studies and attendant age dating were also under-represented in the comments despite the evolving copper gold potential.

AN EXPLORATION VIEW OF FUTURE DIRECTIONS

One advance heard in this meeting is the progress after two years of the CRC LEME campaign of integrated research on regolith, landforms and basin fill topography. The results have particular applications to the more empirical exploration on the Olary side so further CRC LEME work is encouraged with support from hyperspectral surveying. The formalisation of the Olary stratigraphy is welcomed as long overdue, however the mapping is still largely based on the Esso/CEC mapping of the seventies, supplemented by student mapping initiated by Ashley and Plimer and compiled by Laing (Yates, 1993). The PIRSA mapping programme should be rapidly extended from Mingary back to the mineralised Radium Hill-Portia trend to capture numerous unmapped

outcrops of exploration significance and to separate stratigraphic, metamorphic and hydrothermal components of the geology according to the concepts of 2000. Companies continue to give researchers access to the new copper gold systems in the Olary enabling the advance of genetic and exploration models as described by Skirrow et al.(this volume). As for the all the Curnamona, ongoing isotopic studies and age dating including new insights from Re-Os are requisite

The principal omissions from the current meeting are reviews and progress reports on the Broken Hill genetic and target models as reviewed by Burton and Huston et al. in 1998. However one of the main developments of this meeting is the proposal for geodynamic modelling of the Broken Hill system (Hobbs et al., this volume). With such modelling applied to simpler(?) systems such as Century (Hobbs et al., 2000), this exciting work will be reliant on a better understanding of the ore-forming system and tectonic framework to constrain models. Two objectives are therefore needed on the Broken Hill side to truly initiate benefits to exploration. Resume deposit studies of the type deposit and continue to advance and test alternative genetic and structural models (e.g. Williams et al., 1999; Davies and Anderson, this volume; Gibson, this volume) with the support of further seismic traverses perhaps detailed with electrical geophysics (Sheard, pers. comm.). Although the CRA /DME stratigraphic mapping provided an excellent basis for shallow geochemical and EM surveying during the eighties and nineties, the failure to make new discoveries requires adventurous research towards the required step change in our knowledge of ore formation and ideas. The monumental task requires collaboration and common goals towards discovery.

REFERENCES

- Anderson, J.A. and Toteff, S. 1990: The base metal potential of the Willyama Inliers, South Australia. Seminar Abstracts, *South Australia – Exploration towards 2000*. South Australia Department of Primary Industries and Resources, Report Book, 90/78.
- Hobbs, B.E., Ord, A., Archibald, N.J., Walshe, J.L., Zhang, Y., Brown, M. and Zhao, C. 2000: Geodynamic Modelling as an Exploration Tool. Conference Volume, *After 2000 – The Future of Mining*. AusIMM Publication Series 2/2000.
- Williams, P.J., Guoyi, D., Prendergast, K. and Pollard, P.J. 1999: Metasomatism and metal mobility in Broken Hill-type deposits. *Mineral Deposits: Processes to Processing*. Stanley et al. eds. Balkema, Rotterdam.
- Yates, K.R. 1993: Company Exploration in the Olary Block. Abstracts, *South Australian Resources*. South Australia Department of Primary Industries and Resources, Report Book, 93/53.

REVIEW OF THE GEOLOGY AND METALLOGENESIS OF THE OLARY DOMAIN, SOUTH AUSTRALIA

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INTRODUCTION

The Olary Domain forms part of the Curnamona Province, a large nucleus of Proterozoic rocks located in eastern South Australia and western NSW. The Olary Domain (OD) is contiguous with the Broken Hill Domain (BHD) to the east and is dominated by metamorphic rocks of the Palaeoproterozoic Willyama Supergroup (WS), together with significant amounts of Palaeoproterozoic and Mesoproterozoic intrusive rocks. Much of the OD occurs beneath cover sequences, especially on the Benagerie Ridge to the north of the main outcropping region. The partially to completely covered region has been the site of several major exploration campaigns, with the location of encouraging mineralisation. This region retains most mineral exploration potential. A variety of mineralisation styles is recognised in the OD, with significant potential for future discoveries of stratabound/stratiform PbZnAg, epigenetic CuAu(Mo) and UThREE deposits. This review is based on results of a joint university mapping and research program (mainly the Universities of Melbourne and New England, with 37 Honours and 3 PhD projects), collaborative work with PIRSA and AGSO, and company data.

WILLYAMA SUPERGROUP IN THE OLARY DOMAIN

The WS sequence in the OD displays regional correlations with that in the BHD, although there are differences in detail (Clarke et al., 1986; Laing, 1996; Ashley et al., 1998a; Leyh and Conor, 2000). The WS is composed of a sequence of sedimentary, plus felsic and mafic volcanic and intrusive rocks. These are interpreted to have been developed in an intracontinental rift, with initial intercalated terrestrial, lacustrine/sabkha and marine sequences being succeeded by deeper marine/lacustrine sequences (e.g. Willis et al., 1983; Leyh and Conor, 2000). Subsequently, the sequence was multiply deformed and metamorphosed, with further intrusion by felsic and mafic magmas. There is presently no generally accepted stratigraphic scheme for the WS in the OD (Leyh and Conor, 2000). However, an informal scheme has been in common use for at least 20 years (e.g. Clarke et al., 1986; Flint and Parker, 1993) and it will be followed here, but bearing in mind that formalisation is currently being proposed (Conor, this conference).

The lower part of the OD sequence is dominated by quartzofeldspathic and psammopelitic composite gneiss and migmatite. These rocks grade into, and are probably a more extensively melted equivalent of the widespread Quartzofeldspathic Suite (QFS) which is considered to be an equivalent of the Thackaringa Group in the BHD. The current informal stratigraphic scheme has the QFS composed of the "Lower Albite", dominated by ~1715-1700 Ma A-type metagranitoids and co-magmatic felsic metavolcanic rocks (Ashley et al., 1996; Page et al., 1998), the "Middle Schist", dominated by psammopelitic schist and composite gneiss, and gradation into the "Upper Albite" (UA), dominated by finely laminated albitite, plus minor amounts of psammopelite and rare iron formation. Metasedimentary rocks of the UA have sources ranging in age from ~1920 Ma to ~1730 Ma, but were probably deposited at ~1710 Ma (Page et al., 1998). The UA component of the QFS grades into overlying laminated calc-albitite, with minor associated calcsilicate and oxidised Mn-rich rocks (piemontite-bearing). The calc-albitite-dominated sequence has been termed the Calc-silicate Suite, but, in fact, the UA albitite simply grades into calc-albitite, by the incoming of minor amounts of calc-silicate minerals. It is thus recommended that the term "Calc-silicate Suite" is abandoned and the UA and calc-albitite grouped to form a single entity (Conor, this conference). Stratigraphically above these strongly sodic metasedimentary rocks is the Bimba Formation which may be equivalent to the Ettlewood Calc-silicate Member in the BHD. The Bimba Formation is dominated by calc-silicate rocks, marble, psammopelite, pelite and albitite, locally with abundant Fe(CuZn) sulphides. From preserved textures and compositions, portions of the Bimba and underlying rocks can be inferred to have contained former evaporitic minerals. The Bimba is overlain by a regionally sharp contact with the Pelite Suite, composed of pelite and psammopelite, with local graphitic facies, psammite, tourmalinite, manganiferous iron formation and calc-silicate rocks. The Pelite Suite comprises two distinct sequences (possibly equated with the uppermost Broken Hill Group/Sundown Group and Paragon Groups in the BHD) and was deposited between ~1710 Ma and ~1650 Ma (Page et al., 1998). As was noted by Cook and Ashley (1992), and Leyh and Conor (2000), there is a regional-scale redox boundary across the position of the Bimba Suite. The sequence below is commonly oxidised (with magnetite $\pm$ hematite), the Bimba represents the transition and the Pelite Suite rocks are typically rather reduced (e.g. presence of pyrrhotite, pyrite, graphite, ilmenite). This transition is also commonly marked by a major change in magnetic properties, with the lower sequence

commonly having moderate to high susceptibilities, and the upper sequence being magnetically "quiet". This transition zone has been the focus of many exploration programs.

INTRUSIVES, DEFORMATION, METAMORPHISM AND HYDROTHERMAL ALTERATION

Several intrusive suites occur in the Olary Domain and there have been at least five deformation and metamorphic events. Associated with these events have been episodic regional-scale and local hydrothermal alteration, as well as mineralisation. Temporal relationships have been investigated by a variety of geochronometers, including U-Pb on zircon and titanite, Sm-Nd on garnet-epidote, Ar-Ar on muscovite and Re-Os on molybdenite (Cook et al., 1994; Ashley et al., 1996; 1998a; Bierlein et al., 1996; Lu et al., 1996; Page et al., 1998; Kent et al., in prep; Skirrow et al., this conference). A-type granitoids were emplaced and co-magmatic rhyolitic volcanic rocks erupted at ~1715-1700 Ma. The WS sequence may have been deformed prior to intrusion of mafic igneous masses at ~1680 Ma (cf. Nutman and Ehlers, 1998). Several small I-type granitoid bodies were emplaced into the central part of the Olary Domain at ~1640-1630 Ma. A major episode of deformation occurred during the Olarian Orogeny at ~1600 Ma, accompanied by upper amphibolite metamorphism in the south-central part of the OD, grading to lower amphibolite-upper greenschist facies in the northern OD. Emplacement of voluminous two-mica S-type granitoids and associated pegmatite bodies also occurred at ~1600±20 Ma, in part as a consequence of anatectic processes during the Olarian Orogeny. Regional-scale retrograde metamorphism and alteration may have occurred episodically between ~1600 Ma and ~1500 Ma, and there were further thermal perturbations during the Musgravian Orogeny at ~1200-1100 Ma. Mafic dyke emplacement at ~820 Ma was a precursor to development of the Adelaide Geosyncline and at least two episodes of deformation and greenschist facies metamorphism occurred between ~500-450 Ma during the Delamerian Orogeny.

Regional-scale, grading to local-scale, hydrothermal alteration has affected much of the OD, (Cook and Ashley, 1992; Bierlein et al., 1996; Ashley et al., 1998a; 1998b; Skirrow and Ashley, 1998; Skirrow et al., this conference; Kent et al., in prep.). Although some regional-scale sodic alteration in rocks up to the Bimba level may have been early (e.g. diagenetic), fluid inclusion and isotopic results have shown that most fluids responsible for alteration were at high-temperature (~450-600°C) and were oxidising and saline. They may have been derived by metamorphism of the host sequence, although the involvement of magmatic fluid could be implied. Widespread episodic alteration of the WS and some of the intrusives has occurred between ~1630 Ma and ~1500 Ma, and maybe during the Delamerian events. There has been widespread development of Na(Fe) assemblages (mainly albite ± Fe oxides, pyrite), with local strong Fe-metasomatism of iron formations and albitites (magnetite, hematite, quartz, pyrite), NaCaFe alteration of albitites and calc-albitites (in places associated with spectacular calc-silicate-matrix breccias), and mafic to felsic intrusives (albite, actinolite, clinopyroxene, epidote, quartz, hematite), CaFe(Mn)-metasomatism of calc-silicate rocks, marble and quartzofeldspathic rocks and local KFe-metasomatism (biotite, K-feldspar, magnetite). Replacement of calc-silicate-bearing rocks and marble have produced coarse skarn-like andradite (-epidote-quartz-actinolite-magnetite) assemblages.

MINERALISATION

Several styles of mineral deposits are recognised in the OD, including early, syn-sedimentary or diagenetic types, various hydrothermal deposits related to intrusives, to metamorphic and alteration events, and to later weathering and redox controlled processes (Ashley et al., 1998a; Robertson et al., 1998; Leyh and Conon, 2000). Early (i.e. pre-metamorphic) mineralisation styles are represented by iron formations and associated stratiform barite in the QFS, Mn-bearing iron formation in the lower Pelite Suite, and disseminated Fe (ZnPb±Co) sulphides and scheelite in the Bimba Formation (with the sulphides also possibly occurring in the lower Pelite Suite). The Pelite Suite-hosted iron formations have close compositional affinities with iron formations associated with the Broken Hill ore bodies. In the Bimba and immediately overlying Pelite Suite, stratiform laminated to disseminated sulphides are common in calcsilicate, marble and pelitic rocks (e.g. at Hunters Dam, Dayanna, Lawson, Telechie Valley, Dome Rock, Putts Well, Mt Howden, Blue Dam). Sulphides (mainly pyrite, pyrrhotite, sphalerite, galena) have equilibrated as part of metamorphic assemblages. Weathering of this type of mineralisation has given rise to extensive base metal-anomalous gossans (Lawie and Ashley, 1996).

Epigenetic CuAu(Mo) mineralisation is widespread in the OD and has been the focus of exploration in recent years (Skirrow and Ashley, 1998; Skirrow et al., this conference), with discovery of the significant prospects at Portia and adjacent area, Kalkaroo and White Dam, and re-appraisal of old mines (e.g. Dome Rock, Waukaloo and Walparuta). Although there are vein-type deposits high and low in the OD sequence, most mineralisation of this type is stratabound, occurring in the interval from the upper part of the QFS, up to and including the Bimba Formation/lower Pelite Suite. It is hosted in albitite, calc-albitite, iron formation, calc-silicate rocks,

quartzofeldspathic gneiss and psammopelite, and in places has been superimposed on earlier FeZnPb mineralisation. Sulphides (mostly chalcopyrite and pyrite, with sporadic molybdenite) and gold occur in lamination-parallel masses, and replacements of diagenetic carbonate, as well as in veins, stockworks and breccias. In places, mineralisation contains associated anomalous values of Co, As, Bi, Ba, F, REE and U. Mineralisation has been largely emplaced syn- to post-peak metamorphism in the latest Palaeoproterozoic to earliest Mesoproterozoic, based on field relations and geochronology (Skirrow et al., this conference). Mineral deposition has occurred at moderate to high temperatures, and from moderately saline to hypersaline fluids which in places were oxidising. It is associated with variable alteration styles, commonly including magnetite, hematite, actinolite, albite and K-feldspar in the footwall, and also with actinolite, biotite, magnetite, K-feldspar, albite, chlorite, sericite, carbonate, allanite, fluorite and barite, commonly in fracture-fillings. Although the origin of the CuAu(Mo) association could be superficially attributed to magmatic hydrothermal processes, it is difficult to unequivocally prove such a link based on currently-known field, geochronological, chemical and isotopic constraints. An alternative might reside in the concept that some form of metal concentration occurred in the WS sequence prior to high grade metamorphism, perhaps of stratabound nature and controlled by the regional redox gradient centred on the interval between the upper QFS and Pelite Suite. It could be speculated that metals could have been episodically leached from the WS sequence during the Olarian Orogeny (perhaps assisted by granitoid "heat-engine" effects), with stratabound CuAu(Mo) mineralisation being subsequently deposited in suitable chemical and structural sites by rock reaction (redox and sulphidation processes), fluid mixing and unmixing, and by reduction of temperature (e.g. Bierlein et al., 1996). Potentially favourable I-type granitoids in the OD have a very limited extent and are older than most dated mineralisation. Approximately syn-mineralisation S-type granitoids are reduced, do not contain any significant CuAu(Mo) mineralisation and do not show significant evidence of fluid evolution consistent with the generation of such mineralisation. If there is a magmatic connection with the CuAu(Mo) mineralisation, potential sources may not be currently exposed or recognised. CuAu(Mo) mineralisation in the OD represents part of the worldwide Proterozoic iron oxide-CuAu mineralisation spectrum and evidently there are several variations on the theme in the region.

A magmatic link is more plausible in the OD for the genesis of various styles of UThREE mineralisation and of numerous pegmatites. These appear to be related to the regionally extensive S-type granites, although certain UThREE deposits are associated with unusual leucocratic sodic granitoids (e.g. the brannerite-dominated Crookers Well deposit containing disseminated and breccia- and vein-hosted mineralisation). Other U-rich deposits such as Radium Hill and Mt Victoria are vein systems hosted in shear and fracture zones cutting migmatites, gneisses, sodic granitoids and pegmatites. Davidite, ilmenite, rutile and brannerite are typical minerals in these systems. Modern research is required on the OD UThREE deposits in order to better place them into a temporal and geochemical (and hence genetic) framework. Pegmatite deposits include complex rare element-bearing types with BePNbFBUTHREE minerals and simple types (essentially feldspars, quartz, muscovite $\pm$ biotite $\pm$ tourmaline) which have been worked for feldspar. The wollastonite deposit at Ethudna, hosted in the Bimba Formation (Crooks, 2000) is proximal to an S-type granite and could represent a skarn-like replacement. Alternatively, the alteration of host marble may be related to the previously-mentioned regional-scale metasomatic fluid processes.

Supergene processes have affected many mineral deposits in the OD, with major chemical and mineralogical changes being imposed on the CuAu(Mo) systems. It is likely that much of the OD and extension in the Benagerie Ridge region was covered by ?late Cretaceous to early Tertiary clay-rich regolith and subsequent uplift has caused partial stripping and exhumation of the Proterozoic basement (e.g. Callen, 1990). In outcropping regions of the OD, depth of weathering is modest and gossan and "leached capping" mineral assemblages are immature. In covered regions, however, the fossil weathering profiles are buried by up to 100 m or more of Tertiary-Recent sediments and profiles of up to 100m or more in thickness are preserved. A wide variety of secondary Cu-bearing carbonate, arsenate, silicate and phosphate minerals occur in the weathering profiles, along with native copper, Cu oxides and Cu sulphides. Gold (locally nuggetty) and secondary Mo minerals are also found. Supergene enrichment has been important at many small Cu deposits and also is evident in the Portia group of deposits and at Kalkaroo. In the latter two systems, patchy strong Au enrichment has taken place, with enhancement by fluvial processes at Portia. Tertiary palaeochannels draining from the outcropping OD contain several major sediment-hosted "roll-front" U deposits (Callen, 1990) including Honeymoon and Goulds Dam. The source of U may be from the OD and recycled Tertiary sediments. Following dissolution and transport in groundwater, U was precipitated by redox processes.

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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., Conor, C.H.H. and Skirrow, R.G., 1998a. Geology of the Olary Domain, Curnamona Province, South Australia. Field guidebook to Broken Hill Exploration Initiative excursion, 13-15 October, 1998. South Australia Department of Primary Industries and Resources, Report Book, 99/12, 53 pp.
- Ashley, P.M., Lottermoser, B.G. and Westaway, J.M. 1998b. Iron-formations and epigenetic ironstones in the Palaeoproterozoic Willyama Supergroup, Olary Domain, South Australia. *Mineralogy and Petrology*, 64, 187-218.
- Bierlein, F.P., Ashley, P.M. and Seccombe, P.K. 1996: Origin of hydrothermal Cu-Pb-Zn mineralisation in the Olary Block, South Australia: Evidence from fluid inclusions and sulphur isotopes. *Precambrian Research*, 79, 281-305.
- Callen, R.A. 1990., Explanatory notes for the Curnamona 1:250 000 geological map. Geological Survey of South Australia, 56 pp.
- Clarke, G.W., Burg, J.P. and Wilson, C.J.L. 1986. Stratigraphic and structural constraints of 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. Adelaide, Australian Mineral Foundation, 19.1-19.5.
- Crooks, A., 2000. Ethiudna wollastonite deposits. *MESA Journal*, 16, 26-27.
- Flint, R.B. and 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.
- Kent, A.J.R., Ashley, P.M. and Fanning, C.M., in prep. Metasomatic alteration associated with regional metamorphism: an example from the Willyama Supergroup, South Australia. Submitted to *Lithos*.
- Laing, W.P., 1996. Stratigraphic subdivision of the Willyama Supergroup - Olary domain, South Australia. *MESA Journal*, 2, 39-48.
- Lawie, D.C. and Ashley, P.M. 1996: Geochemical characterisation of iron-rich regolith materials in the Olary Block of South Australia. *AGSO Journal of Australian Geology and Geophysics*, 16, 243-251.
- Leyh, W.R. and Conor, C.H.H., 2000. Stratigraphically controlled metallogenic zonation associated with the regional redox boundary of the Willyama Supergroup - economic implications for the southern Curnamona Province. *MESA Journal*, 16, 39-47.
- Lu, J., Plimer, I.R., Foster, D.A. and Lottermoser, B.G., 1996: Multiple post-orogenic reactivation in the Olary Block, South Australia: evidence from $^{40}\text{Ar}/^{39}\text{Ar}$ dating of pegmatitic muscovite. *International Geology Review*, 38, 665-685.
- 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., Conor, C.H.H. and Sun, S.-S., 1998. Geochronology of metasedimentary and metavolcanic successions in the Olary Domain and comparisons to Broken Hill. *AGSO Record*, 1998/25, 89-93.
- Robertson, R.S., Preiss, W.V., Crooks, A.F., Hill, P.W. and Sheard, M.J. 1998. Review of the Proterozoic geology and mineral potential of the Curnamona Province in South Australia. *AGSO Journal of Australian Geology and Geophysics*, 17, 169-182.
- Skirrow, R.G. and Ashley, P.M., 1998. Copper-gold mineral systems and regional alteration, Curnamona Craton. *AGSO Record*, 1998/25, 104-108.
- Willis, I.L., Brown, R.E., Stroud, W.J. and 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.

THE REGIONAL CONTEXT OF COPPER AND GOLD MINERALISATION AT GRASMERE, THE KOONENBERRY BELT'S BEST KEPT SECRET

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The Grasmere 1:100 000 map sheet area is home to the namesake Cu, Zn Au and Co mineralisation as well as many other prospecting pits, shafts and costeans which have remained under-prospected and in many cases unknown to modern exploration. Recent mapping of the sheet concentrated on the Cambrian and older basement rocks that host the Grasmere mineralisation and has resulted in the identification of Teltawongee and Kara beds in the area and also a subdivision of the Ponto beds. This subdivision provides a basis for understanding both the known mineralisation at Grasmere and a stratigraphic framework for further exploratory work.

SUBDIVISION OF THE PONTO BEDS

Previous mapping of the Koonenberry Belt (Mills, 1992) has recognised the multiplicity of units within the Ponto beds and apart from the geophysics driven subdivision of Direen (1999), no attempt has been made to erect an internal lithostratigraphy. During this study a tentative subdivision of the Ponto beds was established. Mapped rock types were collected into a group with subgroups and constituent beds. These subgroups are collections of rock types, not necessarily cohesive stratigraphic units yet they have served to define regional trends within the Ponto beds.

The Nunthorungie Subgroup is characterised by the abundance of basic volcanic rocks and is considered to be the uppermost unit of the subdivision (Figure 1). The primary rock types within the group consist of feldspar phyric, vesicular and pillow textured tholeiitic basalt, immature sandstones and sediment of mafic tuffaceous derivation. Response to deformation within the subgroup is somewhat atypical of the Ponto beds with strain partitioned into more discrete zones and is usually restricted to the margins of mafic bodies or coherent sandstone units. Deformation is most intense adjacent to the Koonenberry Fault which forms the upper boundary of the subgroup against Devonian strata. The contact with the underlying Grasmere beds of the Palgamurtie Subgroup is defined by the sharp base of a regionally consistent and distinctive feldspar phyric, metabasalt. The Nunthorungie Subgroup, although more magnetic than adjacent Devonian rocks, has a relatively indistinct magnetic response when compared with the Palgamurtie Subgroup.

The Palgamurtie Subgroup has a much more complex and generally higher aeromagnetic response than the overlying Nunthorungie Subgroup. The subgroup includes three constituent units; the Grasmere beds; Weinteriga Creek beds and the Paddys Creek beds. The Grasmere beds include the Grasmere sulphide lodes and gossan, minor altered mafic rocks, cherty tuff horizons and quartz magnetite rocks all hosted by strongly deformed and kink banded phyllite. A regionally consistent quartz magnetite and cherty tuff horizon defines the lower contact of the Grasmere beds. The Weinteriga Creek beds consist exclusively of sandy phyllite and serve to separate the Grasmere beds from the Paddys Creek beds. Further mapping of the Ponto Group may prove the Paddys Creek beds to be a thrust repeat of the Grasmere beds as they contain a very similar lithology. The lower contact is sharp and clearly identifiable in areas of good outcrop by well-defined bedding in the underlying Teltawongee Beds.

The Ponto Group includes, in the western half of the Grasmere sheet, polydeformed slates and mica schists, with rare interbedded metabasalts (Direen 1999) referred to in this study as the Baroorangee Creek Subgroup. Rocks of the subgroup are atypical of the remainder Ponto Group. They reach amphibolite grade to the east of the Mt Wright Fault (Zhou, 1993), have a dissimilar, more diffuse magnetic response and occur distal to the Koonenberry Fault and other Ponto Group rocks.

STRUCTURAL SETTING

The most prominent structural feature in the area is the N-S striking Koonenberry Fault, which bisects the area. The area west of the fault is dominated by Cambrian or older basement whilst the Eastern area comprises Devonian strata. Explanation of the apparent bend in the Koonenberry fault on the Grasmere sheet has, until now, remained problematic. Mapping undertaken during the current study has revealed a sinistral offset of the Koonenberry Fault by the northwest-southeast striking Prospectors Creek Fault (Figure 2).

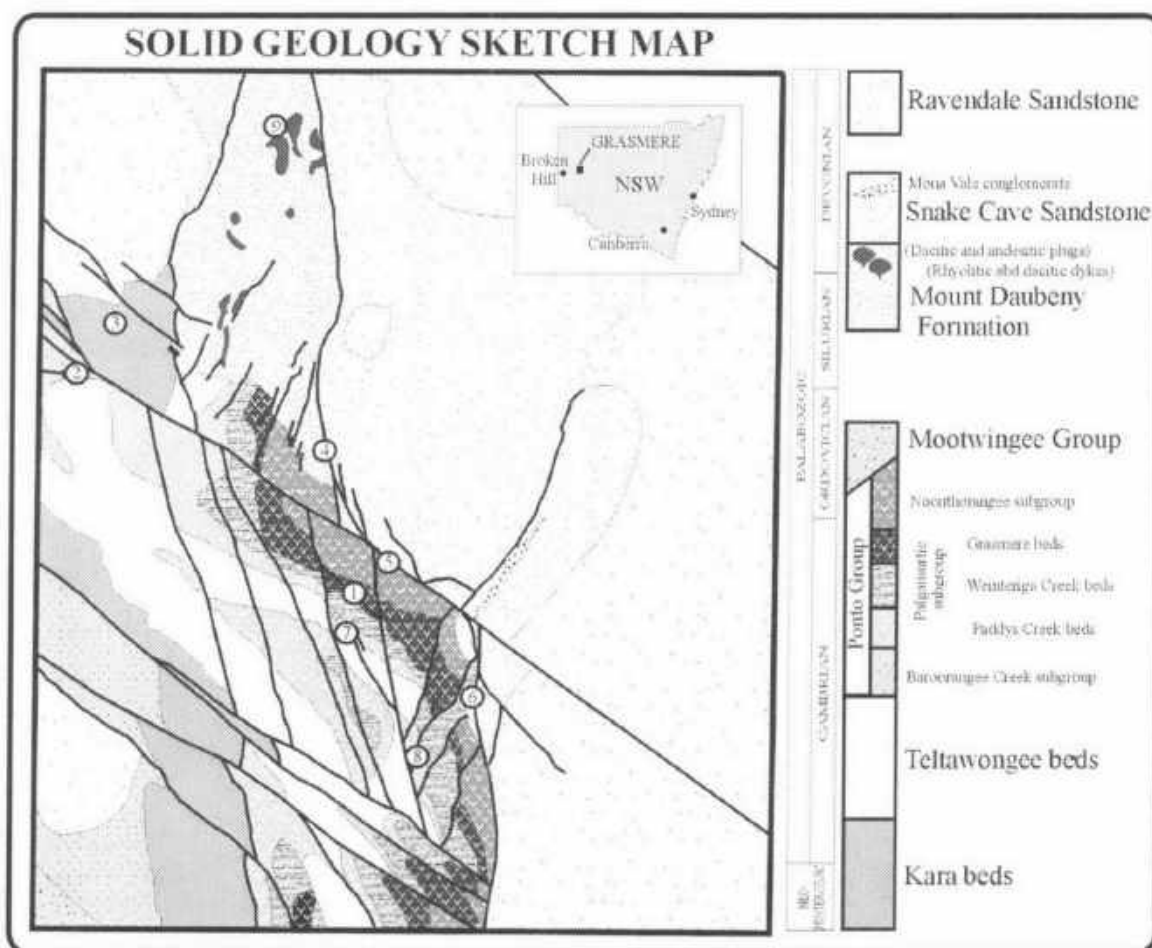


Figure 1. Solid geology sketch map of the Grasmere 1:100,000 sheet area. ① Grasmere (Cu, Zn, Au, and Ag) massive sulphide and gossan. ② Rawlins tank (Cu, Au) shear and breccia zones. ③ Black Mountain ferruginous slates (? Ag). ④ Prospectors Creek (Au) shear zones. ⑤ Koonenberry Fault (? Base metal, Au, Ag) mafic hosted shear zones. ⑥ Previously unreported Devonian basal conglomerate (? Au). ⑦ & ⑧ numerous unexplained and previously unreported pits and shafts developed within quartz and epidote altered basalt.

The offset of the Koonenberry fault is likely to have initiated during the deposition of the Mt Daubney Formation and continued into mid Devonian time. The final stages of faulting may have been synchronous with the deposition of parts of the Snake Cave Sandstone. The Moona Vale Conglomerate (Figure 1), most likely represents a boulder conglomerate debris flow generated at a fault scarp by a dip-slip component of movement on the Prospectors Creek Fault.

If the Koonenberry Fault is reconstructed into its original N-S orientation by sliding back the ~10 km of lateral offset along the Prospectors Creek Fault, the independently mapped faults north and south of the Prospectors Creek Fault also come into alignment (e.g. Bedford and Gap Faults, Figure 2.B). The dextral offset of the Bedford Fault forms the western boundary of a central structural zone with the Koonenberry Fault forming the eastern boundary (Figure 2B). Between the Bedford and Koonenberry Faults, northeast-southwest striking faults and siliceous, ankeritic veining occur south of the Prospectors Creek Fault in Cambrian basement whilst faults with similar orientations and related mafic dyke intrusions occur within the Devonian Mt Daubney Formation north of the Prospectors Creek Fault. The Mt Daubney Formation on the Grasmere sheet exhibits many features consistent with an idealised pull-apart basin, developed between the Bedford/Gap and Koonenberry Faults as a result of southwest and northeast directed compression. Apart from gross basin morphology other features within the Mt Daubney Formation consistent with this hypothesis include irregular basin margins and related folds at non-faulted sides, rapid facies changes basinward and complex unconformities, particularly at basin corners and the development of a igneous centre within the basin floor.

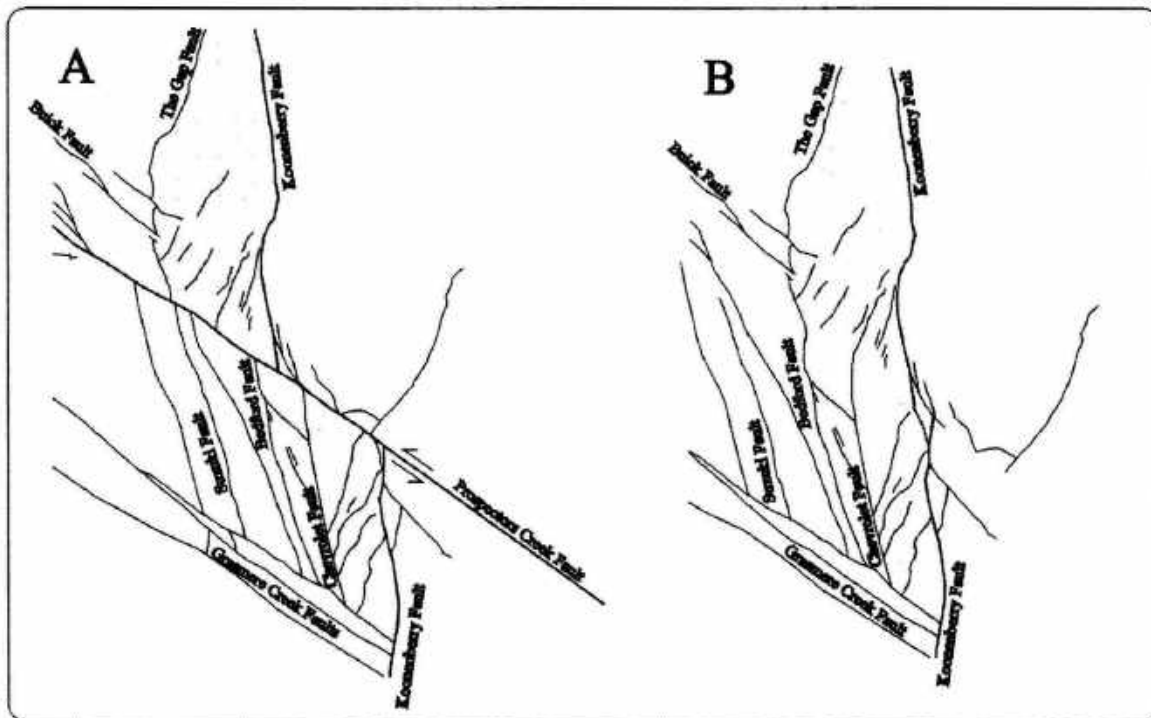


Figure 2. Fault reconstruction diagram. (A) Represents faults mapped and interpreted as per 1:100,000 scale map (these also appear in Figure 1). (B) Represents faults existing prior to the mid Devonian, lateral sinistral movement on the Prospectors Creek Fault. Note that when the Koonenberry Fault is realigned (B) other north south striking faults both north and south of the Prospectors Creek Fault also come into alignment.

GRASMERE COPPER AND GOLD

High grade, secondary copper minerals were mined at Grasmere during the late 1800's to early 1900's. At the Grasmere Mine primary Cu, Zn and precious metal mineralisation occurs along a line of quartz and magnetite lode with some 4 km of outcropping strike length. Whilst the area immediately surrounding historic workings received renewed exploration interest in the late 1900's, exploration of the lode horizon along the large strike extent of both lode rocks and their prospective, enclosing lithology has been limited.

Siliceous and ferruginous gossans with secondary copper minerals occur above steeply dipping primary massive sulphide dominantly consisting of pyrite with lesser chalcopyrite and sphalerite. Best intersections include 1.6m @ 3.54% Cu and 3.3g/t Au (61.4-63m) and 3.6m @ 3.78% Cu, 1.12% Zn and 0.16g/t Au, whilst Cu, Zn, Ag and Au values are usually in the 2-3%, 1-2%, 5g/t and 0.10g/t range respectfully. Outcrops of the gossan appear to transgress the mapped local stratigraphy of interlayered tuff, quartz magnetite rock and magnetite, epidote and pyritic basalt of the Grasmere beds however the lodes may be syngenetic and simply transposed and perhaps upgraded by later fault movement.

FURTHER EXPLORATION POTENTIAL

Most notable prospective areas, apart from the Grasmere mine, are a group of pits and shafts at Rawlins Tank, shafts and alluvial workings at Prospectors Creek and The shafts at the Black Mountain Silverfield. Other, previously undocumented and possibility prospective areas include: a three metre deep shaft with a drive of indeterminant length developed within the basal conglomerate member of the Pevril Peak outcrops of the Devonian Snake Cave Sandstone. A grab sample of mullock returned anomalous values of 0.044 ppm Au and 13.0 ppm U. Dilational zones adjacent to the Koonenberry fault are also a valid target for precious metals as well as perhaps Cobar style structural traps. A grab sample taken from a gossanous quartz vein returned an assay of 0.33 g/t Au, 1.5 ppm Te and 118 ppm Co. Also previously undocumented are numerous shafts developed within quartz and epidote altered basalt of the Paddys Creek beds. The Grasmere area remains a geological "Marie-Celeste".

REFERENCES

- Direen, N.G., 1999. Geology and Geophysics of the Koonenberry Belt, far-western New South Wales, and eastern Australian correlates. *Phd Thesis, The University of Tasmania*, (Unpubl.)
- Mills, K.J., 1992. Geological evolution of the Wonominta Block, C.L. Fergusson and R.A. Glen (Editors), *The Palaeozoic Eastern Margin of Gondwanaland: Tectonics of the Lachlan Fold Belt, southeastern Australia and Related Orogens. Tectonophysics*. 214, 57-68
- Zhou, B., 1992. Petrological, Geochemical and Sr-Nd Isotopic Studies of Metamorphosed Mafic Rocks in the Wonominta Block, Northwestern New South Wales. *Phd Thesis, The University of Sydney*. (Unpubl.).

REGOLITH RESEARCH IN THE BROKEN HILL REGION: AN OVERVIEW OF CRC LEME ACTIVITIES

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INTRODUCTION

Despite being highly prospective, the outcropping Broken Hill Block has delivered only minor finds since the discovery of the world-class Broken Hill Pb-Zn deposit late in the 19th century. A sense of urgency is now added by the imminent closure of that mine, scheduled for 2005. Thus, the Cooperative Research Centre for Landscape Evolution and Mineral Exploration (CRC LEME) has identified the Broken Hill region as one of its main priority areas for carrying out regolith research.

Weathering of the bedrock on the Block and, most importantly, the cover of sediments blanketing its margins are perceived to be the major impediments to exploration in the region. Given the extensive exploration that has been carried out on the outcrop over the last 100 years or so, and given the overwhelming size of covered versus exposed areas, chances of making another world-class discovery in the Broken Hill region, assuming such deposit exists, are much greater under cover than in outcropping areas. This rationale led CRC LEME to coordinate a series of research projects in the Broken Hill/Olary area (see Caritat *et al.*, 1998). This paper aims to present many of these projects (see Figure 1) to give an overview of our activities and review progress during the last 2 years, whilst separate abstracts in this volume focus in more detail on selected projects.

REGOLITH-LANDFORM (RL) MAPPING PROJECTS

Several Regolith-Landform (RL) mapping projects have been, or are still being, carried out at various scales in the region:

1. Broken Hill 1:500,000 (Gibson & Wilford, 1996) and Curnamona 1:500,000 (Gibson, 1996)
2. Broken Hill 1:100,000 (Hill, 2000)
3. Wonnaminta 1:100,000 (Gibson, 2000)
4. Detailed site maps, eg Silverton, Umberumberka, Yalcowinna, Stephens Creek, Campbells Creek 1:25,000 (Hill, 2000)
5. Balaclava 1:25,000 (Foster, 1998, Shirliff, 1998, Foster *et al.*, 2000) and Redan 1:25,000 (Holzapfel, 1998, West, 1998, Foster *et al.*, in prep)
6. Thackaringa West 1:25,000 (Willis, 1999) and Triple Chance West 1:25,000 (Jones, 1999)
7. Triple Chance East 1:25,000 (Debenham, in prep), Pinnacles West 1:25,000 (Senior, in prep), Kinalung West 1:25,000 (Brachmanis, in prep) and Quondong West 1:25,000 (Maly, in prep)

These projects are carried out by staff or by students. The 1:25,000 map scale series aims to ultimately cover much of the Broken Hill southern marginal area with detailed RL maps. These are being compiled by Honours students, so far over 3 academic years, and each study combines mapping with a detailed study of a regolith feature/discipline in the area (remote sensing, geochemical dispersion, sampling media, etc.).

LANDSCAPE EVOLUTION PROJECTS

The development of mineralisation signatures in the regolith has taken place over the timeframe of the region's landscape evolution. The development of a regional landscape evolution framework has therefore been a major objective of CRC LEME's research in the region. The initial approach has been to develop models accounting for the landscape on a broad regional scale (eg Hill *et al.*, 1997) and from this develop more detailed models for local areas, particularly in the southern parts of the Broken Hill Block and the northern Murray Basin margins. Some highlights of this work include: (1) the recognition of Cainozoic tectonics as a major driving force for regolith evolution and dispersion pathways (eg Hill & Kohn, 1999); (2) the reconstruction of palaeodrainage sys-

tems extending from the Barrier Ranges into the flanking basins (Hill, 2000); and (3) the landscape controls on local dispersion pathways and the expression of mineralisation in transported regolith materials (eg Jones, 1999).

REGOLITH SAMPLING MEDIA

A variety of case studies have focussed on detailed investigations of the use of various regolith materials (carbonates, silcretes, ferruginous crusts, etc) for geochemical sampling (see Hill S.M. *et al.*, 2000). These studies focus on the distribution, landscape position, detailed geochemical composition, morphology and evolution of these materials. Examples of these studies include:

1. Regolith Carbonate Accumulations (RCAs) (Hill *et al.* 1999, McQueen *et al.*, 1999)
2. Gypsum (Shirliff, 1998)
3. Ferruginous materials (Shirliff, 1998)
4. Siliceous materials (Holzapfel, 1998)
5. Partial leaching (Jones, 1999)
6. Plant materials (Jones, 1999, Hill L.J. *et al.*, 2000, Hill, in prep)

GEOCHEMICAL DISPERSION: REGIONAL STUDIES

The sediment-covered western margin of the Broken Hill Block and northern margin of the Olary Block are currently the focus of a series of investigations aiming to constrain the framework within which mechanical and hydromorphic dispersion has occurred, or is possibly still occurring. These studies, discussed in further detail in Caritat *et al.* (2000), focus on: (1) the geochemistry and mineralogy of the surface regolith material; (2) the downhole geochemistry and mineralogy of the sedimentary cover; (3) the 3D architecture of the basin fill; and (4) the groundwater geochemistry.

GEOCHEMICAL DISPERSION: CASE STUDIES

Detailed investigation of Au dispersion from mineralised basement into the surrounding regolith have been undertaken, for instance on the Benagerie Ridge (Tan, in prep) and at the Great Goulburn deposit (Jones, 1999).

For instance, the work on the Benagerie Ridge has determined a rugged palaeotopography covered by 50-70 m of Quaternary and Tertiary sediments at the Portia/North Portia area (Tan *et al.*, 2000). The chemistry and morphology of Au, found at the prospect in the basal Tertiary sediments (the Portia Unit) as well as in the Proterozoic saprolite and fresh bedrock, indicate that it likely has a detrital origin in the sediments and a residual, *in-situ* origin in the saprolite (Tan *et al.*, in press). Further, the 3D distribution of geochemical characteristics within the regolith has been established, and models of dispersion accounting for the observed element patterns and associations are being constructed (Tan, in prep).

At Great Goulburn a range of potential geochemical sampling media were compared to understand the 3D dispersion and anomaly patterns in the regolith at an area of known mineralisation. Although all sampling media provided some signature of the local mineralisation, the anomaly thresholds and characteristics varied. This relates to the different abilities of these materials to act as hosts for mineralisation signatures and the different geochemical dispersion processes and pathways associated with these materials. For example Au showed a marked lateral dispersion pattern, closely corresponding with the regolith-landform units mapped in this area, particularly in partially leached components of soils and vegetation (see also Hill S.M. *et al.*, 2000).

HYPERSPECTRAL MAPPING

The primary objective of the Broken Hill HymapTM project is to develop regolith exploration methodologies based on airborne spectroscopic techniques. This is possible through recent technical developments of airborne hyperspectral scanners, and through the availability of HymapTM hyperspectral data.

The first phase of the study is to gain an appreciation of the spectral characteristics of the mapped regolith units of the area. This will provide the basis for more detailed spectral studies over mineralised areas. This pilot study is carried out over the Balaclava East area, 30 km south of Broken Hill, which was mapped at 1:25,000 scale by Foster (1998) and Foster *et al.* (2000). The Balaclava East area is dominated by red aeolian sands, clay pellets, and alluvial and colluvial sediments. Ferruginous lags, colluvium, stream sediments and regolith carbonate accumulations provide the main sampling media for recognition of geochemical and physical dispersion pathways. The exploration issues addressed in this study (Papp & Foster, 2000) are: (1) Are there distinct differences in spectral properties of mapped regolith units, such as alluvium, colluvium, aeolian sediments, ferricretes, silcretes, calcretes, and weathered bedrock? (2) Can the known mineralised zones be spectrally differentiated from non-mineralised areas? and (3) Do these spectral signatures persist along dispersion pathways?

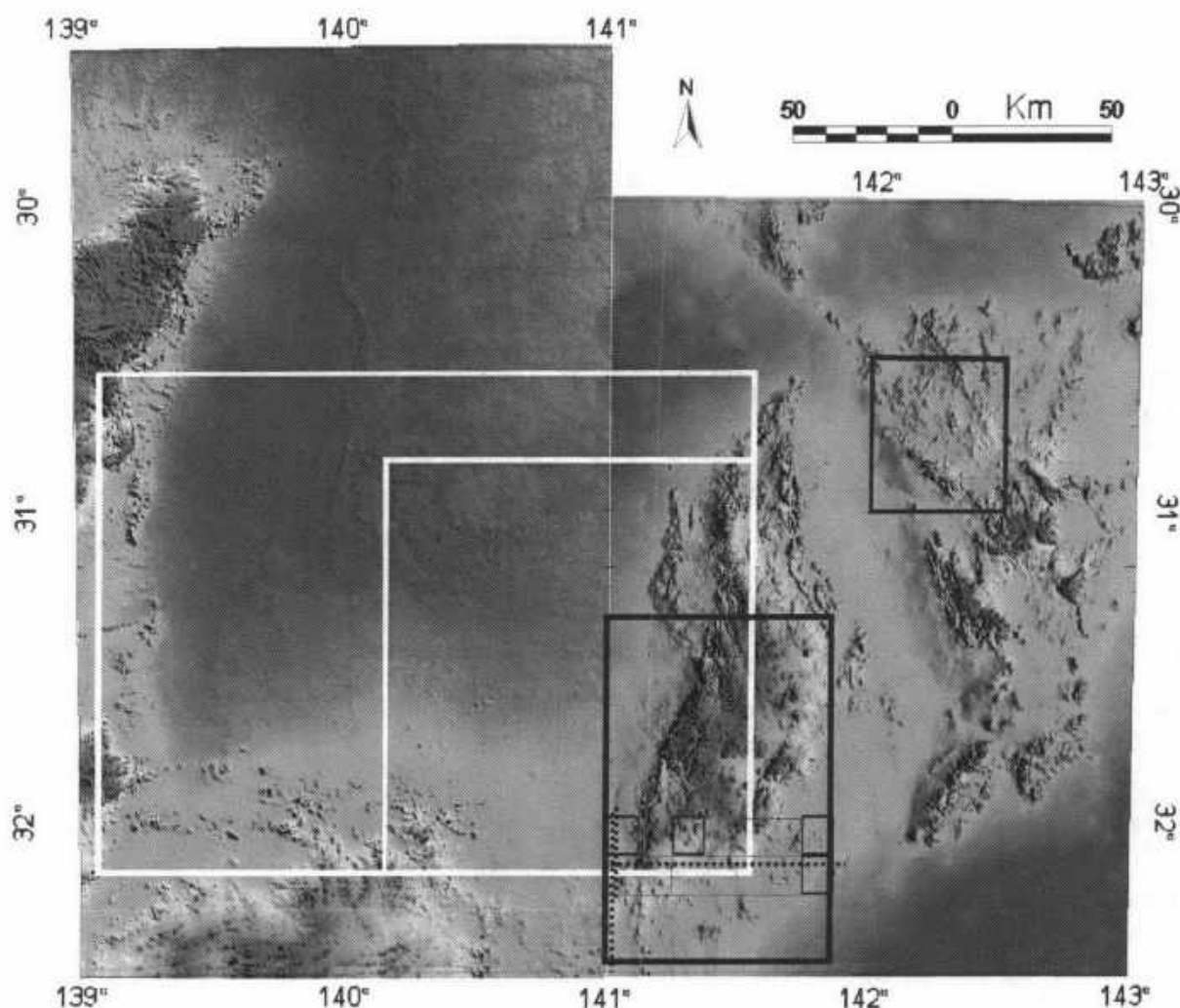


Figure 1. Location of CRC LEME's research areas overlain on a DEM image: Full view are the Curnamona 1:500,000 RL map (Gibson, 1996) and the Broken Hill 1:500,000 RL map (Gibson & Wilford, 1996); the large white rectangle is the 3D sediment model area, whilst the smaller white rectangle is the surface regolith and groundwater geochemistry area (see Caritat *et al.*, 2000); the larger black rectangle is the Broken Hill 1:100,000 RL map (Hill, 2000), whilst the smaller black rectangle is the Wonnaminta 1:100,000 RL map (Gibson, 2000); the small black rectangles with thin outlines are the 1:25,000 RL maps (Foster, 1998, Shirtliff, 1998, Foster *et al.*, 2000, Holzapfel, 1998, West, 1998, Foster *et al.*, in prep, Willis, 1999, Jones, 1999, Debenham, in prep, Senior, in prep, Brachmanis, in prep, Maly, in prep); the 3 dotted lines are the HymapTM surveys.

ACKNOWLEDGEMENTS

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REFERENCES

- Brachmanis, J., in prep. Regolith geology and landscape evolution of Kinalung West, Broken Hill, New South Wales. *University of Canberra, Honours Thesis* (in prep).
- Caritat, P. de, Cruikshank, B., Gibson, D., Hill, S., Killick, M., Lavitt, N., Papp, E. & Tonui, E., 1998. Landscape evolution and mineral exploration in the Broken Hill region: A new initiative by CRC LEME, 1998-2002. *Broken Hill Exploration Initiative: Abstracts from 1998 Annual Meeting* (Broken Hill, NSW, Australia, 19-21 October 1998), *AGSO Record*, 1998/25: 11-12.
- Caritat, P. de, Killick, M.F., Lavitt, N., Tonui, E., Dann, R. & Turner, M.L., 2000. Characterisation of regolith, sediment and groundwater in the Mundi Mundi-Curnamona region. This Volume.

- Debenham, S., in prep. Regolith geology and landscape evolution of Triple Chance East, Broken Hill, New South Wales. *University of Canberra, Honours Thesis* (in prep).
- Foster, K.A., 1998. Regolith geology and geochemistry of Balaclava East, Broken Hill, NSW. *University of Canberra, Honours Thesis* (unpublished), 96 pages.
- Foster, K.A., Holzapfel, M., West, D.S. & Hill, S.M., in prep. Redan Regolith Landforms map (1:25 000 scale). *Cooperative Research Centre for Landscape Evolution and Mineral Exploration*, Perth/Canberra.
- Foster, K.A., Shirliff, G. & Hill, S.M., 2000. Balaclava Regolith Landforms map (1:25 000 scale). *Cooperative Research Centre for Landscape Evolution and Mineral Exploration*, Perth/Canberra.
- Gibson, D.L. & Wilford, J.R., 1996. Broken Hill Regolith Landforms (1:500 000 map scale). *Cooperative Research Centre for Landscape Evolution and Mineral Exploration*, (CRC LEME) Perth/Canberra.
- Gibson, D.L., 1996. Curnamona Province Regolith Landforms (1:500 000 map scale). *Cooperative Research Centre for Landscape Evolution and Mineral Exploration*, Perth/Canberra.
- Gibson, D.L., 2000. Regolith, landform history and sampling strategies in the Wonnaminta area, Koonenberry Belt. This Volume.
- Hill, L.J., Eggleton, R.A., Caritat, P. de & Field, J., 2000. This Volume.
- Hill, L.J., in prep. *Australian National University, PhD Thesis* (in prep).
- Hill, S.M. & Kohn, B.P., 1999. Morphotectonic evolution of the Mundi Mundi Range Front, Broken Hill Region, western NSW. In: G. Taylor & C.F. Pain (eds) *New Approaches to an Old Continent, Proceedings of Regolith '98*, CRC LEME, Perth, 319-334.
- Hill, S.M., 2000. The regolith and landscape evolution of the Broken Hill Block, western NSW. *Australian National University, PhD Thesis* (unpublished).
- Hill, S.M., Eggleton, R.A. & Graham Taylor, 1997. A regional regolith-landform framework for mineral exploration models in the Broken Hill region. *AusIMM Journal 1997 Annual Conference Proceedings*, 131-138.
- Hill, S.M., Jones, G.L., Foster, K.A., Willis, S.M., Shirliff, G., West, D. & Holzapfel, M., 2000. Mineralisation signatures in the regolith of the Broken Hill Region. This Volume.
- Hill, S.M., McQueen, K.G. & Foster, K.A., 1999. Regolith carbonate accumulations in Western and Central NSW: Characteristics and potential as an exploration sampling medium. In: G. Taylor & C.F. Pain (eds) *New Approaches to an Old Continent, Proceedings of Regolith '98*, CRC LEME, Perth, pp.191-208.
- Holzapfel, M., 1998. Regolith-landscape evolution and silcrete investigation: Redan East, Broken Hill Block, New South Wales. *Australian National University, Honours Thesis* (unpublished), 117 pages.
- Jones, G.L. 1999. Regolith Geology and Geochemistry of Triple Chance West, Broken Hill, NSW. *University of Canberra, Honours Thesis* (unpublished).
- Maly, B.E.R., in prep. Regolith geology and landscape evolution of Quondong West, Broken Hill, New South Wales. *University of Canberra, Honours Thesis* (in prep).
- McQueen, K.G., Hill, S.M. & Foster, K.A., 1999. The nature and distribution of regolith carbonate accumulations in southeastern Australia and their potential as a sampling medium in geochemical exploration. *Journal of Geochemical Exploration* 67, 67-82.
- Papp, E. & Foster, K.A., 2000. This Volume.
- Senior, A., in prep. Regolith geology and landscape evolution of Pinnacles West, Broken Hill, New South Wales. *University of Canberra, Honours Thesis* (in prep).
- Shirliff, G., 1998. Ferricretes and the landscape evolution of the Western Balaclava Area, South Broken Hill. *Australian National University, Honours Thesis* (unpublished).
- Tan, K.P., Eggleton, R.A. & Caritat, P. de, 2000. Geochemical mapping of element distribution in the regolith at Portia and North Portia Prospects, Benagerie Ridge Magnetic Complex, Curnamona, SA. This Volume.
- Tan, K.P., Eggleton, R.A. & Caritat, P. de, in press. The morphology and chemistry of gold grains at Portia Prospect, Curnamona, South Australia. *15th Australian Geological Convention* (Sydney, NSW, Australia, 3-7 July 2000), *Proceedings Volume*.
- Tan, K.P., in prep. Regolith geology and geochemistry of Portia and North Portia prospects, Benagerie Ridge Magnetic Complex, Curnamona, SA. *Australian National University, PhD Thesis* (in prep).
- West, D.S., 1998. Regolith geology and landscape evolution of Redan West, Broken Hill, New South Wales. *University of Canberra, Honours Thesis* (unpublished), 172 pages.
- Willis, S.M., 1999. Regolith geology and landscapes of the Thackaringa-west area, Broken Hill, NSW. *University of Canberra, Honours Thesis* (unpublished).

CHARACTERISATION OF REGOLITH, SEDIMENT AND GROUNDWATER IN THE MUNDI MUNDI-CURNAMONA REGION

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INTRODUCTION

Mineral exploration in the Mundi Mundi Plains and Curnamona Province is complicated by the presence of a cover of weathered Quaternary/Tertiary sediments up to 200+ m in thickness overlying the weathered Proterozoic bedrock of the Broken Hill and Olary Blocks. This presents considerable problems for mineral exploration, especially in the design of exploration techniques and in the choice of sampling media. Several projects have been initiated by CRC LEME to address issues of landscape evolution, geochemical anomaly recognition, and mechanical and hydromorphic dispersion in this basin. The research reported here stems from 4 LEME research projects: (1) geochemistry and mineralogy of the surface regolith; (2) geochemistry and mineralogy of the sub-surface sediments and saprolite; (3) 3D reconstruction of the architecture of the sedimentary basin; and (4) geochemistry of groundwater.

SURFACE REGOLITH

This project aims to characterise the surface regolith in terms of its geochemistry and mineralogy, and to determine if aeolian versus bedrock signatures can be discriminated.

77 surface regolith (0-10 cm) samples were collected over the eastern Curnamona and western Broken Hill 1:500,000 map sheets. Samples were taken mostly from claypans on overbank plains. The samples were sieved through a 1 mm nylon sieve to remove unwanted impurities. A split was dissolved in double deionised water at a solid:water weight ratio of 1:5 for pH and EC determination. Another split was crushed in a tungsten carbide ring crusher, and prepared for XRF analysis to determine major and trace element concentrations, and for LECO C-H-N analysis to determine total C concentration. Further splits were prepared for XRD and PIMA (Portable Infrared Mineral Analyzer) analyses.

Partial results to date indicate a strongly mixed character of the surface sediments, as shown by a most unusual normal or near-normal distribution for many major (and some trace) elements. This is interpreted here to reflect aeolian mixing and transport as a dominating dispersion and mixing mechanism. Clay minerals and quartz are the main components of the surface regolith, with SiO₂ concentration being mostly between 60 and 92%, and Al₂O₃ up to 15%. Samples collected closer to bedrock outcrops (Broken Hill Block to the east, Olary Block to the south) have higher concentrations of elements reflecting fresh(er) primary minerals (eg Al₂O₃, Fe₂O₃, K₂O, MgO, MnO, Na₂O-Olary Block only, P₂O₅, TiO₂, and many traces). With increasing distance westward and northward, these lithogenic signatures become progressively diluted by clay/quartz (eg SiO₂ map) of probable aeolian origin. The distribution patterns for some trace elements suggest mobilisation and movement away from known mineralisation (eg Cu from the Copper Mine; Sn from the Kantappa and Waukerroo tin deposits; Bi, Cs, Pb and Zr from the northern Broken Hill/Euriowie Blocks; also Ba, F, Sn, and U from the Olary Block?). These patterns result from natural weathering processes of mineralised rocks, but are probably exacerbated by historic workings at these sites (shafts, rock crushing, waste rock piles).

SEDIMENTS AND SAPROLITE

This project aims to characterise the sediments under the Mundi Mundi Plains in terms of their mineralogy and geochemistry, and to determine their potential use as vectors to bedrock mineralisation.

6 rotary air blast drillholes were selected for sampling from highly prospective tenements on the Mundi Mundi Plains (P1-P5, SR5). Characteristics of the 'Quaternary'/'Tertiary' sediments, such as their texture, colour, fabric and composition, are used to define stratigraphic units of variable thickness. The Quaternary sediments are defined by coarse to medium-grained, poorly sorted sandy and mottled clay units. The sandy clay units contain abundant detrital rock fragments and quartz (or fine sand), while the mottled clay units are defined by dull-

coloured, earthy, well-defined mottles (Fe-segregations) within dense, cracking, grey clays. The Tertiary sediments consist of fine-grained, poorly sorted, angular to subangular sandy, silty and massive clay units. The clay units are either grey, dark grey, olive grey or greenish grey in colour. The *in-situ* saprolite of Willyama and Adelaidean rocks is soft, highly friable and clay-rich, with clays being highly bleached and less massive.

Mineralogical analysis is based on XRD (qualitative and quantitative), PIMA and SEM (Scanning Electron Microscopy) investigations. PIMA analysis allows differentiation of the various units based on the infrared absorption characteristics of the contained minerals. Moreover, it allows delineation of the unconformity between transported sediments and *in-situ*, weathered bedrock. Bulk mineralogy (XRD) shows quartz, kaolin, smectites and illite to be the dominant minerals within the sediments, with Tertiary sediments having higher amounts of smectites and illite relative to kaolin. The weathered bedrock (saprolite) contains high amounts of quartz, feldspars and kaolin, and lower amounts of muscovite and smectites. SEM analysis shows variable but distinct morphologies of the secondary products from the different units. This is useful for describing their intrinsic characteristics and in determining the nature of the depositional environment or the crystallisation conditions of diagenetic phases.

The Quaternary and Tertiary sediments contain high amounts of SiO_2 , Al_2O_3 , Fe_2O_3 , MgO and K_2O , reflecting high contents of clay and detrital rock fragments. The Tertiary sediments, in particular, have high concentrations of reduced Fe and Mn, which explains the grey/dark grey, or olive grey colours. The Quaternary mottled clays and the Tertiary units show elevated levels of As, Rb, Pb, Ni and Co, which could be related to adsorption onto Fe and Mn-oxides or clays, particularly smectites. One drillhole (SR5) has Cu concentrations up to 500 ppm within the saprolite (Figure 1) as well as anomalous Co (45 ppm), Ni (46 ppm), Bi (68 ppm), Zn (123 ppm), Rb (248 ppm), Ba (2800 ppm) and Cl (3200 ppm), which is probably indicative of bedrock mineralisation. These high concentrations in the saprolite appear to be expressed in the mottled clay (50-80 m depth) and lower levels of dark grey clay (110-130 m) by lower but still anomalous contents of Ba, Ce, Ni, Cs, Cu, Zn, V and Rb. A few carbonate-rich zones show strong associations with La, Ce, Nd, Pr, Sr and Y. Changes in major and trace element concentrations occur at several of the contacts between the sedimentary units. Interpretation of the geochemical profiles takes into account the origin and post-depositional history of the sediments.

3D MODELLING OF BASIN FILL AND SEDIMENT DISTRIBUTION

This project aims to define in 3D the architecture of the sedimentary cover sequence to assist interpretation of landscape evolution and of both mechanical and hydromorphic geochemical dispersion.

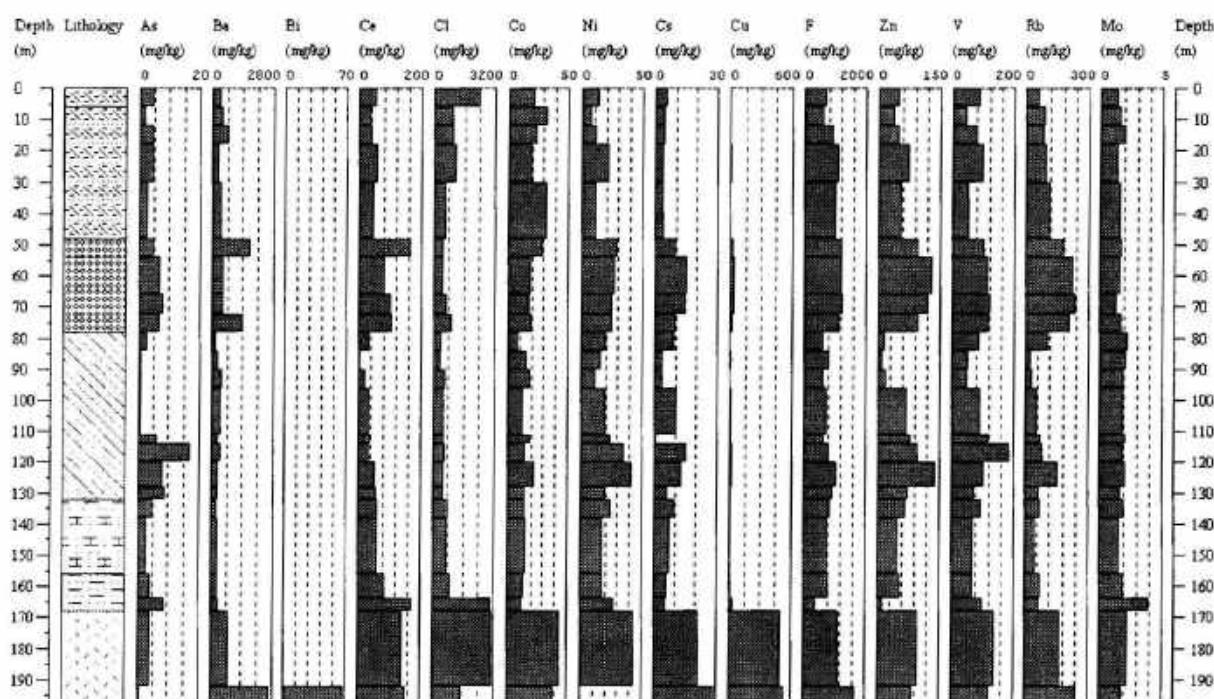


Figure 1. Lithology log and trace element profiles in drillhole SR5.

The 3D model is based on data from 827 drillholes from the area of the Curnamona 1:250,000 scale map sheet, plus the eastward extension of this basin to the Mundi Mundi fault. Logs of these holes have been obtained from open file reports. This set comprises those logs that contain interpretable downhole lithology, and location coordinates. Data from the logs have been digitised, and the lithology numerically coded. Two surfaces have been generated for the area: the modern ground surface, derived from the Auslig 9 second DEM data, and a basal unconformity surface, generated from the drill data. Gridding the drill data has shown some anomalous values for the depth to basement, and these holes have been eliminated from the data set. The remaining data set has been gridded vertically to give a set of 230 files, each of which contains data on the lithology at each drillhole over a 2m interval and at the same elevation. Each of these files has then been horizontally gridded, using nearest neighbour interpolation. This data set has been filtered against the upper and lower bounding surfaces of the basin fill to remove artefacts introduced by interpolating above the ground surface or below the basal unconformity.

Preliminary results show the shape of the basal unconformity surface, with the S-N trending Benagerie Ridge separating the Callabonna (W) and Mundi Mundi (E) sub-basins. A clear pattern to the distribution of different physical classes of materials appears to be controlled by this configuration. Authigenic phases and limestones have been most commonly recognised along and to the west of the Benagerie Ridge.

The coarsest grained sediments (gravels and gravelly sands) are typically situated high in the basin fill close to the Mundi Mundi fault scarp and the Olary outcrop. They are also present low in the system at the crest of the Benagerie Ridge, where they directly overlie the basal unconformity. Adjacent to the crest, these coarse deposits are distributed over the underlying sub-basin fill, suggesting a local source for this material.

Medium grained sediments (clayey silts to sands) are widely distributed throughout the study area, where they form the majority of the volume of sediment. This class of sediments is notably absent from much of the deepest parts of the Callabonna and northern Mundi Mundi sub-basins, as well as over the crest of the Benagerie Ridge. This distribution suggests a palaeotopographic control, with only clay size material being preserved over an emergent Benagerie Ridge, as well as being deposited in the deepest parts of the local sub-basins, possibly coevally with growth faulting at Mundi Mundi.

Fine-grained sediments (clays, silty clays) have a patchy distribution, probably resulting from a palaeotopographic control on sedimentation. In the Callabonna sub-basin, a N-S cross section shows stacks of coarser sediments overlying and deposited basinward (N) of clay deposits trapped in local depressions in the sub-basin. This suggests that the coarser material is an alluvial fill that has prograded across fines, probably deposited in a lacustrine environment, possibly as prodelta deposits of the alluvial system. The Mundi Mundi sub-basin, south of the Kantappa fault, shows a similar pattern of coarse deposits situated over and basinward of fine sediments. The northern part of this sub-basin fill is dominated by fine materials, with rare sheets of coarse sediment. Above the basal gravel layers, deposits along the line of the axis of the Benagerie Ridge are dominated by clay-sized material.

These results show that the depositional style was dominated by alluvial fill of a passive lacustrine basin, initially with significantly greater variation of topographic relief than at present. Movement of the Mundi Mundi fault only outpaced sedimentation, leading to the localised deposition of gravel materials, relatively late in the period of sediment accumulation. Gravels associated with the Benagerie ridge are probably locally derived, possibly from ferruginised and silicified crusts.

GROUNDWATER GEOCHEMISTRY

This project aims to characterise the groundwaters of the Mundi Mundi Plains and Curnamona Province in terms of their geochemistry (major and trace elements, stable isotopes), and to determine the potential use of groundwater geochemistry as a regional tool for discovery of mineralisation within the cover or bedrock.

82 groundwater samples were collected from boreholes over the eastern Curnamona and western Broken Hill 1:500,000 map sheets. Samples were only taken after sufficient pumping of the bores to ensure that water representative of the groundwater in the aquifer was being collected, as opposed to stagnant, oxygenated borewater that may be in equilibrium with the atmosphere. The parameters T (temperature), EC (electric conductivity), pH, Eh (a measure of the redox potential), and DO (dissolved oxygen) were monitored and measured in the field with a set of electrodes. Further, field determination of bicarbonate alkalinity (by titration) and concentrations of Fe^{2+} , S^{2-} , NO_3^- and NH_3 (by spectrophotometry) ensured the best possible measurement of these unstable parameters.

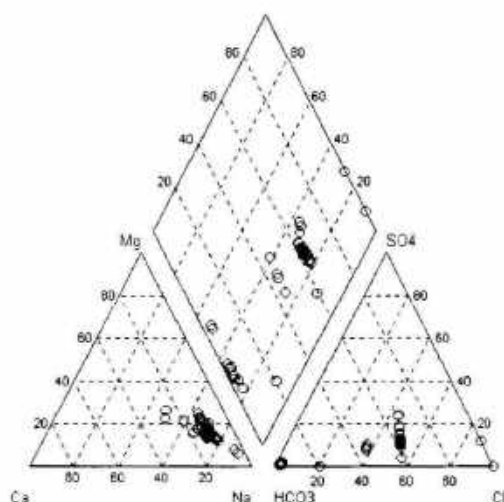


Figure 2. Piper diagram showing relative abundance of major cations and anions (in meq/L).

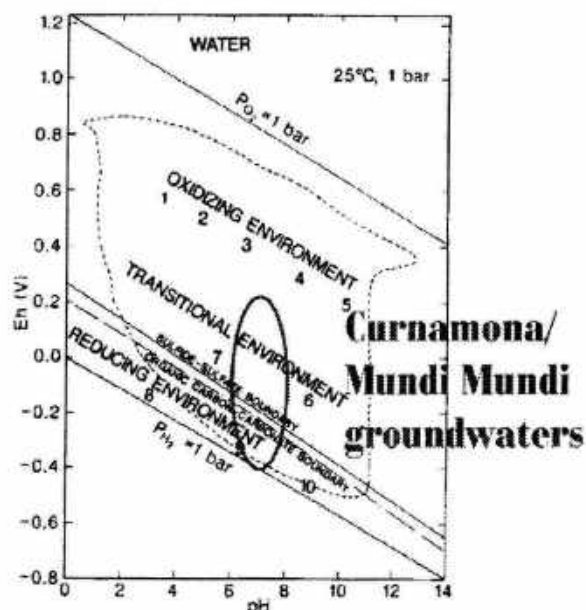


Figure 3. Eh-pH diagram for the Curnamona/Mundi Mundi groundwaters.

Upon return to the laboratory, the samples were subjected to a comprehensive analytical protocol, including laboratory pH and EC, Ion Chromatography (Br, Cl, NO₃, SO₄), Inductively Coupled Plasma-Atomic Emission Spectrometry (Al, B, Ba, Ca, Cu, Fe, K, Li, Mg, Mn, Na, S, Si, Sr, Zn), Ion Specific Electrode (F, I), Inductively Coupled Plasma-Mass Spectrometry (Ag, As, B, Ba, Be, Bi, Cd, Ce, Co, Cr, Cs, Cu, Dy, Er, Eu, Ga, Gd, Ge, Hf, Ho, La, Li, Lu, Mn, Mo, Nb, Nd, Ni, Pb, Pr, Rb, Sb, Sc, Sm, Sn, Sr, Ta, Tb, Th, U, W, Y, Yb, Zr), Instrumental Neutron Activation Analysis (Au), as well as stable isotope determination (C, H, O, S, Sr). This protocol is presently only partly completed.

Groundwaters are dominantly of the Na-Cl-HCO₃ and Na-HCO₃ types (Figure 2), their pH is circum-neutral and Eh is mildly oxidising to strongly reducing (Figure 3). They show general trends of increasing T, EC, Fe²⁺, S²⁻, and decreasing Eh, DO, alkalinity from the margins of the Broken Hill and Olary Blocks towards the deeper basin. Maps of trace element distribution show evidence of regional dispersion in the groundwater. Examination of these changes in groundwater chemistry along hydrological flow paths and the application of mass balance and speciation hydrochemical modelling will allow for the interpretation of water-rock interaction. As a new tool for regional mineral exploration in the Broken Hill and Olary region, initial results indicate that hydrogeochemistry shows great potential for enhancing mineral exploration objectives along the sedimented margins of this prospective province.

CONCLUSIONS

The 4 ongoing projects briefly summarised here will help establish the regional framework in which geochemical dispersion can be interpreted when searching for buried mineral deposits. We are establishing the geochemical patterns of the surface regolith to help interpret transport and mixing mechanisms at this most accessible interface. We are determining the geochemistry and mineralogy of the sediments in the 3rd dimension, where core is available, to help determine processes by which geochemical anomalies move or remain fixed in the sub-surface. Both these studies help define the regional thresholds for exploration in the area. We are constraining the architecture of the sedimentary fill within the basin to help identify significant units, facies or interfaces in terms of mechanical and hydromorphic dispersion, and to help refine the landscape evolution of the area. Finally, we are testing hydrogeochemistry as a regional exploration tool to help determine suitable protocols, constrain water-rock processes governing hydromorphic dispersion, and focus on areas requiring more detailed work.

ACKNOWLEDGEMENTS

We wish to acknowledge financial and logistic support from the New South Wales Department of Energy and Mines (through the 'Discovery 2000' initiative), and logistic support from Primary Industries and Resources South Australia. In addition, Wolfgang Leyh (Eaglehawk Geological Consulting) provided the drillhole samples and Platsearch NL gave permission to present some of this work. This work is supported by the Commonwealth Government's Cooperative Research Centres Program.

EXPLORATION BY TRIAKO RESOURCES LIMITED FOR GOLD AND BASE METALS IN THE BROKEN HILL REGION

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Triako Resources Limited is a listed mining and exploration company producing gold and copper at Mineral Hill in NSW (1999: 38,844 ozs gold, 2,523 tonnes copper in concentrates). Exploration for gold and base metals is focussed around Mineral Hill and at Broken Hill.

Triako considers the Broken Hill region is an attractive mineral exploration environment by virtue of: quality readily accessible data sets, experienced geologists, shallow to deep cover amenable to a range of exploration techniques, a perception of incomplete exploration for gold, gold/copper, zinc $\pm$ lead $\pm$ silver deposits particularly of smaller tonnages and great political will to facilitate the continuation of mining at Broken Hill. Triako is participating in joint ventures and in its own right on groups of tenements in the immediate areas northwest and southeast of Broken Hill (Figure 1).

GOLD

All Triako's tenements are being explored for gold with the primary initial sample medium being the widespread but previously unsampled calcrete and calcareous soils. In the Rupee joint venture with AngloGold this has led to the definition of five targets with anomalous gold-in-calcrete from drilling more than 1500 shallow auger holes. The anomalies range up to 27 ppb gold over background values of less than 1 ppb gold. They occur within structural features including the Rupee and Thackaringa-Pinnacles shear zones, and within strike extensions to the Broken Hill line of lode sequences at White Leeds South and Burt and Cattersons. Rock chip sampling and mapping has outlined targets for RAB drilling. Exploration for the discovery of previously unrecognised styles of gold deposit continues.

ZINC

Given the forecast closure of mining and milling at Broken Hill, Triako considers that there is potential for profitable mining of smaller tonnage, near surface zinc deposits, most likely with negligible lead and silver contents. Both the Rupee and Centennial joint ventures are being intensively explored using geological mapping, calcrete sampling and reassessment of the vast databases from previous exploration, including drillcore, RAB and RC drilling. Recently, RC drilling at Centennial, in joint venture with PlatSearch and Eaglehawk, has discovered near ore grade zinc mineralisation at the Hidden Treasure and Nine Mile prospects. This mineralisation was not detected by previous exploration that had a strong bias towards electrical geophysics (Sirotem). The combination of ultradetailed geological mapping and geochemistry is leading to success.

ZINC, LEAD, SILVER

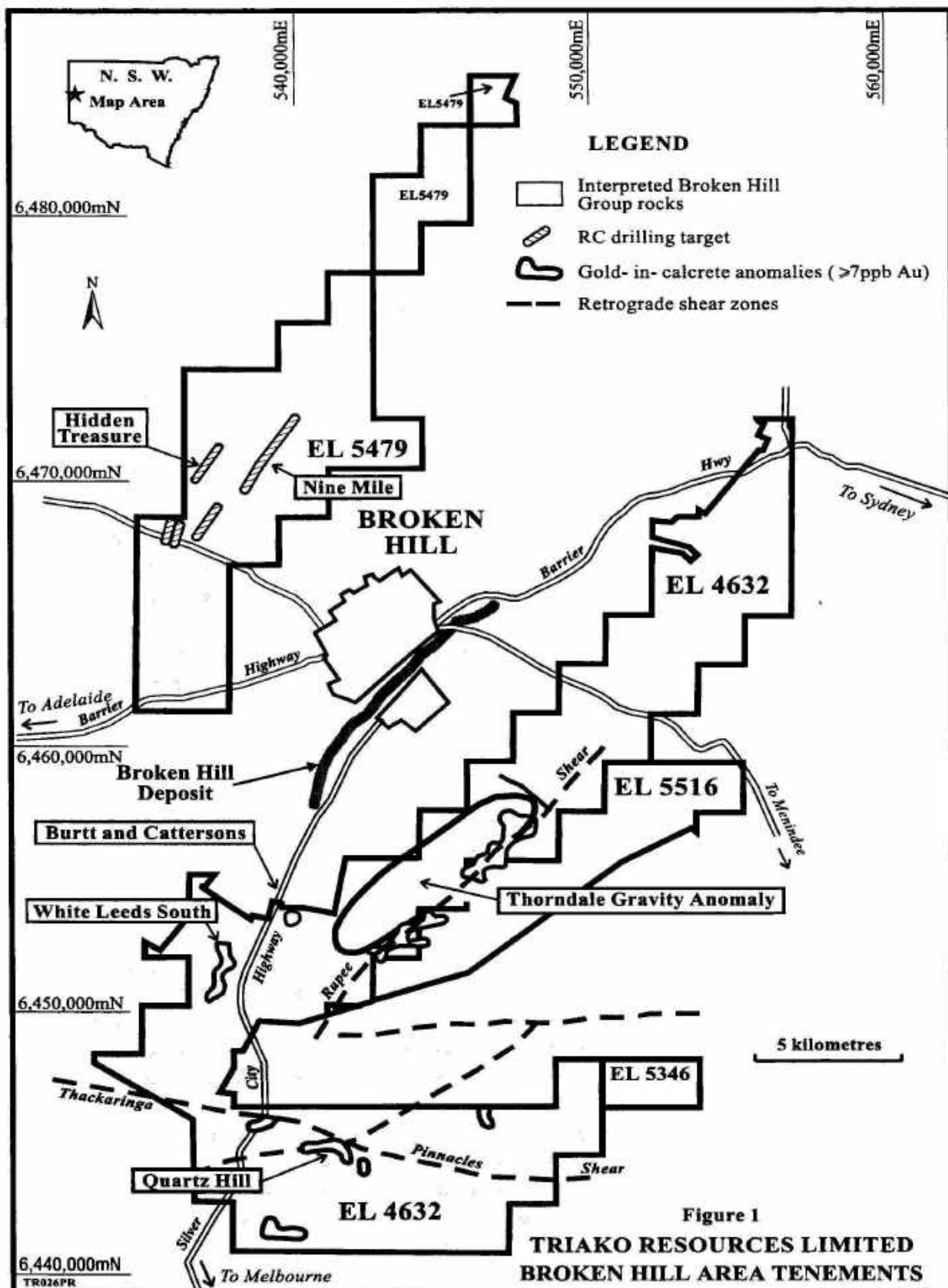
The Thorndale gravity anomaly immediately southeast of Broken Hill airport has been known for many years but remained unexplained. Using the Geological Survey's mapping and particularly the recognition of a south plunging downward facing antiform, the concept was developed that the Upper Broken Hill Group should exist at depth in the antiform and may host a massive zinc, lead, silver deposit at considerable depth within the 10 kilometre long gravity anomaly.

After mapping, re-evaluation of the geophysics plus a somewhat equivocal mobile metal ion geochemical survey that returned very high zinc, lead and cadmium values, a 1224 metre diamond hole was drilled into the core of the antiform. The hole confirmed the downward facing sequence, the antiformal structure and drilled a wide sequence of lode horizon rocks with abundant blue quartz, fine grained garnet, K feldspar porphyroblasts and abundant pyrrhotite. Base metal values were low but weakly anomalous. It is believed that the drillhole has demonstrated the pedigree of the sequence and enhanced the potential of the Thorndale gravity anomaly to host an economic Broken Hill type deposit within five kilometres of the existing processing plant, infrastructure and workforce.

OUTLOOK

By the application of new techniques to the Broken Hill region (eg. calcrete sampling), applying detailed geological mapping, reworking existing data, relying less on electrical geophysics and developing exploration models for deposits that may not have been considered before (eg. shear zone hosted gold) or have been less intensively explored for (eg. smaller tonnage zinc rich deposits), Triako and its joint venture partners have

discovered near ore grade zinc mineralisation and have developed drill targets for gold deposits and Broken Hill type zinc lead silver deposits. These are all within close proximity to the established Broken Hill infrastructure.



TOWARDS A FORMAL LITHOSTRATIGRAPHY FOR THE OLARY DOMAIN, CURNAMONA PROVINCE, SOUTH AUSTRALIA

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A formal stratigraphic scheme is proposed for the Willyama Supergroup and related Palaeoproterozoic and Mesoproterozoic rocks of the Olary Domain (OD), South Australia. This presentation addresses that part of the hierarchy extending from Supergroup to Formation; although Members are recognised they are not described here. Igneous rocks which have a stratigraphic component are treated as 'Suites'. Suggestions from other workers are welcomed. This proposed scheme follows several formal and informal versions of varying usefulness. Some of the more significant ones are by Campana and King, Carpentaria Exploration Company (CEC) and Esso Minerals, and Clarke et al.'s 'Pelite/ Bimba/ Calcsilicate/ Quartzofeldspathic/ Composite Gneiss suites'. This scheme, as is the case of several of the earlier ones, attempts correlation with the widely accepted stratigraphy of the Broken Hill Domain (BHD) (see table).

WILLYAMA SUPERGROUP

The Palaeoproterozoic Willyama Supergroup of the OD is divided into the Strathearn and Curnamona Groups, a division which pragmatically separates the oxidised feldspathic lower part of the Willyama Supergroup from the more reduced pelitic upper part. New geochronological evidence supports this division. The Willyama Supergroup is overlain unconformably by various later volcanics and sediments, but its base has not been observed.

STRATHEARN GROUP

The Strathearn Group comprises pelite dominated lithologies of the upper (and generally northern) portion of the Willyama Supergroup. The Strathearn Group is equivalent to the combined Paragon, Sundown and Broken Hill Groups of the BHD. Also the Strathearn Group is equivalent to the 'Pelite suite'.

MOUNT HOWDEN SUBGROUP

The type area for the Mount Howden Subgroup is the syncline near Mt Howden on Bimbowrie Station. W. Laing has indicated that Paragon Group equivalent rocks are present here, and this has been supported in the field by B. Stevens (pers. comm. and this volume).

Dayana Pelite

The Dayana Pelite is the uppermost formation preserved in the Mt Howden syncline and was distinguished by the mapping of Esso Minerals. The dominant lithology is pale grey, silky schist. The formation is considered to possibly be the equivalent of the Dalnit Bore Metasediments of the BHD.

Mooleulooloo Psammopelite

The Mooleulooloo Psammopelite is below the Dayana Pelite and is characterised by resistant albitic psammite units with interlayered brown schist. Sampling has indicated that there is a tuffaceous component which was U-Pb dated by Page et al. at <1.65 Ga. The formation is considered to be the equivalent of the Bijerkerno Metasediments of the BHD.

Alconie Pelite

The Alconie Pelite is below the Mooleulooloo Psammopelite, and is dominated by dark grey schist which is locally aluminous. Locally it contains a mafic calcsilicate equated with the Kingunna Calcsilicate Member. The base is marked by a chistolite schist. The Alconie Pelite is considered to be the equivalent of the Cartwrights Creek Metasediments of the BHD.

SALTBUSH SUBGROUP

The Saltbush Subgroup contains psammopelitic lithologies similar to the Sundown Group and most of the Broken Hill Group, to which it is considered to be equivalent.

Walparuta Schist

The Walparuta Schist is dominated by pelitic to psammopelitic schist with lesser psammitic layers, which are locally graded. The Walparuta Schist is tentatively correlated with the Sundown and Broken Hill Groups; P. Ashley and M. Laffan suggest that manganiferous iron-formations and coticles (ie garnet rock) in the

Walparuta Schist show chemical similarity with similar rocks in the BHD. The upper contact of the Walparuta Schist has not been observed with any certainty. The base of the Walparuta Schist is graphitic and aluminous and is observed to overlie a friable lithology tentatively equated with the Plumbago Formation.

Plumbago Formation

The Plumbago Formation is a thin, graphitic, friable schist unit which is observed to overlie the Bimba Formation (below). At its type area, in the syncline near Mount Howden, it is tuffaceous with a U-Pb age of <1.69 Ga (Page et al. this volume). A similar lithology is observed above the Bimba Formation near Ameroo Hill (Outalpa Station), in the 'Dead Horse syncline' near Weekeroo Station, and in the BHD above the Ettlewood Calcsilicate Member (also Page et al. this volume).

CURNAMONA GROUP

The Curnamona Group is equivalent to the Bimba, Calcsilicate, Quartzofeldspathic and Composite Gneiss suites of Clarke et al., and everything below and including the Thackaringa Group of the BHD. It is subdivided into the Ethiudna and Wiperaminga Subgroups.

ETHIUDNA SUBGROUP

Named from the 'Ethiudna calc-silicate group' of Campana and King. The Ethiudna Subgroup includes that part of the sequence characterised by calcic minerals, stratiform iron sulphide and significant metal anomalism. It is overlain by units of the Strathearn Group.

Bimba Formation

The Bimba Formation is probably the best known unit of the OD (Bimba horizon of CEC/Esso), and, with its interpreted equivalent the Ettlewood Calcsilicate Member of the BHD, forms a basin-wide marker. The type locality is the syncline near Mount Howden. The Bimba Formation, where present, is generally thin, from a few metres to 50 m or so. If the pyritic host to the Benagerie and Kalkaroo Cu-Au-Mo (Zn) deposits is equivalent then at these localities the Bimba Formation is up to 200 m thick. A volcanic member near the top of the pyritic unit at the Portia Prospect is dated at 1.70 Ga (Teale and Fanning, this volume). The lithological assemblage is fine grained but variable; however calcsilicate and marble are characteristic. Also characteristic is the abundance of iron sulphide and polymetallic anomalism. The Bimba Formation underlies the graphitic base to either the Mount Howden or Saltbush Subgroups, and is underlain by the albitic rocks of the Peryhumuck Calc-albitite or the quartzites and schists of the Whey Whey Schist (below).

Peryhumuck Calc-albitite

The Peryhumuck Calc-albitite comprises two main lithological varieties, the first being fine-grained, alkali-feldspar indurated metasediments, which generally preserve delicate sedimentary structures such as laminae, ripple cross-beds, flaser bedding etc. Magnetite or hematite are the usual iron-bearing accessories, but locally biotite is common. The second variety contains calcsilicate minerals from a few to 50 % of the rock. The variation between the two types may be quite haphazard. Both types locally contain pseudomorphs interpreted to have originated as diagenetic carbonate, gypsum etc. The type section is 600 m south from Cathedral Rock on Bimbowrie station and contains volcanic members dated at 1.71 Ga. It is the equivalent of the 'upper albite' of CEC/Esso. The Peryhumuck Calc-albitite overlies the medium grained albitic rocks of the George Mine Formation or the quartzites and schists of the Mooleugore Schist.

Whey Whey Schist

The Whey Whey Schist is a pelitic unit which is the lateral equivalent of, and interdigitated with, the Peryhumuck Calc-albitite. The type locality of the Whey Whey Schist is the 'Dead Horse syncline' near Weekeroo homestead, where it is some 200 m thick, contains thin quartzite beds and where the basal unit passes locally into a copper mineralised calcsilicate.

WIPERAMINGA SUBGROUP

The Wiperaminga Subgroup is equivalent to the 'Quartzofeldspathic and Composite Gneiss suites', and to the Thackaringa and lower units of the BHD. Typically the rocks are albitic, and comprise both sedimentary and volcanic precursors.

Mooleugore Schist

The Mooleugore Schist is equivalent to the 'middle schist' of CEC/Esso Minerals. In the Mount Howden area it is a finely interlayered psammopelite/pelite assemblage. In the type locality south from Cathedral Rock the Mooleugore Schist is migmatitic, but contains a clean quartzite near the top, and albitic units which are

interpreted to be volcanogenic. Locally this formation is known to be base metal and gold mineralised. Esso showed the base of this unit to be at the volcanic 'lower albite', and this concurs with the Cathedral Rock locality; however elsewhere the Mooleugore Schist merges into the albitites of the George Mine Formation.

Outalpa Formation

Named from the "Outalpa Quartzites" of Campana and King. The lithological assemblage is well layered pelitic to psammitic metasediments with numerous albite granofels layers (the 'quartzites'). Sedimentary structures are well preserved in places. The Outalpa Formation is present in the northern parts of the Outalpa and Weekeroo inliers. The relationship of the Outalpa Formation with the Mooleugore Schist and George Mine Formation is not known, but it appears to be high in the Wiperaminga Subgroup and is possibly a lateral equivalent of the Mooleugore Schist.

George Mine Formation

The George Mine Formation is derived from the scheme proposed by W. Laing. The lithological assemblage comprises interlayered, medium-grained quartz-magnetite albitites, quartz-biotite gneisses and migmatitic schist. Locally there are larger bodies of schist. There are occasional small magnetite iron-formations, some of which are baritic. Felsic volcanics units of the Basso Suite (see below) are liberally distributed, one of which was referred to by CEC/Esso as the 'lower albite unit'.

OTHER MESO-PALAEOPROTEROZOIC UNITS

Morialpa Migmatite

The Morialpa Migmatite is a term suggested by W. Laing for mappable units composed of migmatite and composite gneiss, where the original stratigraphic context is unknown. The Morialpa Migmatite formed metamorphically during the early Mesoproterozoic

BASSO SUITE

P. Ashley has described 1.72 – 1.70 Ga A-type meta-granites and felsic metavolcanics which are restricted to in the lower part of the Willyama Supergroup, ie. Curnamona Group. These lithologies are here named the Basso Suite. The granite bodies of the Basso Suite are assigned to the Ameroo Gneiss Subsuite, the volcanics (ie. proclastics, mass flows, epiclastics, subvolcanic sills) are included in the Abminga Subsuite.

LADY LOUISE SUITE

Pillow structures indicate that the Weekeroo Metabasalt (formerly the Weekeroo Amphibolite) is an extrusive, but its stratigraphic position is not obvious. Intrusive bodies of otherwise similar character are the 'Woman-in-White Amphibolite' and the 'Doughboy Well Amphibolite', the former is emplaced in the Peryhumuck Calc-albitite and has been dated at 1.69 Ga (Fanning pers. comm.). Mafics of similar age are known from the BHD, eg. Parnell Formation. These metamorphosed mafic rocks in the OD are tentatively collated into the Lady Louise Suite. No similar mafic rocks have been observed in the Strathearn Group.

POODLA HILL SUITE

The Poodla Hill Suite (1.64-1.63 Ga) comprises altered granodioritic rocks considered to be of I-type affinity by Ashley et al. The Poodla Hill Suite is not widespread but is recorded near Ameroo Hill (Outalpa Station), Antro Woolshed and Poodla Dam (Bimbowrie Station).

BIMBOWRIE GRANITE

The Bimbowrie Suite (1.59-1.58 Ga) is equivalent to the 'regional S-type granites' in the OD of Ashley et al., and the Mundi Mundi Granite of the BHD. It includes the granitoids of the Crookers Well region.

PROPOSED LITHOSTRATIGRAPHY FOR THE WILLYAMA SUPERGROUP OF THE OLARY DOMAIN

**PROPOSED LITHOSTRATIGRAPHY
STRATIGRAPHY**

BROKEN HILL DOMAIN

OLARY

This paper		Stevens et al.		Clarke et al.
Strathearn Group	Mount Howden Subgroup	Dayana Pelite	Paragon Group; Dalnit Bore Metasediments	Pelite Suite
		Mooleulooloo Psammopelite	Paragon Group; Bijerkerno Metasediments	Pelite Suite
		Alconic Pelite	Paragon Group; Cartwrights Creek Metasediments	Pelite Suite
	Saltbush Subgroup	Walparuta Schist	Sundown Group & Broken Hill Group	Pelite Suite
		Plumbago Formation	Broken Hill Group	Pelite Suite
Curnamona Group	Ethiudna Subgroup	Bimba Formation	Broken Hill Group; Ettlewood Calcsilicate Member	Bimba Suite
		Peryhumuck Calc-albitite	Ettlewood Calcsilicate Member or Thackaringa Group; Himalaya Formation	Calcsilicate Suite or Quartzofeldspathic Suite
		Whey Whey Schist	Thackaringa Group	Calcsilicate Suite
	Wiperaminga Subgroup	Mooleugore Schist	Thackaringa Group	Quartzofeldspathic Suite
		Outalpa Formation	Thackaringa Group	Quartzofeldspathic Suite
		George Mine Formation	Thackaringa Group	Quartzofeldspathic Suite

OLARY – BROKEN HILL DOMAIN BOUNDARY: MINGARY 100K MAP SHEET

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INTRODUCTION

The Broken Hill Exploration Initiative (BHEI) is a joint project of Primary Industry and Resources, South Australia (PIRSA), New South Wales Department of Mineral Resources (NSWDMR) and the Australian Geological Survey Organisation (AGSO). One of the projects PIRSA committed to was the mapping of the Mingary 1:100K sheet area, on the SA-NSW border. One of the objectives of this mapping was to define the nature of the boundary between the Broken Hill and the Olary Domains, of the Curnamona Province. Recognition of the input from B. Stevens (NSWDMR), G. Gibson (AGSO) and A. Donaghy (Monash University) is acknowledged.

Mapping and geochronological work has long recognised that rocks in the Olary and the Broken Hill Domains are parts of the same broad stratigraphic sequence, though detailed correlation has always been difficult. This difficulty reflects the reality that differences between the geological histories of the two regions exists

PREVIOUS DOMAIN BOUNDARY DEFINITIONS

- Clarke *et al.* (1987) report that Thompson (sic) used the SA-NSW border as an arbitrary domain boundary (Thomson, 1976). Clarke *et al.* (1986) appear to have used this arbitrary boundary, but in Clarke *et al.* (1987) a boundary based on the Mundi Mundi Fault was used.
- Stevens (1986) records that Scheibner used the Mundi Mundi Fault as the domain boundary in an unpublished manuscript but he himself recognised no significant differences in the geology on each side of the fault. He therefore suggested a boundary further to the west in South Australia based on a southwesterly magnetic trend, interpreted to be a fault.
- Geophysicists working from the east and west apparently came to a consensus boundary centred on the same southwest northeast-trending magnetic low zone west of Cockburn as identified by Stevens (1986) (Isles, 1983 and Mills, 1986).
- Another criterion that has been used to define the domain boundary is the zone of steep gravity gradient that appears to separate higher density rocks of the Broken Hill Domain in the east from generally lower density rocks of the Olary Domain in the west. It has been suggested (Tucker pers. com.) that this density contrast could be the result of a change in metamorphic grade-high density minerals in the Broken Hill Domain and the lower grade-lower density minerals in the Olary Domain. Conveniently, the edge of this gravity gradient coincided approximately with the accepted domain boundary. Thus, Ashley *et al.* in the annual Olary Domain excursion guidebook, the domain boundary was defined
- “on the basis of lithological and geophysical character with an intense
- gravity gradient and linear magnetic feature striking approximately NE-NNE marking the boundary” (Ashley *et al.*, 1997).

While the magnetic feature is the currently accepted domain boundary, the lithological differences used to describe the differences each side include:

- The absence of a thick sequence equivalent to the Broken Hill Group of the Broken Hill Block in the Olary Domain
- The absence of a Bimba gossan equivalent in the Broken Hill Domain.
- The rarity of the amphibolite sills/dykes/bodies in the Olary Domain relative to the Broken Hill Domain
- A generally lower metamorphic grade in the Olary Domain compared with the Broken Hill Domain.
- The rarity of *circa* 1590 Ma “regional granites” in the Broken Hill Domain when compared with the Olary Domain.

RESULTS

Each of these lithological criteria have been tested during the current Mingary mapping and found to have some validity. However, these define not one but two possible domain boundaries.

The first and perhaps most significant relates to the thinning and wedging out of Broken Hill Group lithologies towards the west, in particular the Hores Gneiss-Potosi Gneiss, the quartz-gahnites and restriction in the distribution of the coeval amphibolite bodies. Each of these latter key lithologies is apparently related to a *circa* 1690 Ma, thermal event (Nutman and Elhars, 1998, Page and Laing, 1992). This event in turn appears to be

related to a fundamental change in basin morphology involving possible extension and crustal weakening. Sedimentary deposition recorded after this, indicates a basin-wide change from shallow water, clastics and volcanoclastics to deeper water, pelites at this time. The extent of the influence of the 1690 Ma thermal event is one criterion for domain subdivision.

Alternatively, a domain boundary can be drawn based on the degree of exhumation of the two domains exposing different crustal levels. While most rocks from the Mingary sheet have seen the same upper amphibolite to low granulite-grade, peak metamorphic conditions that has taken them into the sillimanite=>kyanite, stability fields, the rocks in the northwest are probably the lowest grade. This is in line with the regional metamorphic gradient mapped by Clarke and co-workers (1986,1987) for the Olary Domain implying a regional shallowing to the west. An outcrop zonation of the migmatites to the south and east and S-type granites confined to the north and northwest of the sheet also implies shallowing to the north and northwest. This is based on the same pattern observed in western France and attributed to crustal level zonation with a lower crust zone of granite production, a migma, failed granite, middle crustal zone and a shallow crustal zone of granite emplacement (D'Lemos *et al.*, 1992).

The migma zone is characterised by migmatites and local melts with only partial separation of melt from restite.

Note that the fundamental criteria on which both of these suggested domain boundaries are based, relate to different events 100 million years-plus apart. The earlier is related to basin development at *circa* 1690 Ma. The later is related to peak metamorphism at 1590 Ma, although the current location of the domain boundary based on this is more a product of the much later process of exhumation. These are two separate events which cannot be somehow factored together to form the basis for a single domain boundary and the subdivision of the Curnamona Province into the Olary and Broken Hill Domains require some explicit statement as to which criterion is being used.

The above proposed domain boundaries cross cut the feature on the TMI map which defines the currently accepted domain boundary. Exactly what this feature means in terms of a domain boundary is now not clear, since the criteria for subdivision appear on each side. The significance of the change in regional gravity noted above is also not clear as it does not appear to coincide with any mapped surface geological differences.

REFERENCES

- Ashley, P.M., Lawrie, D.C., Connor, 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 and Energy, South Australia, Report book 97/17*.
- 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.
- Clarke G.L., Guiraud M., Powell R. and Burg J.P., 1987. Metamorphism in the Olary Block, South Australia: compression with cooling in a Proterozoic fold belt. *Journal of Metamorphic Geology*, 5:291-306.
- D'Lemos, R.S., Brown, M. and Strachan, R.A., 1992. Granite magma generation, ascent and emplacement within a transpressional orogen. *Journal of the Geological Society of London*. 149:487-490.
- Isles, D., 1983. A regional geophysical study of the Broken hill Block, NSW, Australia. *University of Adelaide, PhD thesis*, (unpublished).
- 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.
- Mills, A., 1986. An interpretation of regional geophysical data in the Olary region, SA. *South Australian, Department of Mines and Energy, Report Book*, 82/56.
- 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.
- Stevens, B.P.J., 1986. Post-depositional history of the Willyama Supergroup in the Broken Hill Block, NSW. *Australian Journal of Earth Science*, 3:73-98.
- Thomson, B.P., 1976. Tectonics and regional geology of the Willyama, Mt Painter and Denison Inliers. In: *Economic Geology of Australia and Papua New Guinea* (ed. Knight, C.L.) pp 469-475. *Australian Institute of Mining and Metallurgy*.

OLARIAN WAVES: DEFORMATION, FLUIDS AND ALTERATION IN THE WESTERN WILLYAMA

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SUMMARY

A review of the structural and hydrothermal evolution of the Olary region reveals a northwest vergent deformation history that involved the development of a major fold-thrust belt. Coupled regional scale fluid generation and flow resulted in an alteration/mineralization 'front' that migrated outwards and was progressively reworked as the orogen expanded. This highlights a dynamic, time dependent environment in the Olary Domain in which alteration and mineralization events do not occupy discrete time slots, but evolved as a 'continuum event' in space and time that was closely linked to the prograde expansion of the Olarian Orogen.

INTRODUCTION

Whilst much research has been directed at the Broken Hill region, relatively little attention has been given to the Olary domain. With some exceptions, the few studies that addressed the geological and metallogenic evolution ignored the critical structural component and were dominated by stratigraphic approaches (Cook and Ashley, 1992; Ashley et. al., 1996). Clarke et. al. (1986) formulated a model for the structural evolution of the Olary domain that involved southeast verging nappes, based partly on an established informal stratigraphy. Critically, their interpretations were never integrated with any stratigraphic or alteration interpretations. This prompted a review during 1997-1998 by the current authors, aspects of which are reported here.

REGIONAL GEOLOGICAL SETTING

The Palaeoproterozoic stratigraphic scheme for Olary remains an informal one. The most commonly used scheme describes five 'Suites' of dominantly immature sediments, metasediments (andalusite bearing), metavolcanics, para- and orthogneisses (andalusite, sillimanite, kyanite), where the highest grade rocks occupied the base of, and the lowest grade rocks the top of an informal stratigraphic column. The bulk of the succession is older than ~1648 Ma, although a minimum age lies somewhere between ~1600 and 1648 Ma (Page et. al., 1998). Although this paper does not specifically discuss the stratigraphic framework of the region, or speculate on potential correlations, our results indicate that the existing informal scheme should be the subject of major revision and requires a substantially improved lithostratigraphic resolution before a meaningful regional understanding can be achieved. As this study progressed it became clear at an early stage that in the absence of a well constrained structural framework, the existing stratigraphic model could not be sustained, and the 'Suite' approach had, therefore, to be abandoned.

The Olary domain underwent a major orogenic event, the Olarian Orogeny, at around ~1630-1590 Ma. The currently exposed orogenic remnants are characterized by regional metamorphic and strain gradients. The metamorphic gradient is defined as a broad northwestward decrease in grade from transitional granulite/upper amphibolite to greenschist and below. Narrow, linear east-northeast trending domains interrupt the broadly uniform gradient. The regional strain gradient is less well defined, but essentially parallels that of the metamorphic changes. It is described by higher bulk strains and complex structural reworking in the gneissic rocks and progressively lower bulk strains and less reworking the northwestern areas. In very outboard areas, strain magnitudes are quite low, with limited penetrative fabrics developing and folding that is open. Brittle deformation dominates in these distal environments.

STRUCTURAL FRAMEWORK

The structural environment is dominated by consistently northwest verging elements, which contrasts with the interpretation of Clarke et. al. (1986). These are best defined by recumbent through strongly asymmetric to inclined regional to mesoscale folds. The recumbent folds are major regional scale structures that could be interpreted as nappes or thrust-nappes and are most readily identified within the gneissic domain, although folds with horizontal axial surfaces can be observed in lower grade rocks that mantle this domain. Significantly, lower grade metasedimentary 'enclaves' within the gneisses also contain recumbent structural elements. At least three deformation events have influenced the evolution of the gneisses:

1. an early high temperature event (D1) resulting in the formation of a migmatitic layering (S1),
2. a second high temperature event (D2) associated with northwest verging tight to isoclinal recumbent folding (F2) followed by localized partial melting in the central part of the exposed gneissic domain, and

3. a third high temperature event (D3), though here conditions were below minimum melt temperatures and at P-T conditions equivalent to lower amphibolite grades, and associated with northwest vergent refolding (F3) of F2 folds.

The dominance of low to moderate dips on S1 in the gneiss domains is indicative of the importance of the regional overturned to recumbent F2 folds in the structural framework. The boundary between the migmatitic gneiss domain and amphibolite grade metasediments in the enclaves, or immediately mantling the gneiss domains, is almost always very sharp. These boundaries are marked by high strain zones and contain planar fabrics displaying shallowly southeast plunging stretching lineations. We interpret these to be thrusts, and part of a northwest verging regional thrust system that forms the backbone to the regional structural architecture (Fig.1). In the lower grade metasediments these thrusts control local exhumation of higher grade (andalusite bearing) schists, resulting in isograds that approximately parallel the structural grain. In tectonic terms the lower grade domain can be regarded as a foreland basin, with a fill consisting primarily of turbidites.

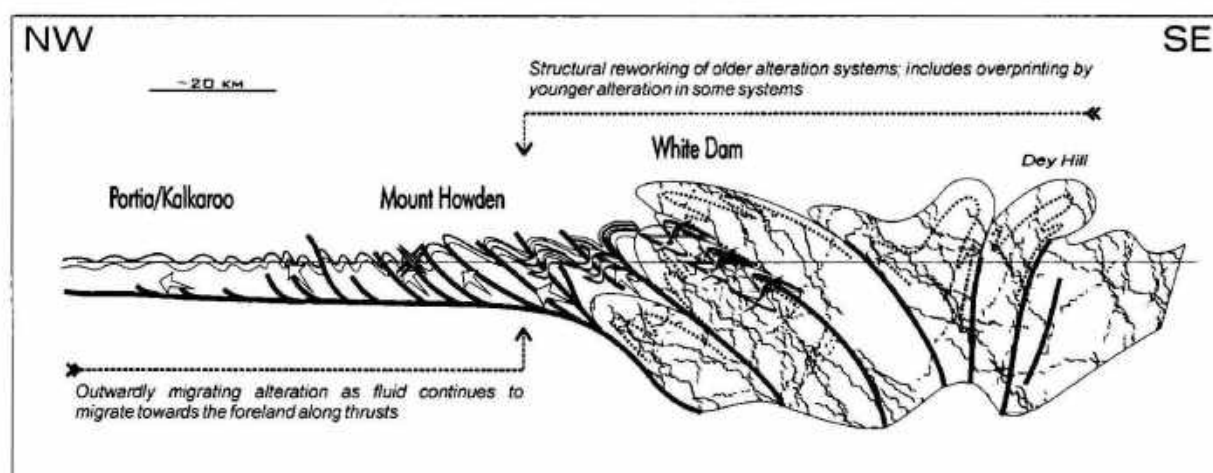


Figure 1 Interpreted intermediate stage in the evolution of the Olary Domain. Fluid flow along thrust system is shown by arrows. Approximate positions of mineralized systems are shown. Note that reworking of older alteration systems takes place as the orogen expands. The gneisses have a textured fill; the foreland metasediments have no fill.

Within the lower grade metasedimentary enclaves progressive shortening is characterized by inhomogeneous strain. Sub-horizontal extension and related vein formation was driven by shortening along steep to near vertical axes, a consequence of tectonic loading caused by exhumation of the gneisses during D2 and D3. Local excursions into minimum melt conditions produced characteristic layer parallel melts, as well as discordant, thin and narrow quartzo-feldspathic dykes. These became boudinaged and tightly to isoclinally folded with continued shortening. Many of the early folds within the Mulga Bore area have flat lying axial surfaces and describe recumbent structures. Vertical shortening is also observed in the metasediments immediately surrounding the gneiss domain. These features indicate substantial and regionally significant tectonic loading, as well as coincident and significant fluid flow.

Tight to moderately tight asymmetric to upright folds have developed outboard of, and within two to three kilometres of the gneiss domain boundary. Lithologies are dominated by interbedded fine to coarse grained psammites and interbedded pelites. The transition from overturned and recumbent, to upright fold geometries is rapid, indicating structural juxtaposition of the two environments. In the lower grade rocks strain is frequently strongly partitioned and accommodated by shearing along the pelitic interbeds. Preservation of delicate primary sedimentary structures in psammites highlights the degree of partitioning in these interbedded units. Up to three penetrative fabrics are recognized in the metasediments, with the intersection between a partially differentiated crenulation cleavage ($S2_{local}$) and an undifferentiated crenulation cleavage ($S3_{local}$) controlling andalusite porphyroblasts growth. Development of these and other fabric elements is regionally partitioned and such controls are not everywhere evident.

The deformation nomenclature used in the gneissic domains can not be extrapolated to describe structural elements in the lower grade domains. The substantial shortening which has affected the Olary crust and outward migration of deformation 'fronts' means that no direct link between events in the two broad domains can be

established. Thus D2 elements in the gneisses may correlate with the $S1_{local}$ layer parallel foliation in the enclaves, and D3 in the gneisses may be temporally equivalent to the second crenulation cleavage event ($S2_{local}$) in the metasediments outboard of the gneissic domain.

ALTERATION – FLUID – STRUCTURE RELATIONSHIPS

Other workers generally interpret a pre-orogenic timing for regional alteration. Mapping of several important alteration systems showed that they all developed during the structural evolution of the region, based on overprinting criteria. Four generalized styles were identified, all consisting of assemblages that variably contain albite-quartz±amphibole±epidote±magnetite±garnet±pyroxene±sphene:

1. albite-quartz rich assemblages as broadly stratabound units;
2. fold hinge related, pervasive replacement of fine grained psammite and psammopelitic lithologies with fluid distribution controlled by cleavage and bedding;
3. fold related linear breccia systems up to and in excess of 100m in length;
4. vein selvage and associated selective layer replacement systems.

The broadly stratabound systems are best observed in the gneisses. Replacement of both psammitic and pelitic precursor lithologies occurred after peak metamorphism during late D2 or perhaps D3. Rare pseudomorphed andalusite porphyroblasts exist as relict forms in massive quartz-albite rock and constrain the timing of alteration to late D2 or D3. Large scale boudinage and folding of some of these bodies indicates structural reworking, and could be interpreted to further constrain the time of alteration to D2, either during prograde or post-peak times.

The second and third alteration styles, collectively referred to as the 'Big Rock' style, have developed in and near fold hinge positions. Both styles are related to fluid flow along axial surface cleavage and bedding planes and result in restricted to pervasive replacement of the host rock, often making the recognition of the host folds very difficult. The overprinting nature of this alteration style was not previously recognized and maps of the region interpret these systems as stratabound to stratiform, such as in the Tellechie Valley north of Poodla Hill. The breccia systems represent brittle failure in hinge positions during folding and in the Tellechie Valley example the mapped unit represents a structural, rather than stratigraphic position. These highly permeable domains focussed fluid flow, which ultimately produced the calcsilicate assemblages now observed. Examples of these systems to the west of Kalabity show breccia development in hinge zones and parallel to fold axes which strike to the northeast in this area.

The fourth style is poorly represented within the study area and is associated with distal systems such as Kalkaroo and Portia. Unlike the systems just described, these have developed in very high level, low bulk strain structural environments. Potassic and sodic alteration assemblages that range from reduced to oxidized are typical and selective layer parallel replacement has been facilitated by a variable carbonate component in the hosting lithologies. The gneiss hosted White Dam system shows biotite enrichment adjacent to many veins, suggesting a prograde potassic alteration event accompanied vein formation.

Layered calc-silicate rocks represent a possible fifth style and have previously been interpreted as examples of syn-sedimentary alteration. In contrast, our observations lead us to interpret a prograde timing for the formation of these rocks. The nature of the assemblages, plus the distinct symmetry and consistency of the zoning along strike indicates no significant infiltration by exotic fluids occurred. These features echo the mechanism of bimetasomatic skarn formation, which are driven by reactions between adjacent variably impure carbonate and siliciclastic bands. We therefore regard these layered calc-silicate rocks as essentially closed system metamorphic products, rather than open system hydrothermal ones.

FLUID – DEFORMATION – ALTERATION TIMING RELATIONSHIPS

Fluid to rock ratios are suggested to have been low in the evolution of the Olary Domain. Whilst this may be true in specific locations and at a mesoscale, a broader view of the orogen indicates that large volumes of fluid were in fact released and migrated along P and T gradients during structural and metamorphic evolution.

The spatial relationship between alteration systems and structural elements provides clear evidence that fluid flow and distribution in the Olarian Orogen was fundamentally controlled by the thrust system. The geometric relationships see the bulk of the 'Big Rock' style systems developing towards, and in the hinge domains of fault propagation folds. In the lower grade domains these have developed above blind thrusts, or in the hangingwall of thrusts that are themselves splayed off a major upper to mid-crustal decollement (Fig.1). In this environment fluid flow was more focussed when compared to proximal positions, where higher bulk fluid:rock ratios are more

likely. The greater volume of albite-quartz alteration in the proximal positions supports this view. By integrating these observations and interpretations with those that define the relative timing of alteration to deformation and metamorphism, including the reworking of early syntectonic alteration and post-peak metamorphic systems, it becomes obvious that a fully coupled alteration-fluid-deformation-metamorphic system was operational during the evolution of the Olarian Orogen.

What do the integrated observations mean? We believe that the coupling, when viewed in a four dimensional context, describes a dynamic regional hydrothermal history where alteration migrates outwards in parallel with strain and metamorphic 'fronts'. The principal implication is that there is not a series of discrete hydrothermal events at an orogen scale, but rather a continuum exists, in which sites of fluid generation and alteration migrate outwards from the expanding orogen. In effect, therefore, we could view the hydrothermal evolution of the Olarian Orogen in the context of a set of 'waves', or fluid pulses, generated near the expanding high grade core of the orogen. At any given time in the evolution of the orogen, therefore, alteration systems that formed in medial to outboard positions are being reworked in inboard positions as the latter are 'overtaken' by the tectonically expanding higher grade core (Fig.1). At the same time new fluid source rocks are being accessed.

CONCLUSIONS

The interpretation presented here represents a significant departure from previous views of the structural evolution of the Olarian Orogen and the place occupied by regional alteration. Our observations indicate that the bulk of alteration systems are related to the structural and metamorphic evolution of the orogen. The implication that regional alteration/metallogenesis represents a continuum, rather than a series of discrete and unique events in space and time, has significant implications for how the relationships between the hydrothermal and physical evolution of the whole Willyama are interpreted.

REFERENCES

- Ashley, P.M., Cook, N.D.J., & Fanning, C.M., 1996. Diversity of metallogenesis in the Willyama Supergroup, Olary Block, South Australia. *In Australian Research on Ore Genesis Symposium, Adelaide, Australian Mineral Foundation*, 18.1-18.5.
- 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.
- Cook, N.D.J., & 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.
- Page, R.W., Conor, C.H.H., & Sun, S-s., 1998. Geochronology of metasedimentary and metavolcanic successions in the Olary Domain and comparisons to Broken Hill. *BHEI, Abstracts from 1998 Annual Meeting, AGSO Record 1998/25*, 89-93.

STRUCTURE AND GEOLOGICAL EVOLUTION OF THE KOONENBERRY FOLD BELT, NSW: IMPLICATIONS FOR MINERALISATION

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Consideration of the latest geophysical datasets and new mapping and stratigraphic data shows the Koonenberry Belt of far western NSW, to be an Early to Late Palaeozoic fold-and-thrust belt.

This study presents the results of geologically-controlled qualitative interpretation and two-dimensional modelling of gravity and magnetic data which permit a new tectonic interpretation, relying upon the different petrophysical, structural and metamorphic attributes of three distinct tectonostratigraphic packages.

The oldest known succession in the belt consists of shales, sands, dolomites and strongly magnetic transitional alkaline basalts, which are considered to exist in large volumes at depth, producing a major magnetic anomaly. This package represents Late Neoproterozoic continental rifting, dated at 587 Ma. These rocks are disconformably overlain by a regionally extensive ?Early to ?Middle Cambrian turbidite succession, interpreted to be related to Early Cambrian volcanic passive margin formation. Dense, rifted blocks of Neoproterozoic sedimentary successions are considered to underlie this remnant margin at depth, based on high gravity signatures.

A second widespread rifting or crustal attenuation event is represented by marine shelf successions interbedded with minor volumes of calc-alkaline volcanic rocks. This event has been dated around 525 Ma.

A series of highly deformed Cambrian to ?Early Ordovician quartz-rich turbidites and tholeiitic basaltic volcanics with E-MORB characteristics is considered to represent a marginal basin which formed in response to the 525 Ma rifting. These rocks are in fault contact with older turbidites and broken shelf successions along major regional faults, in some places marked by melanges. Further volumes of Cambrian to ?Early Ordovician rocks are implied at depth by both geophysical and structural considerations. These relationships suggest that this package was thrust from the east over and onto a multiply rifted passive margin. The timing for this event is constrained by zircon dating of tuff horizons in the turbidites, and biostratigraphy of overlying syn- to post-collisional sedimentary rocks. These dates suggest that the deformation of the margin was a diachronous event occurring from the late Middle Cambrian until at least the end of the Late Cambrian, and may have continued into the Early Ordovician.

In the Darling River Lineament and Scopes Range areas to the south of the main thrust belt, the Late Cambrian deformation is associated with two pulses of localised magmatism. The first is of medium- to high-K calc-alkaline character, and is considered to represent post-collisional volcanism dated between 508 and 486 Ma. A temporally later pulse of tholeiitic dykes is considered to mark an aborted rift phase.

Geological and geophysical considerations indicate that successions up to and including the Ordovician were further deformed by folding and thrusting between the Middle Ordovician and the Late Silurian, before deposition of Late Silurian- Early Devonian red-beds.

The general style of faulting in the thrust-belt is constrained by analysis and modelling of geophysical data, which shows across-strike repetitions of various successions, and listric fault geometries.

These features strongly suggest that the belt is both a polydeformed fold-thrust belt with both southwest and northeast vergence that detaches in the mid-crust, and a zone of overlap between the Delamerian Orogen of South Australia, and the Lachlan Orogen of eastern Australia. Features identified in deep seismic data strongly suggest strike-slip control by late, Carboniferous-age structuring.

Comparison of the belt to successions elsewhere, indicates tectonic equivalence between the early transitional alkaline volcanics, and alkaline volcanics in South Australia, picrite lavas in westernmost Victoria and on King Island, and tholeiitic volcanics in western Tasmania. These correlations support the hypothesis of widespread continental rifting and volcanic passive margin formation between 600 and 585 Ma.

Comparison of turbidite successions in the belt and South Australia indicates fewer similarities than previously thought; equivalent passive margin successions to those in western NSW may lie in westernmost Victoria.

Equivalents to the Cambrian shelf successions exist within the Warburton Basin of northern South Australia, and indicate that the second episode of rifting, dated at 525 Ma, was widespread.

The late Middle Cambrian-Late Cambrian thrusting event and subsequent post-collisional volcanism in the belt is also considered to be represented in western Victoria and western Tasmania. In these locations, it is represented by allochthonous slices of intra-oceanic arc mafic-ultramafic complexes and overlying 'in situ' post-collisional volcanics. The structural and metamorphic character of these successions, and their common timing, contrast strongly with the exposed successions of the Adelaide Fold Belt and other portions of the Ross-Delamerian Orogen in Antarctica, and strongly suggest that the orogen is divided into internal and external zones. Analysis of differences in timing and character of deformation, and the distribution of granitoids between the two zones suggests that the Delamerian Orogeny was a long-lived, mantle-driven process with widespread thermal effects in both space and time. This has been overprinted by more-localised deformation effects (rifting, arc collision) from short-lived plate-geometries. This model contrasts with earlier suggestions of a rigid arc-continent style collision.

Subsequent development of the Koonenberry and related fold-belts in an in-board position is related to long-lived accretion at the free plate margin to the east. Effects include major fold and thrust deformation in the Ordovician-Silurian, and widespread strike-slip-related deformation in the Devonian and Carboniferous. A major Devonian thermal event, which produced widespread granitoid magmatism elsewhere in the Lachlan Orogen is absent within the Belt. The present disposition of units in the Koonenberry Belt appears to be related to tectonic reorganisation during the Carboniferous event.

The tectonostratigraphic successions and deformation style of the belt suggest significant prospectivity for a variety of base and precious metals, and diamonds. Likely mineralising systems include sediment-hosted base metals (MVT, red bed Cu-U); porphyry, skarn and epithermal Cu-Au; VHMS; and structurally-controlled Au. Correlations with equivalent successions elsewhere support this conjecture. The Bancannia Trough has some petroleum potential, with known mature sources and reservoir facies; however, the structural complexity of the belt suggests all plays will have a high element of risk.

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UNDER THE MUNDI MUNDI – IMPLICATIONS FOR DISCOVERY SUCCESS

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One of the greatest challenges facing companies in the discovery business in Australia is how to effectively explore through significant thicknesses of overburden. The increasing exploration maturity of Australia, including the Broken Hill/Olary province, is forcing companies under thicker cover and to use more expensive techniques than compared with the past.

Under the Mundi Mundi Plain, BHP Minerals Discovery has been targeting Broken Hill Type (BHT) mineralisation through overburden up to 150m thick using a number of techniques with some success. Previous work by CRAE in the mid- to late 1980's highlighted the potential for BHT mineralisation at the Woolshed or Polygonum Prospect and was a catalyst for BHP to enter a Joint Venture into the area held by Platsearch.

At Polygonum, a drill intersection within interbedded pelites and psammities averaging 0.13% Pb and 0.17% Zn over 103m is interpreted to be within the Broken Hill Group equivalent (Figure 1). This mineralisation occurs within a 300m thick envelope of widely disseminated fine-grained garnet and occurs stratigraphically above an amphibolite. Microstructural analysis of mineralised core by Hills (1999) identified Cu and Pb-Zn-Ag mineralisation of both pre- to syn-tectonic and post-tectonic origin with a zoning from Cu-magnetite +/- haematite in the footwall quartzo-feldspathic and Calc-silicate sequence to Pb-Zn-Ag-pyrite/pyrrhotite within the Bimba and hanging wall pelite/psammite sequence.

Pre- to syn-tectonic mineralisation is contained within early OD1/OD2 mineral foliation and comprises disseminated aggregates of pyrite and pyrrhotite +/- sphalerite within the Bimba and Pelite Suites and disseminated to stratabound aggregates of magnetite +/- pyrite +/- pyrrhotite +/- chalcopyrite within the Quartzo-feldspathic and Calc-silicate Suites. Pervasive albite alteration is associated with this mineralisation in the former but is weak to absent in the latter. Post-tectonic mineralisation overprints the OD1/OD2 deformational fabric and occurs as veinlets and disseminated to massive aggregates of magnetite +/- chalcopyrite +/- pyrite +/- molybdenite predominantly within the Quartzo-feldspathic and Calc-silicate Suites and within the Pelite Suite as disseminated to laminated pyrite and/or pyrrhotite with associated sphalerite, galena, chalcopyrite, molybdenite, minor arsenopyrite. Mineralisation in the Pelite Suite has associated strong chlorite and sericite alteration.

A number of techniques have been utilised to explore for the BHT deposit style; primarily detailed gravity but also including soil surface geochemistry. Magnetics data has been used as a geological mapping tool to prioritise prospective stratigraphy and gravity targets within it. Drill testing along the trend of prospective stratigraphy has defined an overall strike length of 18 - 20km along which the pelite/psammite package is variably mineralised. Drill testing of other gravity targets within a similar stratigraphic position in other parts of the region has intersected a similarly weakly mineralised package.

Soil surface geochemistry results located over the prospective stratigraphy are apparently detecting the weak Ag/Pb/Zn mineralised mineralisation through up to 150m of transported overburden. Air core drill testing of soil anomalies failed to locate any improved grade within the package.

Exploration through significant thicknesses of cover is expensive and therefore confidence in the techniques employed is very important. The use of gravity as a tool to search beneath this cover is by no means truly effective with resultant anomalies apparently caused by density contrasts of rock packages at the Bimba contact. The ability to target using soil surface geochemistry is not precise but the development of a technique to "see through" thick cover is important for future exploration direction within Australia.

Exploration in the Broken Hill/Curnamona Region and also within the rest of Australia is becoming increasingly more expensive and difficult as companies push out further beneath cover. There is a worldwide trend of a fast declining discovery rate (Blain, 1999), especially within the so-called mature exploration countries, even in the face of dramatically increasing exploration expenditures (Figure 2). Not only does the Broken Hill/Curnamona region face a large challenge but also the entire Australian exploration industry is competing with other parts of

the world where exploration maturity is not as advanced and where exploration initiatives are only just beginning.

ACKNOWLEDGMENTS

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REFERENCES

- Blain, C.F., 1999. Trends in discovery – commodity and ore-type targets. In Stanley, G.A. (Ed.) Extended abstracts volume: North Atlantic Minerals Symposium, September 1999, Dublin, Ireland. Geological Survey of Newfoundland and Labrador and the Geological Survey of Ireland.
- Hills, Q.G., 1999. The nature and origin of the mineralisation preserved within the Bimba Suite, Olary Block, Willyama Inlier, Southeastern Australia. *Unpublished MSc stage 1 report*, Melbourne, Monash University. 56p.

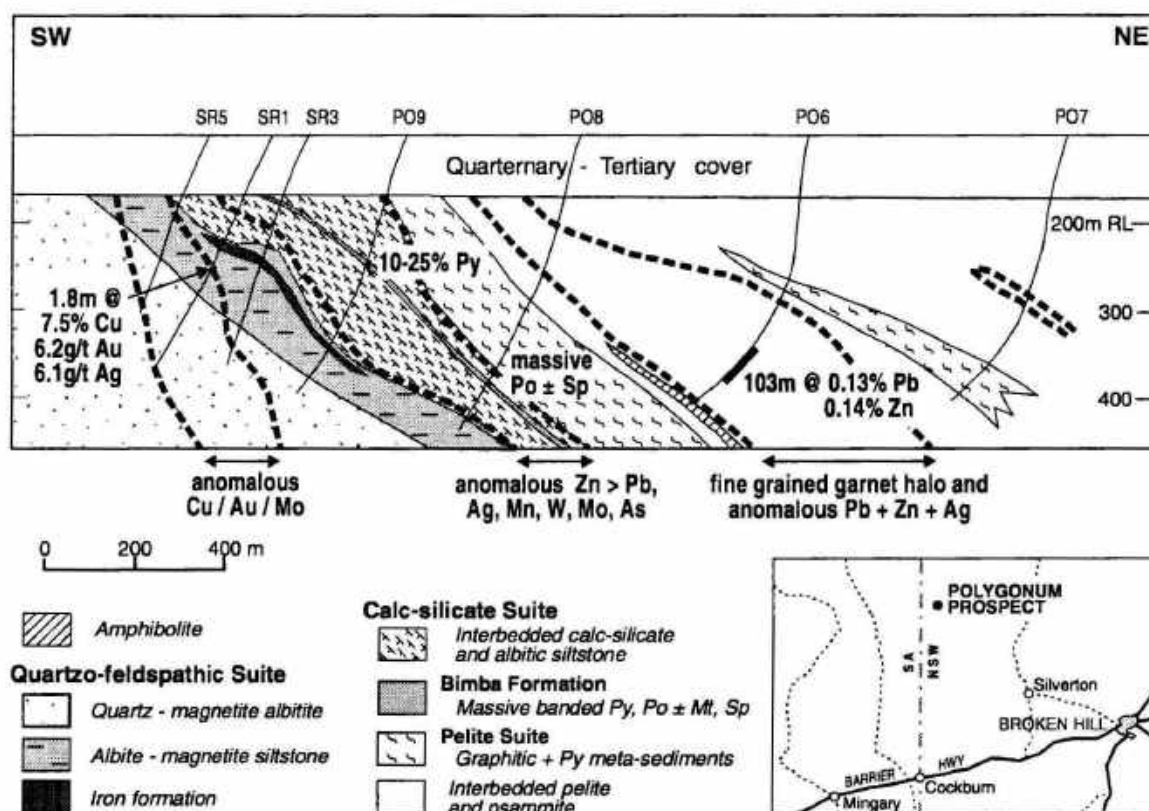


Figure 1 Cross-section of Polygonum Prospect showing mineralisation zoning

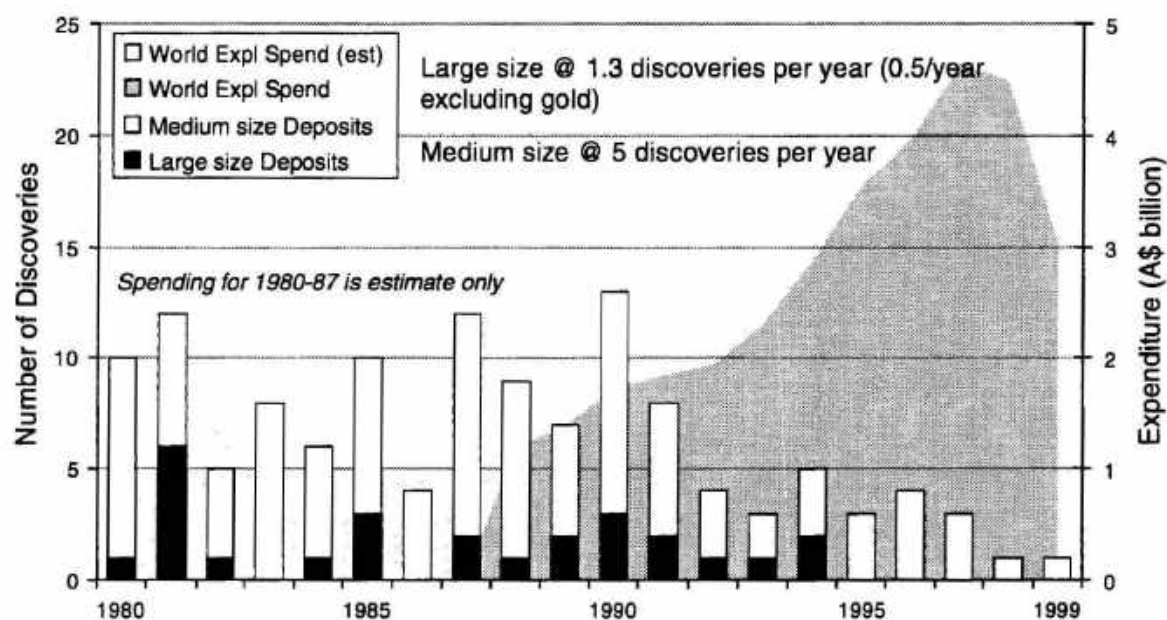


Figure 2 Worldwide discovery frequency since 1980 and exploration expenditure

BALACLAVA 1:25,000 REGOLITH-LANDFORM MAP: DEVELOPING DETAILED MAPPING FOR REGOLITH DOMINATED TERRAINS

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INTRODUCTION

Traditional geological mapping approaches that only represent bedrock exposures have limitations in representing the geology across the entire landscape. This is particularly apparent on the 1:25,000 Balaclava geological map (Brown, 1986). Although the map is a superb representation of the areas of exposed bedrock, most of the sheet area is either a uniform shade of pale yellow (representing "Cainozoic rock units") or is covered by the map legend. Regolith-landform mapping of this sheet at 1:25,000 scale is designed to complement the existing geological map, providing a geological representation of areas where bedrock is not exposed. For exploration geologists it provides a representation of the existence and location of potential geochemical sampling media, associated dispersion pathways and areas that can be treated similarly for exploration strategies and data interpretation. The maps also provide valuable information for land managers, including a detailed representation of the surficial geology (including soils, areas of erosion and sedimentation), while derivative maps can show dominant vegetation communities and nutrient dispersion pathways.

BALACLAVA REGOLITH AND LANDSCAPE

Balaclava is located near the southern margins of the Broken Hill Block where it is overlain by sediments associated with the Murray Basin. Bedrock exposure makes up less than 5% of the area. Pine Creek subdivides the area into two broad landscape types: to the west the landscape mostly consists of undulating hills and rises with subcropping weathered bedrock concealed by a thin sedimentary cover; and, to the east the landscape is of low relief and dominated by thicker transported regolith (e.g. alluvial plains and broad colluvial fans). Regolith depths range from several millimetres to over 100 metres. The deepest regolith appears to most closely correspond with shear zones and palaeovalley systems. Grey and red-brown mottled lacustrine silts and clays are exposed at some sites along Pine Creek, and have also been identified from drilling in the area. Exposures of *in situ* regolith are typically in the form of weathered bedrock (saprolite) near the crests of erosional hills and rises, or in erosion gullies, pits and dams. At many sites the *in situ* materials are ferruginised or feature gypsum accumulations. Transported regolith also hosts various facies of induration including regolith carbonate accumulations ('calcrete'), ferruginisation ('ferricrete') and silicification ('silcretes').

MAPPING METHODS AND PRESENTATION

An exciting aspect of this mapping is that it has been largely driven by student research. Not only has this required that their research outputs are of a high standard in order to contribute to a larger research team, but it has also led to the training of young geoscientists with an expertise in regolith mapping and geology. The Balaclava sheet area was the research focus of two honours students: Greg Shirtliff at Balaclava West (Shirtliff, 1998), and Kylie Foster at Balaclava East (Foster, 1998). Steve Hill was a supervisor of these projects but also contributed to some mapping and the later stages of map production and follow-up sampling programs with Kylie Foster. The production of this map has therefore been a team effort, which was of great assistance during the many trials and errors of producing a new type of research product.

The initial stages of map production were largely based on remote sensing and the compilation of existing data (including previous exploration data). Detailed air photographs (1:12,500) provided through the NSW Geological Survey and Pasminco Exploration were of great benefit in constructing preliminary regolith-landform polygons. This information was complemented by radiometrics, Landsat TM and magnetics data obtained through AGSO as a part of the NSW Discovery 2000 program. Fieldwork involved the mapping of regolith-landform polygons, detailed site descriptions and sampling. Site description information was entered into AGSO's RTMAP database and final map production used ArcInfo.

Regolith mapping is a relatively new discipline within Earth sciences, and the development of robust mapping schemes has been a major challenge. The approach used here is based on the AGSO regolith-landform scheme (Pain et al., 1991) with some minor modifications. This scheme was initially designed for regional scale regolith-landform mapping (e.g. 1:250,000), and prior to this project had not been applied to maps published at 1:25,000. Regolith-Landform Units (RLUs) provide a description of the relationship between regolith types and their

landscape setting. In order to describe the regolith and landform types a simplistic code system is used with specific letter combinations conveying the general information for each RLU. For example:

CHfc₁

- the upper case letters (CH) describe the main regolith type (which in this case are sheet flow deposits);
- the lower case letters (fc) describe the main landform type (which in this case is a colluvial fan); and,
- the modifier (1) is added to represent subtle differences in attributes within each RLU (such as surface lag type etc.)

Further information for each RLU is also provided in the map legend. Care has been taken to minimise genetic interpretation within the descriptions within the mapping legend, where although the RLUs are broadly classified according to a dominant genetic regolith process (e.g. alluvial, colluvial, aeolian etc.) their description is largely based on the description of regolith materials (especially lithology), landforms and other attributes. It is also important to note that these maps are designed to complement bedrock geological mapping and not replace it. Areas of bedrock exposure are mapped according to their regolith-landform features rather than their bedrock lithologies. This typically involves an account of the degree of bedrock weathering and their landform expression. In most cases the bedrock exposures conform to slightly weathered bedrock on erosion rises (shown by the code SSer). Bedrock information is actually kept to a minimum in the map presentation, thereby increasing the value of combining this regolith map with existing geological maps within GIS systems. Induration modifications of regolith materials are shown as an overprint pattern covering their specific regolith-landform hosts. Contrary to some previous regolith mapping approaches, this means that an indurated regolith material such as a 'silcrete' is first mapped according to its host material, such as alluvial sediments on an erosional rise (shown by the code Aer), and then according to its facies of induration modification, such as nodular silicification (shown by a corresponding overprint pattern). Using this approach, derivative maps of indurated materials can be easily produced, complex materials with several induration facies can be shown, and the nature of the regolith host maintains its integrity in map presentation.

APPLICATIONS, DERIVATIVE PRODUCTS, AND FUTURE DEVELOPMENTS

As regolith forms the interface at the landscape surface the applications of regolith maps are varied.

One of the user groups that the map is most valuable to are members of mineral exploration programs. The maps show the distribution and location of specific sampling media, either on the main map or on derivative maps produced in GIS. For example the Balaclava map features a derivative map showing the distribution of the dominant regolith carbonate ('calcrete') facies in the area. This in effect works as a regolith carbonate sampling "go-map", delineating areas where this sampling medium can be easily found for companies using this exploration approach. Similar derivative maps could be chosen for other sampling media. The RLUs effectively show areas where similar sampling media can be found and interpreted in an equivalent way. These can also be related to specific geochemical dispersion pathways and processes helping to develop links between geochemical anomalies within the regolith and possible mineralisation sources.

The map also has potential value to land managers. The RLUs show the dominant surficial geology materials and including soils, sediments and areas of erosion. Attribute information is also collected on the dominant vegetation communities, and as such derivative vegetation maps can be produced. Some landowners find the representation of regolith carbonate materials particularly useful as these materials have a very close association with the favoured locations of rabbit warrens. The similar principles for using these maps as geochemical exploration frameworks can also be used to understand trace element and nutrient dispersion and cycling in the landscape, and on a broader scale areas of groundwater recharge and discharge. For example the location of many station bores and dams correspond closely with regolith-landform patterns related to the area's hydrogeology (e.g. along palaeovalley systems, or along the lateral slip-off channels associated with alluvial and colluvial fans).

Future developments of this map include a soon to be released digital version of the map with an accompanying database. The database will include multi-element geochemistry of selected regolith materials, sample site descriptions and photographs, thin section photos, mineralogical information, drill hole information (including depth to basement) and other attributes available at each site. A report will also accompany the GIS release.

It is hoped that the publication of this map will be the first in the release of a series of other 1:25,000 maps from the region, particularly from the southern part of the Broken Hill Block and northern Murray basin margins.

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REFERENCES

- Foster, K. A., 1998. Regolith geology and geochemistry of Balaclava East, Broken Hill, NSW. University of Canberra, Honours Thesis (Unpublished), 96 pages.
- Foster, K.A., Shirliff, G., & Hill, S.M., 2000. Balaclava Regolith-landform map (1:25,000 scale). CRC LEME, Canberra/Perth.
- Pain, C. F., Chan, R. A., Craig, M. A., Hazell, M., Kamprad, J. & Wilford, J., 1991. RTMAP, BMR Regolith Database Field Handbook. Minerals and Landuse Program, Series 1. *Bureau of Mineral Resources, Geology and Geophysics*, Record 1991/29
- Shirliff, G., 1998. Ferricretes and the landscape evolution of the Western Balaclava Area, South Broken Hill. Australian National University, Honours Thesis (unpublished).

REGOLITH, LANDFORM HISTORY AND SAMPLING STRATEGIES IN THE WONNAMINTA AREA, KOONENBERRY BELT

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The Koonenberry Belt is one of the least geologically understood and explored regions in NSW. Until the Geological Survey of NSW began 1:100 000 scale mapping in the area several years ago, geological data were limited to 1:250 000 maps rapidly produced in the 1960's and a few specialised studies. Published regolith information is presently limited to regional data in the regolith map of Australia (Chan *et al.*, 1986), the 1:500 000 Broken Hill regolith maps and explanatory notes (Gibson, 1999), soils data in the 1:2 m soils map of Australia (Northcote, 1968), 1:250 000 land system maps (Walker, 1991), and a landsystem study which included part of the area (Corbett *et al.*, 1972). Known mineral occurrences are limited. Reasons for lack of knowledge of the area include its apparent lack of mineralisation, remoteness, generally low relief, and regolith veneer.

REGOLITH MATERIALS

A preliminary regolith map of the Wonnaminta 1:100 000 sheet is presented at this conference. This is based on about 2 weeks of field traverses mostly along roads and tracks, and detailed interpretation of 1:50 000 colour airphotos. Observed regolith materials consist of:

1. Lag. This is extremely variable, consisting of combinations of angular vein quartz and quartz/hematite fragments (derived from erosion and weathering of quartz/iron veins in basement rocks), silcrete formed in transported sediments (locally ferruginised), fragments of ferruginised bedrock and sediments, magnetic 'buckshot' pisoliths, angular fragments of resistant bedrock, and rounded pebbles and cobbles, mostly milky quartz. In many cases, the lag reflects the underlying rock types, but locally the lag is unrelated to the underlying rocks, and is interpreted to be a winnowed lag derived from former overlying sediment that has been completely eroded.
2. Soil. Two main soil types are present on basement rocks. Calcareous gypseous loams with vegetation contour banding predominate in areas of low relief, and sandy loam lithosols in higher relief areas over more resistive rock types. Soils are also present in transported alluvial and aeolian deposits.
3. Soil hardpans on some slopes adjacent to hills and rises of Mesozoic sediment.
4. Surficial sediments. Aeolian dunefields and sand sheets are present in the west and south of the area. Small patches of aeolian sand, and source-bordering dunes are locally present elsewhere. Sandy to silty alluvium is ubiquitous along watercourses.
5. Regolith carbonate. This is exposed as a hardpan coating at the rock-soil interface over some basement rocks, especially in more rugged areas of Devonian sediments, and is present as powdery carbonate in soils.
6. Weathered Mesozoic sediments.
7. Silcrete formed in a sedimentary host, probably mostly Mesozoic sediment.
8. Ferruginised Mesozoic sediments.
9. Weathered basement rocks, including ferruginised rocks.
10. Gypsiferous clay of unknown origin underlying some silcrete outcrops.

MESOZOIC SEDIMENTS AND LANDSCAPE HISTORY

The long-term landscape history of the area is the most important factor in understanding the regolith of the area. Shallow dipping to flat-lying Mesozoic rocks of the Eromanga Basin surround the area of Palaeozoic rocks of the Koonenberry Belt to the west, north and east. It is considered probable that the basement outcrop areas represent a broad uplifted area where the Mesozoic rocks have been stripped. At the 'Three Hills' in the central Wonnaminta Sheet area, Mesozoic sediments (with plant fossils; Brunker, 1967) overlies basement rocks (Fig 1). The unconformity is at a level only a few metres above the surrounding plain eroded on basement rocks, suggesting that erosion has proceeded only a small way below the exhumed unconformity surface. About 50 m of Mesozoic sediment is present at this locality, with bleached mudstones overlying sandstone/conglomerate.

Neef (1998) interprets that the Eocene Eyre Formation was deposited through the Koonenberry Belt area and also west of the Bancannia Trough in the Fowlers Gap area. Gibson (in press) has shown that Neef's Eyre Formation in the Fowlers Gap area is in fact Mesozoic, and thus part of the Eromanga Basin. In the absence of age data or detailed distribution for Neef's Eyre Formation, and the presence of sediments continuous with the Eromanga Basin in the northeast and northwest of the area, and dated Mesozoic sediments at the 'Three Hills', it is assumed that all the sediments in the Wonnaminta area are in fact also Mesozoic.

Silcrete has formed in the upper part of the preserved Mesozoic sequence at the Three Hills to form a hard cap. However, silcrete formed in sediment resembling the Jurassic sandstone is also present on low rises around the hills, suggesting that silcrete has also formed in the bottom part of the Mesozoic section. Some authors consider that silcrete in the area formed at a palaeo-landsurface, the 'Cordillo Surface' of Wopfner (1974), interpreted to be present in the area by Neef (1998). Results from this study suggests that silcrete bodies have formed in the Mesozoic sediments at many levels prior to erosion, and that these form resistive layers which now cap erosional landforms. As well as being silicified, some horizons within the Mesozoic sediments are ferruginised.

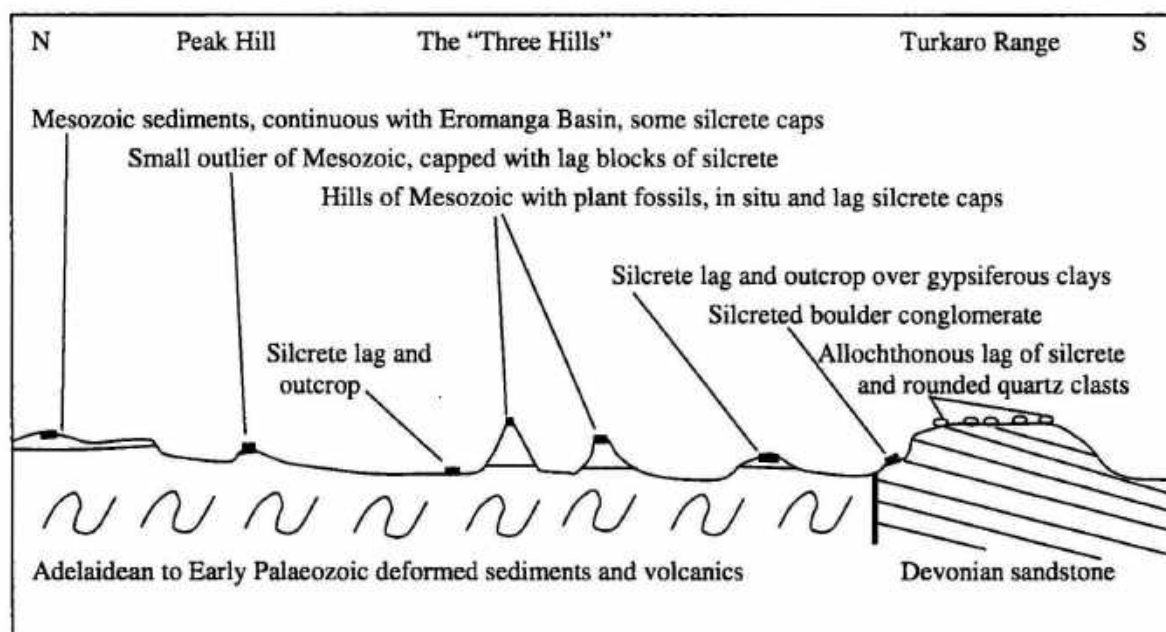


Figure 1. Sketch north-south section across the Wonnaminta sheet, showing relationships of Mesozoic sediments, silcrete, and allochthonous lag on the Turkaro Range.

Many areas underlain by basement rocks within the Wonnaminta area are punctuated by rises with a lag of, or outcrop of silcrete, formed in sediment which is lithologically similar to the Mesozoic sediments. Exposures beneath the silcrete are generally of bleached gypsiferous clays. Similar gypsiferous clays are associated with the silcrete cappings at the 'Three Hills'. This material may be very highly weathered Mesozoic mudstone, but might also have a bedrock origin. If the former is the case, there has been very little erosion below the unconformity over much of the area.

Ferruginous lag is locally abundant. In some areas this is clearly derived from ferruginised basement rocks or from quartz/iron veins, but elsewhere, and in places mixed with basement-derived ferruginous material, there are ferruginous fragments that are derived from ferruginised sediment, i.e. the Mesozoic sequence.

Locally, magnetic 'buckshot' lag is abundant. This is locally present on ridges, and magnetic images show it forms part of the alluvium in major creeks. There is a possibility that the material in these iron pisoliths was originally derived from the Mesozoic sequence. The pisoliths have persisted as lag on some bedrock ridges, where erosion has been slowest, and it has also been transported to creeks. Thus this material may have undergone at least two stages of physical dispersion, first from the Mesozoic sediments to the ridge-top localities, and the second dispersion to the creeks.

There are indications that some of the modern topography consists of Mesozoic relief that has been buried, and since exhumed. The Turkaro Range in the south of the area, consisting of shallow-dipping Devonian sandstone, has extensive low relief summit surfaces which cut across bedding and have a ubiquitous lag of rounded quartz clasts, and fragments of silcrete formed in sediment with rounded quartz clasts. Neither of these materials has been derived from the Devonian rocks, but their nature is consistent with being sourced from Mesozoic

sediments previously covering the range. K. Mills (pers comm, 2000) has located outcrops of sediment consistent with Mesozoic lithologies in one area of the range top. Locally, silcreted sandstone and conglomerate are exposed around the steep margins of the range. Clasts in the conglomerate consist of rounded quartz pebbles and cobbles, and clasts of Devonian sandstone range from 5 cm to 3 m in diameter. Either the silcreted sediment represents Mesozoic sediments which included locally derived talus boulders and allochthonous rounded quartz pebbles, or post Mesozoic talus, derived from the local slopes which included outcrop of Mesozoic sediments. The former model is preferred, with the range first forming a Mesozoic inselberg surrounded by an actively depositing floodplain with mostly allochthonous sediment. The range was progressively buried by alluvial, and then most probably marine deposits: Gibson (in press) has shown that the basal part of the Mesozoic sequence in the Fowlers Gap area to the west is shallow marine. Some of the boulder conglomerates may in fact represent rocky shoreline deposits. Fragments of Devonian sandstone also make up a minor component of the clasts in silcreted Mesozoic sediment several kilometres north of the range. After burial of the range and cessation of Mesozoic sedimentation, the sediment was weathered, and in part silcreted at various depths. Later erosion of the generally poorly cemented sediment, exhumed the pre-existing landscape of resistant rocks, leaving winnowed lags of silcrete fragments and larger quartz clasts exhumed from the sediment.

It is not known whether the Koonenberry Range had a similar history. Mesozoic sediments have been mapped to within about 1 km east of the range, to the east of the Koonenberry Fault. These sediments contain subrounded quartz pebbles, but no clasts of Devonian sandstone, which would be expected if the range existed at the time. It is possible that there has been displacement along the Koonenberry Fault, west side up, since the Mesozoic, as there is an incised zone with a local divide immediately west of the fault; this zone is characterised by skeletal soils and far more rock outcrop than is present elsewhere in the area. This may be an uplifted zone from which the Mesozoic remnants and weathering profiles have been stripped. As the Koonenberry Range sits within a bifurcation of the fault, it is possible that it has been uplifted since the Mesozoic by compression in the fault zone. However, if Mesozoic sediments can be identified actually abutting the range, this would indicate the range was present in the Mesozoic, and that it has since been buried and exhumed. So far, this type of relationship has not been observed.

It is possible that remotely sensed data can help to distinguish surface material types across the area, particularly lag. However, as there are four forms of silica (aeolian sand, basement-derived vein quartz, silcrete derived from the Mesozoic sediments, and reworked quartz pebbles from the Mesozoic), and four types of iron-rich materials (ferruginised basement rocks, ferruginised Mesozoic sediment, quartz/hematite vein fragments, and 'buckshot' gravels), it is probable that sophisticated multispectral techniques such as 'Hymap' may be needed to help distinguish between these lag types.

POSSIBLE SAMPLING MEDIA

1. Lag. Much of the lag is allochthonous, being derived by winnowing from the Mesozoic cover sequence. In particular, magnetic lag may be derived from the cover sequence, and thus have chemistry unrelated to local bedrock mineralisation. The magnetic lag appears to have also undergone several stages of physical dispersion. Non-magnetic ferruginous lag is sourced from both basement and cover sequence. Bedrock-sourced lag, if recognisable, could be used as a sampling medium.
2. Soil. There are two distinct soil types formed on basement rocks, a powdery calcareous gypseous loam in low relief areas over mostly highly weathered rocks, and stony lithosols over fresher, more resistant rocks. Areas characterised by the calcareous gypseous loams have been subdivided on the map depending on degree of local relief, and whether vague bedrock structural trends are visible on airphotos. Any soil sampling data should be grouped into populations based on regolith landform mapping units for statistical analysis. Areas of aeolian sand have been delineated on the map, but it is possible that part of the material in the calcareous gypsiferous loams is aeolian derived, thus diluting any bedrock geochemical signature. Sieving or geochemical normalisation may be needed.
3. Stream sediments. At least some of the alluvial sediments in the area have been reworked from allochthonous aeolian sediment. Thus any upstream mineralisation signatures will be diluted. The degree of dilution may vary, causing variations in observed geochemistry. Sieving or geochemical normalisation may be needed.
4. Regolith carbonate. The chemistry of regolith carbonate and the potential of carbonate in soils as a sampling medium in the area have not been studied. However, it is important to note that calcrete is abundant as a hardpan coating on Devonian rocks around the Turkaro Range. The bedrock here is quartz sandstone which should be virtually free of calcium; hence the calcium present is probably allochthonous, possibly from rainfall or aeolian processes.

5. Silcrete. Silcrete has been suggested as a sampling medium for gold in the Gawler Craton in areas where regolith carbonate is absent (Lintern & Sheard, 1998). However, in the Wonnaminta area, virtually all silcrete has formed in transported sediment, and at this stage it appears unlikely that this could form a reliable sampling medium.
6. Rock chips. The degree of weathering of rock chips should be noted, and results divided into populations depending on degree of weathering, including a population of ferruginised rocks.
7. Drill sampling. Ferruginous zones within saprolite may be local concentrators of metals. The author's experience from the Cobar area shows that pallid saprolite may be devoid of metals even in mineralised areas.
8. Biological sampling. Leanne Hill (CRC LEME PhD student, ANU) is studying the potential of plant matter as a sampling medium at several sites in western NSW, including a site on Kayrunnera Station, immediately east of the area. There is an abstract on this study in this volume.

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REFERENCES

- Brunker, R.L., 1967. Cobham Lake, SH/54-11. 1:250 000 Geological Series, Explanatory Notes. *Geological Survey of New South Wales, Sydney*.
- Chan, R.A., CRAIG, M.A., D'ADDARIO, G.W., GIBSON, D.L., OLLIER, C.D. & TAYLOR, G., 1986. The regolith terrain map of Australia 1:5 000 000. *Bureau of Mineral Resources, Australia, Record 1986/27*.
- Corbett, J.R., Mabbutt, J.A., Milthorpe, P.L., Ngethe, J.C., & Sullivan, M.E., 1972. Land Systems of the Fowlers Gap - Calindary area. Fowlers Gap Arid Zone Research Station, *University of New South Wales, Research Series 4*, 7-40.
- Gibson, D.L., 1999. Explanatory notes for the Broken Hill and Curnamona Province 1:500 000 regolith landform maps. *CRC LEME Open File Report 77*, CRC LEME, Perth.
- Gibson, D.L., in press. Post-Early Cretaceous Landform Evolution along the Western Margin of the Bancannia Trough, Western NSW. *Australian Rangelands Journal*, accepted for publication.
- Lintern, M.J. & Sheard, M.J., 1998. Silcrete – a potential new exploration sample medium. *MESA Journal*, 11, 16-20.
- Neef, G., 1998. Early Cretaceous-Recent landscape evolution of the Copper Mine Range and adjacent areas far west New South Wales. *Journal and Proceedings of the Royal Society of New South Wales*, 131, 77-84.
- Northcote, K.H., 1968. Atlas of Australian Soils; explanatory data for sheet 10, central Australia. CSIRO, Melbourne University Press.
- Walker, P.J., 1991. Land systems of western New South Wales. Soil Conservation Service of New South Wales, *Technical Report 25*.
- Wopfner, H., 1974. Post Eocene history and stratigraphy of northeastern South Australia. *Transactions of the Royal Society of South Australia* 98, 1-12.

TECTONIC EVOLUTION OF THE PALEOPROTEROZOIC WILLYAMA SUPERGROUP, BROKEN HILL: THE EARLY YEARS

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INTRODUCTION

Base-metal mineralisation in the Broken Hill region has been variously interpreted as stratiform or structurally controlled. Based on exhaustive studies of the geology in the mine sequences, many early workers (e. g. Gustafson et al., 1952) concluded that the Line of Lode formed in a high-temperature shear zone (belt of attenuation) through selective replacement of favourable beds by mineralising fluids introduced after the peak of metamorphism and deformation. More recently, the weight of opinion has favoured a syngenetic origin for mineralisation. Proponents of this interpretation (e. g. Laing et al., 1978; Laing, 1996; Willis et al., 1983) have argued that mineralisation occurred contemporaneously with rifting and deposition of the Paleoproterozoic Willyama Supergroup and for this reason is largely stratiform and confined to particular horizons within the sequence (e.g. Hores Gneiss). They acknowledged earlier observations that mineralisation along the Line of Lode is not always stratiform but argued that this was due to redistribution of pre-existing ore by later deformation rather than a primary feature. In order to better assess these competing views and give greater context to any ensuing discussion about the relative merits of a structural versus stratigraphic control on mineralisation, AGSO undertook detailed structural studies in the Willyama Supergroup at key localities around the Broken Hill region with a view to determining the tectonic history of the region as well as providing further constraints on the origin, timing and three-dimensional geometry of the major structural elements. This necessitated a re-evaluation of previously published tectonic models for the Broken Hill region where the Willyama Supergroup has been described as a Paleoproterozoic fold and thrust belt (White et al., 1995) or a stack of D1 nappes/thrusts (e.g. Marjoribanks et al., 1980; Laing, 1996) responsible for widespread overturning of the regional stratigraphy.

EARLY STRUCTURES (D1-D3) IN WILLYAMA SUPERGROUP

Deep seismic imaging along a NW-SE transect orthogonal to regional strike in the Willyama Supergroup shows that the crust in the Broken Hill region is subdivided into different structural domains by SE-dipping shear zones (Gibson et al., 1998), many of which penetrate to considerable crustal depths and truncate shallower-dipping reflectors representing older shear zones or regions of "normal" layered crust. This structural geometry is readily interpreted in terms of a northwest-vergent fold and thrust belt superimposed upon an older orogenic fabric (Gibson, 1998). A similar geometry has been revealed in seismic images of other orogenic belts, including the Grenville front (tectonic zone) where thrust-stacking of micro-terranes was followed by crustal penetrating ductile imbrication under high pressure-high temperature conditions leading to ramping of formerly deeply buried rocks to the near surface (Green et al., 1988). Support for the operation of an analogous two-stage process to explain uplift and the present distribution of high-grade rocks in the Broken Hill block comes from the fact that the bulk of crustal thickening and high-grade metamorphism in the Broken Hill block predates formation of the SE-dipping shear zones. These shear zones are interpreted to be of D3 age and dip much too steeply for any attendant thrust stacking to have produced more than a fraction of the 60-65 km crustal thickening estimated to have occurred in the Broken Hill region based on published barometric calculations (0.5-0.6 GPa) for granulites now exposed at the surface (Phillips, 1980). Crustal thickening and high-grade metamorphism more likely occurred during an earlier episode of recumbent folding and associated thrust stacking although whether these events and the shallow-dipping fabric/layering imaged in the seismic profiles are the result of D1 or D2 deformation has yet to be fully resolved. The D1 and D2 deformations both occurred under amphibolite-granulite facies conditions and both gave rise to sub-horizontal or shallow-dipping fabrics (S1 and S2). However, whereas the D2 fabrics are clearly related to the development of asymmetric, SW- or NE-verging mesoscopic folds, the origin of the S1 fabric is much less certain. It is almost everywhere parallel or sub-parallel to bedding and has been previously interpreted as axial planar to an earlier generation of D1 isoclinal folds or nappes (e.g. Marjoribanks et al., 1980; Hobbs et al., 1984). No D1 folds were recognised in the present study and it remains to be seen whether the few D1 isoclinal structures previously reported are indeed of this age rather than being younger D2 structures. D3 folds, best developed within or immediately adjacent to the major D3 shear zones described above, are upright structures with sub-vertical or steeply dipping axial plane fabrics which have been variably overprinted by younger fabrics of Neoproterozoic and Paleozoic age leading to the development of retrograde schist zones.

TECTONIC EVOLUTION OF THE BROKEN HILL REGION

Peak metamorphism in the Willyama Supergroup produced sillimanite - K feldspar - biotite $\pm$ garnet $\pm$ cordierite mineral assemblages in rocks of pelitic composition. These assemblages overprint the S1 fabric as evidenced by straight inclusion trails of sillimanite and biotite contained in post-D1 garnet and K feldspar porphyroblasts. These same porphyroblasts are wrapped by the D2 fabric indicating peak metamorphic conditions were probably reached some time after the D1 deformation took place and prior to the cessation of D2 deformation. This interpretation is consistent with a structural model of early crustal thickening through the formation of D1 nappes followed by extensional collapse of a thermally weakened orogenic belt undergoing high grade metamorphism and contemporaneous intrusion by granitic magmas. A model of crustal thickening followed by extensional collapse is consistent with published anti-clockwise pressure-temperature-time paths for the Broken Hill region in which andalusite-bearing assemblages are replaced by those containing sillimanite (Hobbs et al., 1984). This interpretation is also compatible with the shallow attitude of the D2 structures and the observation that S2 commonly contains a pronounced stretching lineation defined by sillimanite. This lineation trends SW-NE at a high angle to the regional D2 fold axes and, like the shallow-dipping S2 fabric, is shared by both the paragneisses and deformed granites alike.

Alternatively, the D2 event may be thrust-related in which case there is no need to postulate that overturning of the regional stratigraphy occurred exclusively during an earlier phase of D1 nappe/thrust formation (cf Laing, 1996). Crustal thickening and overturning of the regional stratigraphy could just as easily be attributed to the D2 deformation whose associated folds are demonstrably recumbent or gently reclined in character. If this scenario is indeed correct, then it raises important questions about the origin and character of the earlier D1 structures. One possibility is that the D1 structures are extensional rather than compressional in origin. Conclusive evidence in support of this interpretation is difficult to find but an extensional origin for the D1 structures would go some way towards explaining why D1 folds are so rare and why the S1 fabric is almost everywhere layer parallel. Perhaps more significant in this context are the rapid, and sometimes abrupt, increases in metamorphic grade across some lithostratigraphic boundaries which have also accommodated large amounts of layer-parallel shearing. Displacement on these boundaries appears to have been dominantly normal and involved the emplacement of younger, low grade rocks over older rocks metamorphosed under higher temperature conditions. It is also evident that displacement on these shear zones occurred early in the tectonic evolution of the Willyama Supergroup because both the shear zones and their associated metamorphic rocks have been affected by the D2 deformation. These low-angle detachments most likely originated during the earlier D1 event although it has yet to be determined whether these extensional structures occurred independently of crustal thickening or were superimposed upon a crust already thickened during an earlier stage of the D1 deformation. In either event, the early deformational history of the Willyama supergroup is evidently much more complex than previously believed, incorporating elements of both extension and crustal shortening.

TIMING OF EVENTS AND IMPLICATIONS FOR MINERALISATION

While D1 and D2 were both accompanied by high-grade metamorphism, peak metamorphism is generally regarded to have occurred around 1600 Ma (Page and Laing, 1992). Considering that peak metamorphism also post-dates D1, it follows that D1 cannot be any younger than 1600 Ma and may, in fact, be significantly older. Further, given that some of the earliest recognisable shear zones in the Broken Hill region may be extensional in origin and most likely of late D1 age, it is not inconceivable that the D1 deformation was linked to the same extensional or rift-related processes that gave rise to deposition of the Willyama Supergroup, critical parts of which (Broken Hill and Sundown Groups) range in age from ca 1690-1670 Ma (Page et al., this volume). For this reason a D1 age of 1670-1690 Ma is not unreasonable. In tectonically active rifts it is not uncommon to have magmatism, high-grade metamorphism and deformation all underway at deep crustal levels whilst sedimentation is occurring at higher crustal levels in the same rift system (e.g. Wickham and Oxbrugh, 1975). Magmatic rocks intruded into the Willyama Supergroup include granites and Fe-rich tholeiites now represented by two-pyroxene granulite and amphibolite, almost all of which have yielded 1670-1690 Ma U-Pb zircon ages (Nutman and Ehlers, 1998; Donaghy et al., 1998; Gibson et al., unpubl. data). Less easily determined is whether these zircon ages record the time of (syn-tectonic?) magmatic intrusion or high-grade metamorphism although at least one amphibolite contains 1690 Ma zircon with inclusions of metamorphic hornblende (Gibson et al., unpubl. data).

Weakly foliated and undeformed granites lying within or cutting across the D3 regional fabrics constrain the D3 deformation to be no older than 1600 Ma and no younger than about 1590 Ma old (Page et al., this volume). Ehlers et al (1996) reported a comparable 1590 Ma age for metamorphic zircon extracted from a garnetite forming part of the Mn-halo around the Line of Lode. While this date points to a D3 age for the garnetite, it is about 100 Ma younger than the generally accepted age for deposition of the base-metal host rocks (Broken Hill Group) thereby supporting earlier interpretations for the introduction of mineralising fluids after peak

metamorphism and deformation (e.g. Gustafson et al., 1952). Galena from the Line of Lode, on the other hand, has yielded a Pb model age of 1675 Ma (Sun et al., 1996). Moreover, since there has probably been virtually no radiogenic Pb growth from the time of ore formation, this model age could be seen as evidence supporting a syn-sedimentary or syngenetic origin for the Broken Hill ore-body. However, other interpretations are not precluded, including formation and/or recrystallisation of the ore-body through voluminous fluid flow accompanying high grade metamorphism at 1670-1690 Ma. In any event, there have been at least three periods of high grade metamorphism and deformation in the Willyama Supergroup, each one of which is likely to have been accompanied by significant fluid flow with consequent effects for mineralisation or its subsequent redistribution. D3 emplacement and/or redistribution of ore is evident in vein- and shear-hosted mineralisation in areas far removed from the Line of Lode (e.g. Thackaringa and Allendale Mine areas). These and other occurrences of shear-hosted base-metal mineralisation indicate that a stratiform origin for mineral deposits in the Broken Hill region cannot always be assumed and that mineral exploration in the region should be broadened to include possible structural traps. Some shear zones and related structures in the Broken Hill region have clearly served as former conduits for mineralising fluids and might therefore be host to a major ore-body themselves or at the very least point to a rich source of metals at depth.

REFERENCES

- Donaghy, A. G., Hall, M., Gibson, G. M., and Nutman, A. P., 1998. The age of deposition and first deformation of the Palaeoproterozoic Willyama Supergroup, Broken Hill, Australia. *Geol. Soc. Aust. Abstracts* 49: p. 118.
- Ehlers, K., Foster, J., Nutman, A. P., and Giles, D., 1996. New constraints on Broken Hill geology and mineralisation. *Codes Special Publ. 1*: 73-76.
- Gibson, G. M., 1998. Regional structure in the Willyama Supergroup and its relevance to mineral exploration in the Broken Hill Inlier. *AGSO Record* 1998/25: 39-41.
- Gibson, G. M., Drummond, B., Fomin, T., Owen, A., Maidment, D. W., and Wake-Dyster, K., 1998. Structural and tectonic evolution of the Broken Hill region revisited: implications for mineral exploration in the Willyama Supergroup. *AGSO Record* 1998/2: 75-77.
- Green, A.G. et al., 1988. Crustal structure of the Grenville front and adjacent terranes. *Geology* 16: 788-792.
- Gustafson, J.K., Burrell, H. C., and Garretty, M. D., 1952. Geology of the Broken Hill Ore Deposit, Broken Hill, NSW. *Bur. Min. Res., Geol., & Geophys. Bull.* 20: 86pp.
- Hobbs, B. E., Archibald, N. J., Etheridge, M. A., and Wall, V. J., 1984. Tectonic history of the Broken Hill Block, Australia. In: A. Kroner and R. Greiling (Eds.), *Precambrian Tectonics Illustrated*. E. Schweizerbart'sche, Stuttgart, pp.353-368.
- Laing, W. P., 1996. Nappe interpretation, palaeogeography and metallogenic synthesis of the Broken Hill-Olary Block. *Codes Special Vol. 1*: 21-51.
- Laing, W. P., Marjoribanks, R. W., and Rutland, R. W. R., 1978. Structure of the Broken Hill mine area and its significance for the genesis of the orebodies. *Econ. Geol.*, 73: 1112-1136.
- Marjoribanks, R. W., Rutland, R. W. R., Glen, R. A., and Laing, W. P., 1980. The structure and tectonic evolution of the Broken Hill region, Australia. *Precambrian Res.*, 13: 209-240.
- Nutman, A. P. and Ehlers, K., 1998a. Evidence for multiple Palaeoproterozoic thermal events and magmatism adjacent to the Broken Hill Pb-Zn-Ag orebody, Australia. *Precambrian Res.* 90: 203-238.
- 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. *Econ. Geol.*, 87: 2138-2168.
- Phillips, G. N., 1980. Water activity changes across an amphibolite-granulite facies transition, Broken Hill, Australia. *Contrib. Mineral. Petrol.* 75: 377-386.
- Sun, S-S., Carr, G. R., and Page, W. P., 1996. A continued effort to improve lead-isotope model ages. *AGSO Research Newsletter* 24: 19-20.
- White, S. H., Rothery, E., Lips, A. L. W., and Barclay, T. J. R., 1995. Broken Hill area, Australia, as a Proterozoic fold and thrust belt: implications for the Broken hill base-metal deposit. *Trans. Inst. Mining Metall.*, 104: B1-17.
- Wickham, S. M. and Oxburgh, R.E., 1985: Continental rifts as a setting for regional metamorphism. *Nature* 318: 330-333.
- Willis, I. L., Brown, R. E., Stroud, W. J., Stevens, B. P. J., 1983. The Early Proterozoic Willyama Supergroup: stratigraphic subdivisions and interpretation of high- to low-grade metamorphic rocks in the Broken Hill Block, New South Wales. *Geol. Soc. Aust. J.*, 30: 195-224.

MODERN APPLICATIONS OF CONVENTIONAL GEOCHEMISTRY IN THE OLARY DOMAIN, SOUTH AUSTRALIA

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The Drew Hill Joint Venture area is centred approximately 30 km northeast of the Olary Township within the South Australian portion of the Proterozoic Curnamona Craton. The Drew Hill Joint Venture is between Mount Isa Mines Ltd, Western Metals Resources Ltd (formerly Aberfoyle) and Normandy Mining Ltd. MIM Exploration Pty Ltd (MIMEX) became Manager of the licence in 1996 when it farmed into the Joint Venture.

CONVENTIONAL GEOCHEMISTRY

Utilising expertise from our Joint Venture partner, Normandy Mining Limited, Regolith Landform Mapping was completed over the Drew Hill Joint Venture ground. Mapping was completed at 1:25,000 scale and involved systematic ground truthing of TM, magnetic and to a lesser degree radiometric data. Regolith units were mapped on the basis of landforms and were divided into the three main categories: residual, erosional and depositional. The regolith map is utilised to complete a more rigorous analysis of the soil results.

Alluvial deposits and aeolian sand dominate soil profiles in the eastern two thirds of the Drew Hill tenement holdings. The depth of cover is interpreted to be less than 10m thick. The western third of the tenement area is dominated by erosional terrain. Sieved -80# soil samples (~100g) are collected over erosional areas that are proximal to subcrop and outcrop. Over depositional areas, -1.6mm sieved soils (~2-3kg) are collected and analysed by a *BLEG* method. These geochemical methods have been a useful part of MIMEX's arsenal for generating targets in the Olary area.

HISTORY OF SOILS

Aberfoyle Resources Limited completed a -200# soil survey over the central and northern parts of the tenement holdings in 1989. This survey revealed Au anomalism in the area now known as the White Dam Prospect.

Early on, MIMEX completed a number of orientation surveys within the Drew Hill tenements. These surveys concentrated on mesh size, analytical technique, spacing and cost effectiveness. The conclusion was to use -80# over erosional areas and the larger *BLEG* sample technique over depositional areas. Quality control procedures are incorporated into the sampling programs with both standards and duplicates taken regularly.

DATA ANALYSIS

MIMEX has a large soil database in the Olary area with a minimum of three different soil sampling techniques. The assay data from these different methods are levelled using percentiles of each of the individual techniques. This levelling of the soil results produces an almost seamless data set. The results can be easily overlain on regolith maps and geophysical data.

CONCLUSIONS

Soil sampling in the Olary Domain:

- Conventional geochemistry is a very useful tool for getting explorers into mineralised systems under shallow cover.
- The White Dam deposit and surrounds are examples of discoveries under thin cover by conventional geochemical methods.

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RE-EXPLORING THE CURNAMONA THROUGH DATA PROVISION – ARE MATURE TERRAINS RISKY --- OR RIPE FOR DISCOVERY?

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The Broken Hill Exploration Initiative (BHEI), which was conceived in 1993 with the objective of accelerating exploration in the Curnamona Province, has succeeded in its attempt to rekindle our belief that more orebodies remain to be discovered in the Broken Hill Region.

Provision of a wide range of data and information to assist the Industry has been the major accomplishment of the Initiative to date to date. These data include

- airborne and ground geophysical data
- geological, geochemical, cultural and drill site information in GIS format
- stream sediment data over the Broken Hill and Koonenbery areas
- 30 km of deep seismic
- detailed geological maps and
- new geochronological data.

One measure of the impact of the Initiative is the six-fold increase in annual exploration expenditure in the Province since commencement in 1994. Another measure is the ten-fold increase in area under licence over the same period, which demonstrates how the industry has absorbed these new data and information and transformed them into exploration activity. The only disappointment to date has been that no major discoveries have been made. Nevertheless, data provision from Initiatives like this help the industry improve by adding value to the large existing data sets currently available over one of the most intensively explored areas in the world.

From an exploration perspective, the BHEI is about contributing in a significant way to increasing the probability that drilling a hole will discover an orebody. We are constantly being reminded that exploration is a very risky business and that areas with long exploration histories such as Broken Hill have been completely explored. Many would argue that the probability of not having a discovery is very high and therefore it would follow that the area is high risk. This is a dangerous trap, as many examples of brown-fields discoveries are recorded in mature districts, and when combined with the vast size of the Curnamona Province, at least one additional large, economic deposit should await discovery.

The issue for all of us is where to focus renewed effort to re-explore the district to find this large deposit. Inevitably an important part of this process of identifying new opportunities in mature terrains, is the difficult task of assessing past exploration. To accomplish this task successfully, data needs to be readily and easily available. Upon examination of past exploration data we find we are constantly surprised with the results of past work and we discover we know much less than we thought we did about the geological controls of mineralisation. Indeed, the accuracy of our predictions is extremely low. An assessment process of this kind also reveals that as more information is available, more ideas are generated and more exploration targets are in turn defined. In spite of this untiring ability to generate targets, we do not seem to be much closer in Broken Hill to finding the next orebody compared with our great success in finding minor amounts of mineralisation.

It is instructive to look at a brief history of exploration in the Curnamona to understand what we have learned over time. In the areas of exposure in the southern Olary Block, exploration was motivated by an abundance of old copper workings, gossanous occurrences and strong geochemical anomalism over considerable strike lengths. Numerous Companies, large and small, explored these prospects with minimal success. In contrast work conducted in areas of cover to the north by Uranium explorers in the early 60s and 70s applied different tactics and had a profound impact on the exploration which followed. This work was responsible for generating large amounts of data, which over time was utilised for targeting more traditional Pb/Zn and Cu/Au deposits. Discoveries to date have not become mines.

The Broken Hill Block has been the subject of much more intense exploration, the strategy for which has been changeable and cyclical. Exploration has swung from empirical to conceptual and back over time with the effectiveness in some cases tied to the integrity of the fashionable model.

The empirical approach "in the right address" was all about exploring areas with distinctive rock types, focussing on drilling the line of lode by local mining companies and by the large external companies exploring any ground they could find. This activity dominated the '50s, '60s and early '70s.

Conceptual programs driven by acceptance of synsedimentary/volcanic models flourished in the '70s and '80s. Three independent phases of geological mapping demonstrated good agreement in distribution of rock types and this was interpreted as stratigraphy. These interpretations formed a foundation for synvolcanic thinking during the late 60s, 70s and early 80s with parallels drawn between young volcanic terrains and the upper parts of the Mine Sequence at Broken Hill characterised by presence of felsic gneisses.

The encouragement given by the greatly improved geological framework by the Survey mapping renewed exploration effort in the 1980s and provided a strong catalyst to refine the Line of Lode stratigraphy and this went hand in hand with a major drilling initiative by ZC Limited from 1980 – 1986. An important by-product of that high level of activity was a much improved understanding of the stratigraphy of the Line of Lode and keener appreciation of the sorts of short range variability in lithologies which can be expected at Broken Hill. In particular it demonstrated that we have trifling understanding of 3-dimensional geology and architecture in areas other than the Line of Lode. As exploration moves to greater depths, as it must in future, it is essential to tackle this issue and to promote exploration below the surface skin.

During the 80s detailed magnetics arrived as an extremely valuable exploration tool. Geologists were thinking more about structure and stratigraphy from a basin perspective and attempting to relate mineralisation to facies changes, with the aide of good quality magnetics. A natural extension was to understand sedimentology and timing of mineralisation. Exploration programs started to be driven heavily by conceptual models.

In the 90s we have extensive databases available to us together with rapidly growing user-friendly GIS applications to allow interrogation of multiple layers of data. We are now re-evaluating the data and the more we do it the more ideas we have and the more targets emerge. Pasminco's experience with regional gravity and geochemistry has been quite revealing in its attempts to re-explore the district.

The dilemma we may now face is that we may again be lead to discovering more anomalies with low amounts of metal rather than making significant ore discoveries. Armed, as we are, with data and information from the BHEI are we now well positioned for the next conceptual or predictive wave, which will lead to discovery?

To move forward from here we must accept that we know much less than we think we know – not only in two dimensions on surface but also in the third dimension, at depth. This should not be surprising when we look at the quantum of deep drilling in the district, which reveals that after 117 years we still have not plumbed the depths outside a few small areas.

The real challenge is now to better understand the 3D geometry and architecture of the variations we see in the host packages and to use this in a predictive way for sub-surface testing. In doing so, we must ask ourselves two simple questions. Is another big orebody present in the Province? If the answer is yes then do we have the capabilities to find it?

Government Exploration Initiatives are here to help us improve our capabilities - to be more predictive and to increase the probability that we will find an orebody. To be better positioned to target our exploration, we need to be provided with data and information, which is easy to use and interpret. We need to think more about collaboration and sharing of data in order to avoid duplication and wastage. We need to redirect these resources into drilling highly ranked targets based on well-constrained predictive models, which increase the probability of finding ore in a province, which is ripe for discovery.

BIOGEOCHEMICAL AND GEOCHEMICAL DISPERSION AND RESIDENCE IN LANDSCAPES OF WESTERN NEW SOUTH WALES

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A major continental division in climate, vegetation and regolith types has been identified extending across southern Australia. In Western Australia this has long been referred to as the Menzies Line, although in south-eastern Australia this division has only recently been recognised (Hill *et al.* 1999). Prior to this study there has been little detailed work constraining the characteristics and genetic controls on this environmental division, although the associated environmental differences and their landscape expressions are likely to have widespread implications for variations in biogeochemical and geochemical dispersion pathways. This is of major importance for determining the presence and utilisation of certain geochemical sampling media, such as regolith carbonates.

From preliminary observations, a division in the distribution of regolith types extends across southern Australia. This division is most strongly reflected in differences in regolith carbonate accumulations. Pedogenic regolith carbonate accumulations are widespread across the landscape in semi arid areas immediately to the south of the division, whereas groundwater (or valley) regolith carbonate accumulations are found to the north of the divide. This suggests that the use of pedogenic carbonate accumulations as a mineral exploration sampling media is restricted to the north of this division. In addition, red-brown hardpans are more widespread to the north. Differences in groundwater chemistry have also been recorded. These differences in regolith and groundwater distribution (summarised in Hill *et al.* 1999) have an enormous impact on geochemical dispersion and cycling.

Similarly, the divide also marks a significant difference in vegetation, with mulga communities dominating to the north and mallee to the south. In eastern Australia, a division in the distribution of biological crusts, grass species (C-3 versus C-4 photosynthetic pathways), chenopods and other flora species, reptiles, amphibians, birds, mammals, crustacea and biological soil crusts along the divide has also been observed (Hill *et al.* 1999; Hill in prep.). These factors are all part of the system of chemical cycling and dispersion pathways across the region, however, their significance and the nature of their relationships is unknown.

The controls for the distribution of regolith material, flora and fauna are unknown. Gray & Lintern (1998) suggest that seasonal variations in plant growth and root respiration may be an important control. Rainfall seasonality and chemical differences have also been suggested (Hill *et al.* 1999; Hill in prep.). Keywood (1995) discusses the linkage between precipitation sources and seasonality concluding that winter dominated rainfall chemistry has a high marine influence (eg. high in Ca and Mg), with summer rainfall mainly derived from off the north coast of Australia being more dilute along its southern most extent. Areas receiving Ca- and Mg-rich winter rainfall and also characterised by relatively high evaporation to precipitation ratios will therefore experience a widespread addition of carbonate materials in the pedogenic zone.

Vegetation variations may be partly a response to these changes in soil chemistry, but they are also expected to have a major influence on geochemical dispersion pathways in the regolith. A preliminary study in the Broken Hill region by Hill (1998) showed major chemical differences in mulga and mallee coexisting on aeolian cover over ultramafic rocks. Plant species in the area exhibited an ability to process and differentiate certain chemical elements by accumulation and exclusion, resulting in distinct biogeochemical and geobotanical associations. In addition, all plants contribute and remove elements from the regolith and the characteristics of this differ for different species. For example some plants may draw chemical signatures from broad areas, in many cases from great depths beneath a transported or highly weathered cover. Hence some plants may be effectively used as biogeochemical sampling media, potentially providing an easily accessible and widespread sampling media for mineral exploration programs, and provided the biogeochemical dispersion pathways specific to particular species is understood, could also provide enlarged and high contrast chemical anomaly signatures.

The principal objective of this research is to examine the nature of chemical dispersion pathways in a variety of landscape components (eg. vegetation, regolith and rainfall). Specifically, it aims to account for the location in the landscape where certain elements reside; to investigate attributes of chemical cycles across the rainfall

divide; to be able to assess the applications of findings to the selection of mineral exploration sampling media in different landscapes; and to consider the usefulness of vegetation to detect chemical signatures from beneath regolith cover, in particular transported overburden.

In New South Wales the rainfall division follows an east-west trend, and is approximately located between Broken Hill and Fowlers Gap. A range of study sites across these variable environmental settings have been selected through Central and Western New South Wales including semi-arid to arid environments which provide the best opportunity to examine the close relationship between vegetation and bedrock as many xeromorphic species will have extensive root systems. Sites at West Wyalong and Lake Cargelligo experience predominantly winter rainfall, while precipitation at Tibooburra and Kayrunnera (near White Cliffs) is mainly of summer incidence. Rainfall at Cobar is more evenly spread throughout the year. Research has begun on the sites at Tibooburra and West Wyalong, with the other three sites to follow in 2001.

Some of the components of biogeochemical cycles within landscapes considered at each of the study sites include monthly collections of precipitation for multi-element (ICP-MS) chemical analyses; and vegetation and regolith sampling along transects across local changes in regolith materials and landforms. Materials to be sampled include: transported overburden, soil B-horizons, indurated materials, and underlying parent material (e.g. bedrock interface sampling). In addition, individual plant species offer a range of organs as sampling media including: leaves; twigs; and bark. Each of these may have different geochemical concentrations, thresholds and dispersion pathways. Samples will be collected during summer and winter months over two years to account for temporal variations.

An increased understanding of biogeochemical cycling at these sites will help to constrain chemical dispersion pathways associated with selected environmental chemical sampling media within a wide range of landscapes in southern Australia, and could be of value to geochemical sampling surveys in regional mineral exploration programs in the Broken Hill region.

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REFERENCES

- Hill, L.J. 1998. Geobotanical and Biogeochemical associations at the Thackaringa serpentinites South-Western New South Wales. Honours Thesis, Department of Geography, University of Melbourne (unpubl.).
- Hill, S.M. 2000. The Regolith and Landscape Evolution of the Broken Hill Block, Western New South Wales, Australia. PhD Thesis, Australian National University (in prep.).
- Hill, S.M., McQueen K.G. & Foster, K. 1999. Regolith carbonates in eastern Australia: characteristics and potential as an exploration sampling medium. In: Regolith '98, New approaches to an old continent. Program and abstracts, 191-208.
- Gray, D.J. & Lintern, M.J. 1998. Chemistry of gold in soils from the Yilgarn Craton. In: R.A. Eggleton (ed) *The State of the Regolith. Proceedings of the second Australian conference on landscape evolution and mineral exploration, Brisbane, Queensland, Australia, 1996. Geological Society of Australia. Special Publication number 20*, 209-221.
- Keywood, M.D. 1995. Origins and sources of atmospheric precipitation from Australia: Chlorine-36 and major-element chemistry. PhD Thesis, Australian National University (unpubl.).

MINERALISATION SIGNATURES IN THE REGOLITH OF THE BROKEN HILL REGION

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INTRODUCTION

The Broken Hill landscape is dominated by regolith. An understanding of this material and its landscape setting is therefore important for mineral exploration programs exploring here. Although the Broken Hill geoscience community has a long and distinguished history of geological research and exploration, the development of a regolith geology research framework has been a much more recent achievement. The main objective of this research has been to establish a framework for the greater understanding of the three-dimensional evolution of the landscape to aid the discovery of concealed world-class ore deposits. The following abstract provides a brief overview of some of these achievements specifically with respect to finding and understanding mineralisation signatures in the regolith.

PREVIOUS EXPLORATION PROBLEMS IN REGOLITH DOMINATED TERRAINS: "THROWING GOOD RESOURCES AT POOR EXPLORATION PRACTICES"?

Mineral exploration programs in the region have traditionally considered regolith as a hindrance, concealing bedrock targets. The major exploration focus has therefore been on bedrock dominated terrain, where very few bedrock exposures have escaped attention. The regolith is therefore one of the major exploration frontiers in the region, with the greatest likelihood of future exploration success occurring in regolith dominated terrain. Most previous exploration approaches in the region's regolith dominated terrains have relied heavily on geophysical approaches or else drilling programs where intersections through the regolith are discarded or only given cursory attention. For example, a recent air core drilling program in the Broken Hill region drilled through regolith to depths typically in excess of 50m. The sampling approach was basically to analyse the material at drilling refusal (typically fresh to slightly weathered bedrock), and discard the regolith. The bedrock in the area featured small, low contrast anomalies, whereas a multi-element orientation study of the drill cuttings from the regolith revealed large, high contrast anomalies associated with redox fronts and hydromorphic interfaces. Obviously this company is discarding a valuable sampling media, that can be more easily sampled than the "hit and miss" and expensive approach of only sampling at drilling refusal. The logging and stratigraphic interpretations of regolith materials associated with these drilling programs are also typically of extremely poor quality. The limitations of previous exploration approaches to regolith materials highlights a need for at least some investment in regolith orientation studies rather than continuing to throw good resources at poor exploration practices.

NEW REGOLITH EXPLORATION MODELS: IMPROVING THE SEARCH FOR MINERALISATION

Some important advantages with considering a regolith-based exploration approach to complement existing exploration practices include:

1. sampling convenience from near surface settings;
2. in many cases secondary dispersion haloes are larger than primary haloes and therefore provide larger exploration targets; and,
3. the regolith may host enriched (e.g. supergene enrichment, placer deposits) geochemical signatures, providing greater anomaly to background contrast (high contrast anomalies).

There are three main steps to consider before possible links can be made between regolith sampling programs and mineralisation, including:

- i) the recognition and choice of sampling media;
- ii) distinguishing the features of a geochemical anomaly from background geochemical features; and,
- iii) the ability to trace the origins of a discovered anomaly to possible mineralisation sources.

An orientation study including the mapping and characterisation of regolith materials at the exploration tenement scale will help to develop an exploration approach suitable for particular leases and exploration goals. Some of the aspects of orientation studies from the Broken Hill region are given in the remainder of this abstract.

RECOGNITION AND CHOICE OF SAMPLING MEDIA

There is a great diversity of regolith sampling media to choose from in the Broken Hill region. Many of these have been the focus of presentations at previous BHEI conferences or other publications (e.g. Hill *et al.*, 1997; 1999; McQueen *et al.*, 2000). One of the most important aspects to consider when choosing sampling media is using a material that is widespread across the exploration area. For example, regolith carbonate ('calcrete') sampling programs may be suitable in the immediate vicinity of Broken Hill where they are abundant, however further to the north, such as near Tibooburra, these materials have a more restricted occurrence. Stream sediments, soil B-horizons, biogeochemistry (e.g. vegetation and biological soil crusts), regolith carbonates, and partial leaching techniques appear to have widespread applications in the Broken Hill region. In local areas or for low sampling density surveys across broad regions, gypseous, silicified, and ferruginised regolith may also be used. In some new developments silicified regolith is showing potential as a valuable regolith sampling medium, particularly on sedimentary basin margins (e.g. flanking the Barrier Ranges) where these materials are widespread at the landsurface. Although anomaly thresholds are typically low many sample sites warrant further investigation, such as the "Teilita silcrete anomaly" (Hill, 1998), along with similar anomalies in silicified materials in the Balaclava, Redan (Holzapfel, 1998; West, 1998), Thackaringa and Triple Chance areas. Gypsum accumulations appear to have complex polygenetic origins, and in some cases (e.g. near Balaclava) the trace element geochemistry and sulphur-isotope chemistry reflect origins from the weathering of local sulphides in the local bedrock that have since recrystallised near the landsurface (Shirtliff, 1998). Biogeochemical sampling and analyses also show encouraging results particularly for detecting mafic and ultramafic complexes that are otherwise concealed by transported regolith where the surface materials host very little geochemical indication of the underlying bedrock (Hill, 1998).

Sampling consistency is important, however achieving it is proving to be a major shortcoming in many previous sampling programs conducted without adequate orientation studies and background regolith knowledge. Many exploration companies feel disheartened that regolith carbonate ('calcrete') exploration programs produce "false anomalies" or 'blind deposits' where known mineralisation occurs. Sampling a consistent facies (e.g. based on morphology or geochemistry) is important to achieve for regolith carbonate sampling programs in the Broken Hill region. The trace metal characteristics of these materials show considerable three dimensional variation associated with major element geochemistry (e.g. Ca:Mg), morphology, and landscape setting. An orientation study in the Copper Blow – Galena Hill area shows that the geochemistry of regolith carbonate accumulations can delineate areas of known mineralisation providing samples of comparable morphology and Ca:Mg are used (Foster, 1998; Hill & Foster, 1998; McQueen *et al.*, 2000). A sampling program targeting nodular morphological facies and high Ca:Mg carbonates provided the highest contrast Au anomalies (many areas featuring >30ppb Au). A sampling program that did not discriminate between morphological and geochemical facies produced irregular and low contrast anomaly patterns appearing as 'false anomalies' or 'blind deposits'. This orientation study established that Au and a selected suite of major and trace elements enabled regolith carbonates to be used as a valuable exploration medium in the search for polymetallic mineralisation (McQueen *et al.*, 2000). Similarly there are at least three major facies of ferruginous regolith ('ferricretes' and 'lateritic materials') each with different geochemical anomaly thresholds and dispersion pathways (Hill *et al.*, 1997).

DISTINGUISHING SIGNIFICANT GEOCHEMICAL ANOMALIES

Once a particular regolith type is sampled and analysed, the challenge remains to identify significant geochemical anomalies. Many of the geochemical signatures in the regolith feature low anomaly thresholds and are very dependent upon environmental setting (such as the abundance of specific secondary minerals to serve as geochemical hosts). Chemical variations within regolith carbonate accumulations demonstrate this. Examples of anomaly thresholds and anomaly styles for regolith materials from the Copper Blow – Galena Hill orientation study suggest (Foster, 1998; McQueen *et al.*, 2000):

- Transported cover: moderate contrast anomalies / 3ppb Au anomaly threshold
- Nodular Carbonate: strong anomaly contrast anomalies / 5ppb Au anomaly threshold
- Hardpan Carbonate: moderate contrast anomalies / 7ppb Au anomaly threshold
- High Ca media: poor to no contrast anomalies / possible 5ppb Au anomaly threshold
- High Ca:Mg carbonates: strongest anomaly contrast / 6ppb Au anomaly threshold

Some data sets have been corrected for sampling inconsistency using multi-element geochemical criteria. Variations in trace metal contents associated with carbonate Ca:Mg, provides a potential basis for adjusting trace element analyses for mixtures of dolomite- and calcite-rich materials. The exciting outcome for this is that it can be achieved by the inexpensive inclusion of Ca and Mg within analytical suites. Similarly silicified (silcrete) and ferruginised (ferricrete) regolith analyses may be adjusted using a range of elements including Fe and Ti, reflecting possible trace element repositories.

LINKING ANOMALIES WITH MINERALISATION SOURCES: DISPERSION MODELS

Once a geochemical anomaly has been recognised from a data set it now needs to be traced to a source. This requires an appreciation of geochemical dispersion pathways in the regolith. Regolith dispersion pathways reflect the nature of landscape processes and the region's landscape features that control where and how these particular processes operate. Initial appraisals typically involve distinguishing between *in situ* and transported regolith hosts, however in many cases the situation is more complex, such as laterally dispersed groundwater overprints hosted by *in situ* regolith. More complicated dispersion models may examine the influences of specific environmental controls such as climate change, eustasy, landscape evolution and tectonism (e.g. Hill & Kohn, 1999). In many cases an understanding of dispersion pathways can be derived from regolith-landform maps. For example silicified regolith ('silcretes') in the Broken Hill region is mostly restricted to palaeovalley systems and associated sedimentary fill. The mapped distribution of many of these silicified palaeovalley systems helps to reconstruct the palaeodrainage networks and associated palaeodispersion pathways. A component of the chemistry of these silicified palaeovalley sediments can then be utilised in a similar way to modern stream sediment sampling programs. This approach has been used in sampling programs in the Warratta area east of Broken Hill, and along the NSW and SA borders on the western halves of the Triple Chance and Thackaringa 1:25,000 sheets (Willis, 1999; Jones, 1999). Surficial dispersion by colluvial, alluvial and aeolian processes are emphasised on the 1:25,000 regolith-landform maps in production by CRC LEME. At more detailed scales more complex local dispersion pathways are able to be shown, although for a general overview at the scale of most exploration tenements a 1:25,000 to 1:10,000 scale map provides a valuable framework for constraining most local dispersion pathways.

ORIENTATION STUDY EXAMPLE: GREAT GOULBURN

A detailed study of the geochemical residence and 3-D dispersion pathways in regolith materials in the vicinity of the Great Goulburn mineralisation provides an example of an orientation study designed to develop an understanding of the links between regolith geochemistry and mineralisation in this area (Jones, 1999). Great Goulburn is 6 km SSE of Cockburn, approximately 50km SW of Broken Hill, and is on the western half of the Triple Chance 1:25,000 geological map (Stroud, 1989). Known mineralisation here consists of cobaltiferous pyrite / quartz-magnetite-iron / copper sulphide associations. Two diamond drill holes revealed:

OT1	(40.9-64.0m)	1381ppm Co, 581ppm Cu, 0.393g/t Au
OT2	(31.6-41.4m)	1445ppm Co, 694ppm Cu, 0.307g/t Au
	(47.4-50.4m)	1530ppm Co, 247ppm Cu, 0.359g/t Au

Mineralisation is centred on two hills with weathered bedrock and gossan occurrences on the hill crest. Sheetflow deposits flank these hills with alluvial and aeolian accumulations on adjacent plains. Regolith carbonates analysed as part of a regional sampling program featured Au contents up to 320ppb adjacent to known mineralisation ranging to contents below detection limit (<1ppb) within 200m. A detailed regolith-landform map (1:10,000) was constructed over the immediate vicinity of the known mineralisation, as well as a map of the surrounding Triple Chance West area at 1:25,000. A derivative surface dispersion map was also constructed from the 1:10,000 regolith-landform map. Sixty-seven sample sites at 50m spacing were located within a grid consisting of four traverses over the known mineralisation at the northern-most hill. Sampling media were analysed for 50 elements and included:

- vegetation (Maireana pyramidata and Maireana sedifolia);
- soil (B-horizon sieved to -80 mesh for traditional analysis);
- soil for partial leaching analysis (Deepleach 11 and Deepleach 35 for the 180um and 250um size fractions);
- regolith carbonate accumulations (noting morphology); and,
- rock chips (from bedrock / regolith interface).

The results showed that all of the sampling media had some potential to reflect the known mineralisation and its extensions beneath regolith, although the way in which this was achieved varied. Vegetation showed irregular anomaly patterns reflecting lateral dispersion pathways, however Pb and Co approached a "bulls-eye" anomaly pattern over the mineralisation. The traditional sampling survey gave results that closely reflected the occurrence of mineralisation, particularly for Au, Cu and Co. Some elements such as As, Zn and Pb showed a marked lateral dispersion and concentration in adjacent valley systems, highlighting the value of a detailed regolith-landform map in showing dispersion pathways. The traditional soil results were comparable with the partial leaching results, highlighting the value of taking consistent materials in soil sampling surveys. The advantage of the partial leaching techniques appears to be that they provide a more consistent sample type than a poorly conducted traditional soil sampling program that does not consistently target a specific part of the profile. Regolith carbonates provided the strongest and highest contrast anomaly pattern over mineralisation, particularly

using Au assay results but also some base metals. A limitation with this approach however was that these materials were absent from the axis of the adjacent valley systems and could not be sampled across the entire study area.

CONCLUSIONS

An improved understanding of landscapes and associated regolith materials can provide a basis to establishing links between geochemical signatures in the regolith and mineralisation. An expected result is that with improved exploration approaches, regolith dominated terrains in the Broken Hill region will become more viable areas for mineral exploration. Exploration approaches in regolith dominated terrains can benefit greatly from initial investments in orientation studies which will greatly improve the ability and efficiency to choose suitable sampling media, recognise geochemical anomalies and link these to mineralisation using dispersion models. CRC LEME has established a program of such orientation studies that are closely associated with its detailed regolith mapping and student research programs.

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REFERENCES

- Foster, K.A., 1998. Regolith geology and geochemistry of Balaclava East, Broken Hill, NSW. *University of Canberra, B.App.Sci(Hons) thesis, University of Canberra* (unpublished).
- Hill, L.J., 1998. Geobotanical and biogeochemical associations at the Thackaringa serpentinites, south-western NSW. *University of Melbourne, Honours Thesis* (unpublished).
- Hill, S.M., Eggleton, R.A., & Graham Taylor, 1997. A regional regolith-landform framework for mineral exploration models in the Broken Hill region. *AusIMM Journal 1997 Annual Conference Proceedings*, 131-138.
- Hill, S.M. & Kohn, B.P., 1999. Morphotectonic evolution of the Mundi Mundi Range Front, Broken Hill Region, western NSW. In: G.Taylor & C.F.Pain (eds) *New Approaches to an Old Continent, Proceedings of Regolith '98*, CRC LEME, Perth, pp.319-334.
- Hill, S.M., McQueen, K.G., Foster, K.A., 1999. Regolith carbonate accumulations in Western and Central NSW: Characteristics and potential as an exploration sampling medium. In Taylor, G.M., Pain, C.F. (Editors.), *State of the Regolith, Proceedings of Regolith 98*, pp. 191-208.
- Holzapfel, M., 1998. Regolith-landscape evolution and silcrete investigation: Redan East, Broken Hill Block, New South Wales. *Australian National University, Honours Thesis* (unpublished).
- Jones, G.L. 1999. Regolith Geology and Geochemistry of Triple Chance West, Broken Hill, NSW. *B.App.Sci(Hons) thesis, University of Canberra* (unpublished).
- McQueen, K.G., Hill, S.M., & Foster, K.A., 2000. The nature and distribution of regolith carbonate accumulations in southeastern Australia and their potential as a sampling medium in geochemical exploration. *Journal of Geochemical Exploration*, 67, 67-82.
- Shirtliff, G., 1998. Ferricretes and the landscape evolution of the Western Balaclava Area, South Broken Hill. *Australian National University, Honours Thesis* (unpublished).
- Stroud, W.J., 1989. Triple Chance 1:25,000 Geological Sheet, 7133-1V-S. New South Wales Geological Survey, Sydney.
- West, D.S., 1998. Regolith geology and landscape evolution of Redan West, Broken Hill, NSW. *University of Canberra, B.App.Sci(Hons) thesis, University of Canberra* (unpublished).
- Willis, S.M., 1999. Regolith geology and landscapes of the Thackaringa-west area, Broken Hill, NSW. *B.App.Sci(Hons) thesis, University of Canberra* (unpublished).

DETAILED REGOLITH-LANDFORM STUDIES IN THE BROKEN HILL BLOCK – MURRAY BASIN MARGINS

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INTRODUCTION

The detailed mapping and study of regolith in the Broken Hill landscape is an ongoing research program by CRC LEME. The emphasis at this stage of the detailed mapping program is to produce a series of 1:25,000 sheets from the margins of the Broken Hill Block – Murray Basin and characterise the regolith in these areas. Regolith dominates these highly prospective terrains particularly towards the Murray Basin in the south, and in the past this has been a major impediment to mineral exploration programs in these areas.

CRC LEME Honours students have been closely integrated into this research program. In 2000 four honours students are conducting research projects in the following areas to the southeast and southwest of Broken Hill:

Kinalung West (Jaclyn Brachmanis);
Pinnacles West (Anthony Senior); and,
Quondong West (Ben Maly);
Triple Chance East (Simon Debenham).

These research projects are structured in a similar way to the CRC LEME's Honours projects from previous years, where the thesis research is subdivided into two parts:

PART A: the characterisation and mapping of regolith-landforms for one half of a standard 1:25,000 sheet area; and,

PART B: the specialist study of an aspect of regolith geology related to their mapping study site.

The objective here is for the students to develop learning outcomes related to regional geology utilising a broad range of approaches and techniques (Part A), as well as experiencing the challenges of a specific research problem in an area of specialist study (Part B). Both aspects of these projects make significant contributions to the research output of CRC LEME in the region. The mapping produced within Part A leads to publication within the 1:25,000 map series, and the specialist studies within Part B contribute to a greater understanding of particular aspects of regolith geology in the region. Previous specialisations within Part B have included studies of: particular sampling media (e.g. regolith carbonates, ferricretes, gypsum, silcrettes, partial leaching techniques), developing geochemical dispersion models, and testing and developing various remote sensing platforms and GIS approaches. The remainder of this abstract outlines some of the research projects being conducted by CRC LEME honours students for 2000.

KINALUNG WEST

Kinalung West is approximately 35km SE of Broken Hill on the margins of the Broken Hill Block and the Murray Basin. The area is being mapped at 1:25,000 and consists of regolith dominated terrain with widely dispersed outcrop of slightly weathered bedrock. The area has a subdued topography and exhibits a diverse range of regolith-landform features, the most prominent being extensive colluvial sheet wash plains to the south, and numerous erosional rises capped by silicified quartzose sediments. These rises of silicified regolith appear to be aligned in a N-S orientation representing palaeodrainage remnants. Weathering and erosion of the landscape has contributed to the topographic inversion of these palaeovalley sediments.

The specific aims of this project are to map and characterise regolith-landform features at 1:25,000, and consider the significance of these features within regional regolith-landform and mineral exploration models. More specifically the reconstruction of the palaeodrainage systems at Kinalung West, will provide a framework for analysing the geochemical dispersion pathways within this partly indurated palaeovalley system. The proximity of areas of known mineralisation at Quartz Reef and The Tors makes this an ideal test study for exploring links between silcrete geochemistry, geochemical dispersion models and mineralisation. This will involve sampling of all of the silcrettes within the mapping area, and presenting multi-element geochemical analyses on a geochemical map. This map will help determine relationships between major elements such as Ti (present in anatase) and any trace metals that may reside within the silcrete. It will also provide us with knowledge of chemical characteristics in relation to variations in silcrete morphological facies. The widespread occurrence of silcrettes in Australia makes these potential developments in the understanding of the applications of these materials to geochemical sampling programs extremely valuable.

TRIPLE CHANCE EAST

Detailed regolith-landform mapping at 1:25 000 is being undertaken over an area, approximately 30 km southwest of Broken Hill. The NW part of this area features bedrock dominated terrain bounded to the west by the Mundi Mundi range front and to the south by the Hillston Fault. The southern parts comprise a more topographically subdued regolith-dominated terrain. Regolith exposed at the surface is characteristically transported material consisting of alluvial fans and colluvial sheetwash plains extending SE from the Hillston Fault. Alluvial channel systems and aeolian materials are widespread throughout the area. Indurated regolith includes widespread regolith carbonate accumulations with minor silicified and ferruginised regolith locally capping erosional rises.

Triple Chance East hosts a number of mineralized areas, namely Angus-Kintore (Pb-Zn-Ag) and the Sentinel (Pb-Zn). Mineral exploration interest in the past has targeted areas of exposed bedrock, however there is an increasing awareness and concern directed towards regolith-dominated areas. An orientation study constraining geochemical dispersion pathways within the regolith and suitable sampling media should improve exploration programs throughout these regolith-dominated terrain.

The aims of this project are to produce a detailed (1:25,000) regolith-landform map and characterise the regolith materials of this area. Furthermore the 3-dimensional, multi-element geochemical mapping of a first order catchment area will constrain geochemical dispersion pathways within these landscape settings which are applicable to a large part of this area. This will target soil, stream sediment, regolith carbonate accumulations and biogeochemical sampling media within this catchment area.

QUONDONG WEST

Quondong West is approximately 40km southeast of Broken Hill. It is an area dominated by a thick regolith cover, with bedrock exposure comprising <5% of the area. The major regolith-landform features of Quondong West include alluvial plains and floodout fans associated with Stephens Creek to the east and Redan Creek to the south. Low-relief colluvial rises and sheetwash plains, with both silcrete and ferricrete capping the rises dominate the northwest portion of the area. The distinction between the colluvial and alluvial regolith in the area approximates the NE-SW trend of the Redan Fault. A mineral exploration challenge in the Quondong West area is to understand the geochemical dispersion pathways in the regolith dominated areas, in particular understanding the processes involved with geochemical dispersion and sedimentation along the margins of the Broken Hill Block and the Murray Basin.

The aims of the project are to:

- produce a 1:25,000 regolith landform map of Quondong West;
- characterise and describe various regolith materials and landform features of Quondong West;
- synthesise regolith-landform data from the area to produce a landscape evolution model for The Quondong West study area;
- consider the regional significance of the relationship between the margin of the Murray Basin and the Broken Hill Block to enhance regional landscape evolution and mineral exploration models;
- review and further examine the stratigraphy of the Murray Basin-Broken Hill Block margins derived drilling samples, water bore and mineral exploration logs; and,
- understand the relationship between the unconformities and surrounding sediments of the Murray Basin stratigraphy through the description and characterisation of these surfaces and in particular their weathering features.

In regolith dominated areas such as Quondong West the effectiveness of traditional methods of bedrock dominated mineral exploration is reduced. This has led to the need for mineral exploration to use various regolith sampling techniques, along with the investigation of sediment and geochemical dispersion along sedimentary basin margins where bedrock exposures are rare. The study of the regolith at Quondong West will enable a better understanding of the relationship between marginal areas of continental basins and hinterland areas, including the processes that effect sedimentation and geochemical dispersion in areas of minimal outcrop, thick regolith and continental basin sediments. The search for mineralisation associated with bedrock underlying the northern margins of the Murray basin is a major exploration frontier for the Broken Hill region. Potential also exists to discover placer deposits within the Murray Basin sediments, such as heavy mineral accumulations associated with Neogene strandline deposits.

PINNACLES WEST

The Pinnacles West area is approximately 16km south of Broken Hill, and comprises the western half of the Pinnacles 1:25,000 map sheet. Mineral exploration has been extensive throughout the area which includes two operational mines (the Pinnacles Pb-Zn-Ag mine located near the Middle Pinnacle and a garnet mine operating at Staurolite Ridge which produces industrial grade garnets).

Exploration in the region has mostly concentrated on the study of bedrock exposures or drilling to fresh bedrock material. Most of the bedrock exposures in the region have been explored and now companies are turning their attention towards the regolith-dominated terrain. Unfortunately geochemical exploration techniques used in bedrock dominated terrains have limited applications in regolith-dominated terrains. Encouragingly, preliminary assays of nodular regolith carbonates from near the Middle Pinnacle reveal locally anomalous Au contents (up to 18ppb Au). This project will increase the understanding geochemical exploration techniques in regolith dominated terrain, as well as identifying how particular regolith sampling media can be used and how subsequent analytical result should be interpreted.

The aims of this project are to:

- 1) study the regolith and landscape evolution of Pinnacles West, including:
 - producing a detailed 1:25000 scale regolith landform map;
 - characterising regolith materials and their landscape settings; and,
 - producing a model of landscape evolution for the Pinnacles West region.
- 2) To study geochemical dispersion and residence in regolith materials from a small catchment in the Staurolite Ridge – North Tank area (within the Pinnacles West sheet), including:
 - understanding how major and trace elements interact with different regolith materials and landscape settings, thereby identifying suitable sampling methods and media;
 - constraining geochemical dispersion pathways; and,
 - developing mineral exploration models for this regolith-dominated terrain emphasising links between the 3-dimensional expression of regolith geochemistry in the landscape with possible mineralisation sources.

ACKNOWLEDGEMENTS

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	KANTAPPA CREEK	CORONA	
	CAMPBELLS CREEK	EURIOWIE	
	BREWERY WELL	GAIRDNERS TANK	MAWARRA
MUNDI MUNDI CREEK	PURNAMOOTA	YANCO GLEN	YALCOWINNA
UMBERUMBERKA	LAKES CREEK	STEPHENS CREEK	GLEN IDOL
SILVERTON	BROKEN HILL	MOUNT GIPPS	WAHRATTA
THACKARINGA	PINNACLES	ROCKWELL	KINALUNG
TRIPLE CHANCE	BALACLAVA	REDAN	QUONDONG
OAKDALE	ASCOT VALE	KANBARA	
BURTA			

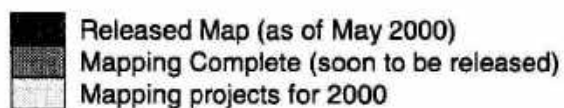


Figure 1: 1:25,000 sheets and areas that CRC LEME has been involved with mapping as of May 2000.

GEODYNAMIC MODELLING OF THE BROKEN HILL MINERALISING SYSTEM

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The origin of the Broken Hill ore body is the topic of considerable controversy and there are at least seven ore genesis models in vogue (Parr and Plimer, 1993). Unfortunately none of the data are definitive with respect to one model or another and progress in the area is hindered by protagonists adhering to their pet model by inventing processes that enable a problematic data set to fit their particular bias. We attempt here to overcome some of these difficulties by adopting a very simplistic approach and assume that each data set is to be interpreted at face value with no attempt to distort the data so that it 'fits' some predetermined philosophy. Our aim is to explore in a quantitative manner the various scenarios and indicate the implications of each scenario for defining exploration criteria for the discovery of a new Broken Hill type deposit.

The data sets to be taken at face value are:

- (i) The carbon isotopic data which are ambiguous and can be taken to indicate either a source of carbon from organic sources and/or from deep crustal/mantle sources.
- (ii) The sulphur isotopic data which indicate a plutonic/hydrothermal source for the sulphur.
- (iii) The lead isotopic data which indicate a crustal source for the lead but perhaps with some mixing with lead from a mantle source.
- (iv) The lead model age which indicates an age for the mineralisation (1675 Ma), 15 million years *younger* than the SHRIMP U-Pb ages for the host sediments (1690 Ma). However the errors are such that an origin synchronous with sedimentation is still compatible with the data.

In the form of model constraints, we also assume that Broken Hill Type mineralisation is a true 'type', namely, Pb/Zn mineralisation that occurs in what are now amphibolite to granulite grades of metamorphism. This observation leads us to two alternatives; the first, a high temperature scenario, implies that the mineralisation is spatially and temporally associated with high grade metamorphism. The second alternative is a low temperature scenario, and implies that the site of mineralisation is associated with diagenesis or low grade metamorphism but is such that late in the geotectonic history that site is predestined to undergo high grade metamorphism.

The only experimental data available on Pb/Zn solubilities involves aqueous, oxidised fluids. These data indicate that it is unlikely that circulating fluids would be saturated in both Pb and Zn at temperatures above approximately 300°C. Accordingly, any mineralizing scenario based on existing experimental data implies that the temperature of the mineralising environment cannot exceed ca. 300°C. However, as we indicated in Hobbs et al. (1998), there is a distinct lack of experimental data involving the solubilities of lead and zinc in non-aqueous fluids. There remains the possibility for the high temperature scenario that the lead and zinc was introduced in a non-aqueous, reduced CO₂/CH₄ fluid derived from the mantle or lower crust.

Accordingly, in this paper, we first explore a high temperature scenario in which the lead and zinc is introduced at the peak of granulite facies metamorphism via a non-aqueous reduced fluid with a deep crustal or mantle origin. We also explore models involving mineralising environments that are post depositional but early in the development of a thrust terrain with the thrusts ultimately over-riding the mineralisation and high grade metamorphism ensuing due to thickening of the crust; perhaps these thrusts are inverted normal faults inherited from an earlier period of extension. We explore two low temperature scenarios in detail: (i) supply of H₂S and CO₂ from a deep crustal source along an early normal fault as it is undergoing inversion to a thrust, and mixing of this fluid with metal and SO₄²⁻ bearing crustal fluids; fluid flow is driven solely by topographic loading arising from early thrusting; and (ii) the same source of fluids as in scenario (i) except now an extra driving force involves fluid convection in a lithostatically pressurised fluid system.

All of these scenarios are capable of producing Broken Hill type orebodies within 1-10 million years although the lack of experimental data for a high temperature, reduced fluid source precludes precise time constraints. We develop exploration criteria for all scenarios involving geographical siting with respect to the thrust systems, alteration patterns in the host rocks, metal depletion halos and host rock permeabilities.

REFERENCES

- Hobbs, B.E., Walshe, J.L., Ord, A., Zhang, Y. and Carr, G.R. 1998. The Broken Hill Ore Body: a high temperature, high pressure scenario. In: Finlayson, D.M., Jones, L.E.A. (Eds.), Proc. Symposium on Mineral Systems and the Crust-Upper Mantle of Southeast Australia, Canberra, Australia, *AGSO Record 1998/2*, pp. 98-103.
- Parr, J.M. and Plimer, I.R. 1993. Models for Broken Hill-type lead-zinc-silver deposits. In Kirkham, R.V., Sinclair, W.E., Thorpe, R.I. and Duke, J.M. (Eds.): *Mineral Deposit Modelling. Geological Association of Canada Special Paper 40*, 253-288.

DETAILED LITHOSTRUCTURAL MAPPING OF BROKEN HILL TYPE MINERALIZATION IN THE BROKEN HILL BLOCK, NSW.

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Lithostructural mapping has been completed over four complex areas containing Broken Hill Type (BHT) lodes within the Willyama Supergroup. Areas include Allendale North and Kinchega-Rockwell mines in the Broken Hill district plus Potosi and Kintore open cut mines on the Broken Hill Line of Lode. Very detailed mapping was controlled by grids and surveyed bench traverses at scales of 1 : 500 and 1 : 250 complimented by insets. The aim of this project was to determine on a comparative basis, the stratigraphic and structural controls on BHT Pb Ag Zn mineralization in a range of geological settings. The mineralized lode exposures all occur in the Broken Hill Group defined by Stevens et. al (1983 a, b) and occupy stratigraphic positions from Parnell Formation through Freyers Metasediments to Hores Gneiss. Simplified examples of the detailed mapping are shown in Figures 1 and 2.

Mineralization is hosted by a wide range of lode rocks. Some of these are obviously stratiform in origin; they include well layered to finely laminated spessartine garnet quartzite and garnet 'sandstone' which are mapped as grading both laterally and vertically into finely laminated manganiferous oxide-silicate facies equivalent banded iron formation (BIF). Conformable syngenetic lode types also include quartz gahnite, blue quartz $\pm$ garnet, granular blue quartz $\pm$ garnet $\pm$ gahnite and saccharoidal-cherty quartz lodes. Other lode types are at least locally discordant being vein like to obviously veined and are remobilized stratiform types to metamorphic / metasomatic in origin. These epigenetic varieties include some types of quartz gahnite, $\pm$ sericite ('K-alteration'), blue quartz $\pm$ garnet $\pm$ gahnite, clear to white coarse granular quartz $\pm$ garnet $\pm$ gahnite, grey quartz and white quartz veins plus lead contaminated grey to green K-feldspar rich metamorphic lode pegmatites'.

The syngenetic and epigenetic lode rocks are hosted by a wide variety of lithologies the majority of which are metasedimentary in origin. They include compositionally quite variable interlayered but mainly well layered to laminated sequences of psammitic, psammopelitic and locally pelitic metasediments. Less commonly quartz-feldspar-biotite-garnet ('Potosi' gneiss) also constitutes a host rock, particularly in Parnell Formation where it is also observed to grade into 'altered' amphibolite.

Within the mineralized lode rich sequences metasediments are often manganiferous, preferentially containing relatively anomalous fine to very fine grained ($\leq 1\text{mm}$) garnets. With increasing abundance these garnets grade to fine grained garnet rich (So=bedding) parallel laminations, then to fine grained garnet bands and ultimately to garnet quartzite lode rocks. These garnet rich host rocks are volumetrically anomalous surrounding many zones of mineralization. Such characteristic garnet rich metasediments appear to reflect a primary syngenetic stratigraphically controlled deposition of (Fe + Mn + Mg) operative in conjunction with stratiform deposition of sulphide mineralization. The process constitutes an integral part of the deposition of the metasediments and lode rocks hosting stratiform sulphides. In particular, the process of deposition appears to have favoured or is more common in generally psammitic grading to psammopelitic metasediments but is also observed within the interlayered pelites. It is therefore not strictly compositionally controlled and is unlikely to be a process of post sedimentation 'alteration' or later 'metasomatism' because it is not seen to replace any particular mineral or lithotype. It is postulated that some type of colloidal depositional process may have been operative in conjunction with the chemical sedimentation of sulphides in the basin of deposition.

Apart from obviously stratiform garnet enriched sequences, other texturally and compositionally unusual types of metasediment occur intimately associated with some mineralization and are also gradational to various lode rocks. These include siliceous fine grained biotite-rich (Si $\pm$ K + Fe + Mg altered?) garnet bearing psammites, blue quartz and/or f.g. quartz rich siliceous (silicified?) psammites, plus locally sericite enriched ('K-altered') strongly lodey metasediments or 'lodey gneiss' with abundant blue quartz, garnet and K-feldspar. It is suspected that these 'altered' rocks either reflect very early synsedimentary pre-lithification diagenetic and/or inhalative alteration processes plus later progressive metamorphically generated 'metasomatic' Si + Mg + Fe + K alteration during the M1 to M3 metamorphic events.

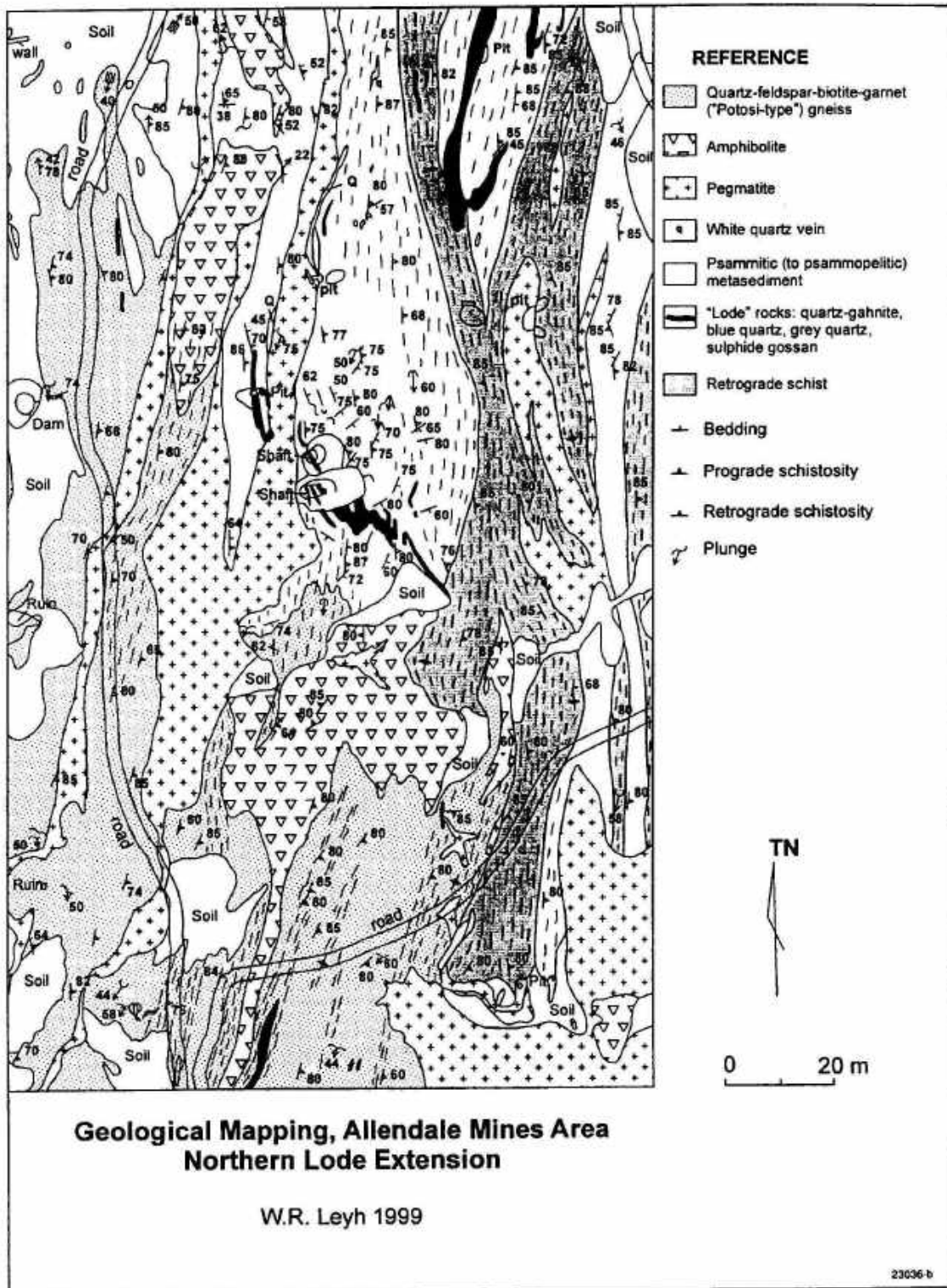
Structurally most of the lode types plus mineralization appear to have undergone both the high grade D1-D3 (M1-M3) tectonic-metamorphic events plus protracted retrograde shear deformations. All areas mapped exhibit evidence of extreme structural modification and sulphide remobilization mainly including dislocative high grade

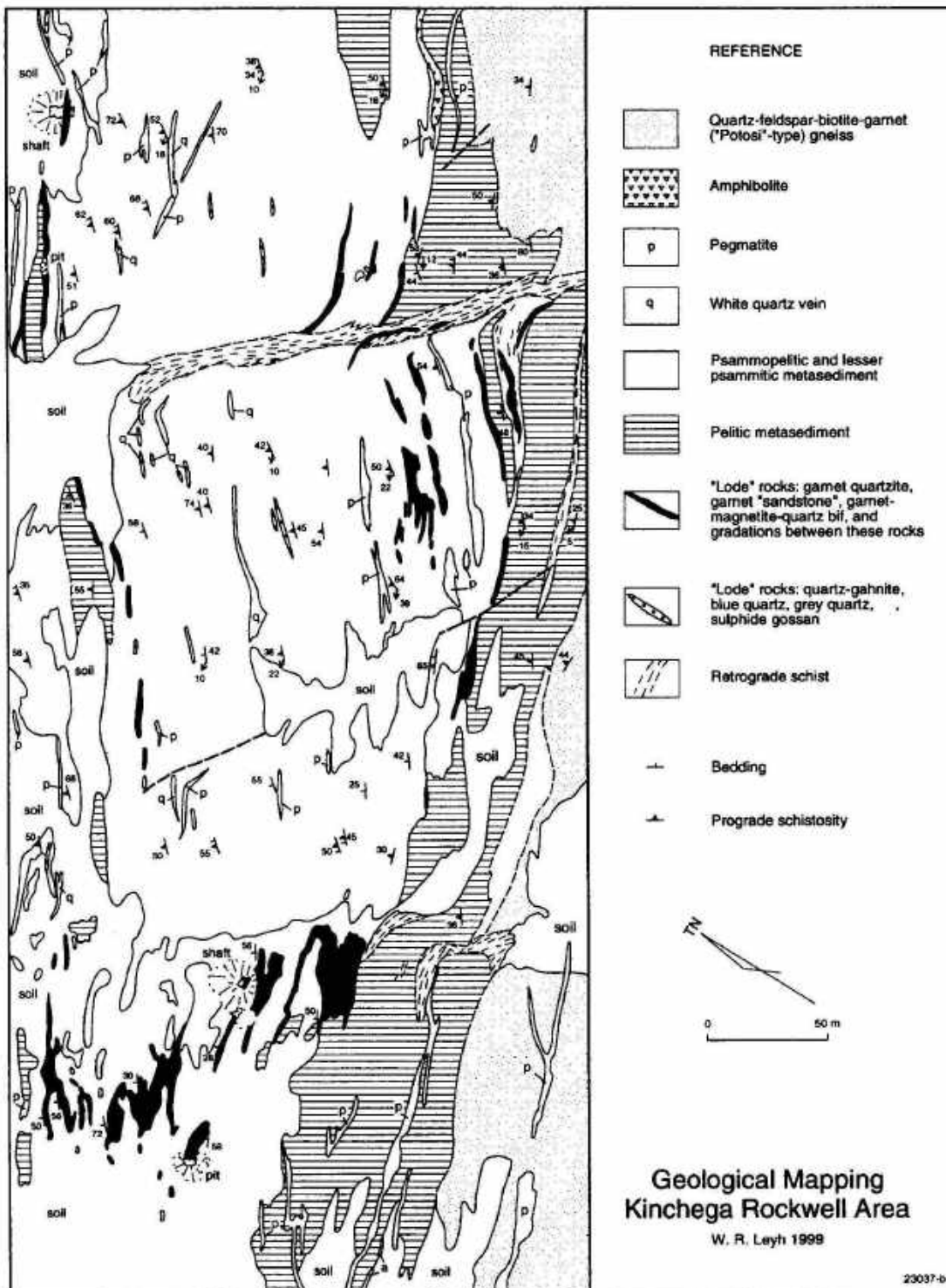
shearing plus partial transposition into probable high grade D2 shears. This was followed by further complex structural modification during the F3 fold event with additional dislocation, mobilization and further sulphide 'durchbewegung' via late stage D3 initiated (sericite schist) shear zones. The D1 (F1) event is only evident from rare poorly defined isolated isoclinal F1 fold hinges and is mainly inferred from the presence of a high grade mineral defined schistosity S1 parallel to So folded about variably open to tight F2 folds with an overprinting S2 (sillimanite $\pm$ biotite) fabric and then by later more open F3 folds with a weakly defined lower grade axial planar fabric (sericite and/or sillimanite).

The intensity of the D2 (F2) event is such that high grade shearing axial planar to F2 folds leads to intense dislocation and transposition of layering So into parallelism with S2 in the more ductile metasediments within tight structures where the form surface of So is only partly preserved by more resistant marker units. These marker units comprise more competent remnant So parallel conformable lode rocks, psammites, amphibolites, calcsilicates, feldspathic gneisses and S1 parallel pegmatites. They also comprise compositionally defined major stratigraphic boundaries between psammite and pelite rich units. Very detailed mapping is required in well exposed areas to effectively outline diagnostic parasitic mesoscopic folds which relate to more major prospective lode plus sulphide bearing structures. Indeed many of the critical fold structures hosting mineralization can only be discerned by such careful sequential lithostructural mapping at scales suitable to the complexity of individual areas. Regional structural measurements along wide spaced traverses provide virtually no realistic indication as to the whereabouts of the localized ore bearing folds and are even less likely to provide any practical useful information as to their true orientation for focussed exploration drilling. It is therefore considered paramount that comprehensive lithostructural mapping be carried out where possible with a strong emphasis on detailed lode vector discrimination of the host rock sequence towards BHT mineralization. Such detailed mapping must then be followed by appropriate closed spaced drilling programmes in order to track down stratigraphic sequences favourable to the deposition of sulphides and locate ore bearing stratigraphic and/or structural thickenings. Effective mineral exploration will then be a natural consequence.

REFERENCES

- Stevens, B.P.J., & Stroud, W.J., (Eds) 1983 (a). Rocks of the Broken Hill Block: their classification, nature, stratigraphic distribution and origin. *New South Wales Geological Survey, Records*, 21:1-323.
- Stevens, B.P.J., Willis, I.L., Brown, R.E., & Stroud, W.J., 1983 (b). The Early Proterozoic Willyama Supergroup: definitions of stratigraphic units from the Broken Hill Block, New South Wales. *New South Wales Geological Survey, Records*, 21:407-442.





REGIONAL LITHOLOGICAL INTERPRETATION OF THE BROKEN HILL AND EURIOWIE BLOCKS, NSW

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Magnetic anomalies in the Broken Hill region are caused by magnetite in stratabound horizons, structurally-controlled zones and igneous rocks (Maidment and Gibson, 1999). Various workers have recognised the presence of magnetite-rich stratabound units (e.g., Tucker, 1983; Stevens, 1999) which include banded iron formation, garnet-poor migmatitic metasediments and metasediments of the Paragon Group. Magnetite has also formed in high-temperature D₂ shear zones, D₃ fabrics, post-Adelaidean structures, and along lithological contacts (Maidment *et al.*, 2000). Some amphibolites are highly magnetic, possibly due to hydrothermal and/or metamorphic magnetite sources, whereas others are weakly magnetised. Altered, post-peak metamorphic mafic and ultramafic intrusives also give rise to conspicuous magnetic anomalies. Retrograde shear zones are generally magnetite-destructive and produce linear zones of low magnetisation.

A 1:100 000 scale lithological interpretation of the Broken Hill and Eurioiwie Blocks has been produced by integrating NSWDMR 1:25 000 scale geology with aeromagnetic, gamma-ray spectrometric and gravity data. The wide range of potential anomaly sources hampers detailed interpretation of aeromagnetics beneath cover. However, certain elements of the geology are conspicuous in aeromagnetic images and these have been used to provide a framework for the interpretation of other features under cover. Retrograde shear zones have been used to define shear-bounded structural blocks and domains of uniform magnetic character were used to define some geological units (eg., Redan Geophysical Zone and parts of the Olary Domain). Geological outcrop maps were then used in conjunction with geophysical data to interpret generalised lithological packages. In some areas, lithological trends could be extrapolated beneath cover using magnetic amphibolites as marker units, where these were sub-parallel to stratigraphy. No attempt was made to interpret detailed stratigraphy since the aeromagnetic data do not consistently discriminate between stratigraphic units.

NSWDMR geological mapping was used to subdivide metasediments into psammite- or pelite-dominated packages, which are most clearly defined in the central and northern parts of the region. Broadly, the southern and southwestern parts of the Blocks tend to be psammite-rich, whereas the northern part is dominated by pelite, with quartz-albite rocks almost invariably associated with the psammitic packages. This distribution may reflect original sedimentation patterns (i.e., a sediment source and basin margin to the present southwest) and is in broad agreement with the interpretation of some workers that the lower part of the Willyama Supergroup in the Olary Block was deposited in a shelf environment (e.g., Cook and Ashley, 1992). This regional pattern is likely to have been modified by later deformation, including the Delamerian Orogeny.

Potosi gneiss tends to occur in association with pelite and pegmatite in the central and northern parts of the Broken Hill Block, whereas in the south, it occurs in psammite-dominated packages. If the Potosi gneisses are volcanic units (Willis *et al.*, 1983), this association suggests that they are not confined to any particular sedimentary facies. Also apparent in the central and northern Broken Hill Block is a NNE-trending belt of psammite and quartz-albite rocks surrounded by a pelite-Potosi-pegmatite association. This may define a regional scale fold, or alternatively, it could be a result of shear-controlled structural repetition.

REFERENCES

- Cook N.D.J. and Ashley P.M. 1992. Meta-evaporative sequence, exhalative chemical sediments and associated rocks in the Proterozoic Willyama Supergroup, South Australia: implications for metallogenesis. *Precambrian Research* 56, 211-226.
- Maidment D.W. and Gibson G.M. 1999. Sources of magnetic anomalies in the Broken Hill region, NSW. *Australian Geological Survey Organisation Record* 1999/6.
- Maidment D.W., Gibson G.M. and Giddings J.W. 2000. Regional structure and distribution of magnetite: implications for the interpretation of aeromagnetic data in the Broken Hill region, NSW. *Exploration Geophysics* 31, 9-17.
- Stevens B.P.J. 1999. Magnetic susceptibility mapping at Broken Hill, Australia. *Exploration Geophysics* 30, 105-112.
- Tucker D.H. 1983. The characteristics and interpretation of regional magnetic and gravity fields in the Broken Hill district. *AUSIMM Conference, Broken Hill, NSW. July 1983*, 81-114.

Willis I.L., Brown, R.E., Stroud W.J. and 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. *Geological Society of Australia Journal* 30, 195-224.

ADVANCES IN MAPPING AND UNDERSTANDING OF THE KOONENBERRY BELT

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The Koonenberry Belt defines the eastern margin of the Curnamona Craton. The exposed older rocks in this belt consist of Late Proterozoic and Cambrian sediments and volcanics that were deposited on the eastern margin of continental Australia during and following the Rodinian break-up. The main structural trends in this belt were defined by the tight folding and thrusting that occurred during the late Cambrian Mootwingee Stage of the Delamerian Orogeny at about 500 Ma.

Continued mapping in the Koonenberry Belt has confirmed the lithological/stratigraphic sub-division of the basement rocks into Kara, Teltawongee, and Ponto beds and Gnalta Group. Most exposed contacts between these units appear to be early thrust faults. Closer geological mapping and further geophysical interpretation has enabled some sub-division of these units. The Ponto beds have been sub-divided into a number of sequences and formations either by detailed mapping (Peter Buckley on the Grasmere sheet) or by the interpretation of magnetic and radiometric patterns coupled with field knowledge (Barney Stevens and Kingsley Mills). The results of this work can be found in the new Grasmere geological map and in the new Koonenberry geological interpretation maps.

Zircon dating of finely laminated chert-like quartzofeldspathic tuff units in the Ponto beds have yielded dates as old as 516 Ma. While the results are not entirely satisfactory from a geological point of view, they do suggest that the Ponto Beds are probably middle Cambrian, and younger than first thought. A progression from calc-alkaline volcanism (525 Ma) in the Gnalta Group in the west, through the alkaline Mt Arrowsmith Volcanics (586 Ma) in the Kara Beds, to tholeiitic volcanism in the Ponto Beds (516 Ma) in the east, may reflect the thickness of the crust under extensional conditions at the various times of volcanism.

In spite of close inspection and a desire to prove up a spectacular geological history, no evidence has been revealed to suggest micro-continent, island arc or terrain collision zones. The sedimentary environments can be interpreted as a shallow passive continental shelf for the latest Proterozoic to earliest Cambrian Kara Beds and nearshore early Cambrian Gnalta Group; turbiditic slope deposits for the early to middle Cambrian Teltawongee Beds; or distal shelf or slope deposits for the ?middle Cambrian Ponto Beds.

The recognition of basic volcanic units in the late Proterozoic (Adelaidean) on the western side of the Bancannia Trough near Fowlers Gap suggests a possible correlation with the Mt Arrowsmith Volcanics and the Kara Beds. There may well be a continuity of basement from the Broken Hill Block to the Koonenberry Belt beneath the Bancannia Trough.

While extensive strike slip faulting has been popular in theory, it is very difficult to obtain concrete evidence of strike slip motion on faults in this area. The Koonenberry Fault and its various subsidiary splays appear to be characterised by dominant dip slip motion. The east-west faults on Wonnaminta and the northwest trending Grasmere and Prospectors Creek faults on Grasmere and Wilandra appear to be candidates for important late stage sinistral strike slip motion.

NEW DISCOVERIES AND ADVANCES IN UNDERSTANDING OF THE KOONENBERRY GEOLOGY

An additional low level geophysical survey was carried out in 1999 to cover an area to the north and NE of the previous 1995 survey. This survey covered an area from White Cliffs to Yancannia to Mount Arrowsmith to Milparinka. Apart from filling some areas of known bedrock exposure this survey revealed clearly some interesting features beneath the shallow Mesozoic cover at the southern margin of the Eromanga basin. On the Kayrunnera 1:100,000 sheet the new survey shows subtle basement features beneath a cover estimated to be less than 60m on the basis of mapped geology and water bore information. Magnetic features include weak SE directed basement structural trends in Teltawongee beds, several zones of secondary folding of these structural trends and a NE trending set of moderately magnetised cross-cutting dykes.

In 1999 a deep seismic line was commissioned by AGSO-DMR to transect the Bancannia Trough and the Koonenberry Belt from the Euriovie inlier to Yancannia. This survey revealed clearly the sedimentary structure within a 6km thick Devonian and Mesozoic section of the Bancannia Trough. Correlations with the Winduck, Snake Cave and Ravendale seismic intervals of the Darling Basin can be made, and steep reverse faults bring basement rocks up and over the trough sediments to the west and east. Several sets of shears can be seen within the deep structure of the Koonenberry Belt and there are suggestions that shears associated with both the Koonenberry and Olepeloko faults may dip at moderate angles to the west.

The strong magnetic stripes that characterise the regional response of the Ponto and some of the Teltawongee beds have been proved to be due to magnetite-bearing quartz-mica phyllite units and, to a lesser extent, altered metavolcanic units. Patches of surficial maghemite over some alluvial areas obscures the magnetic response of deeper features.

A better understanding of the Mt Arrowsmith Volcanics, an alkali basaltic suite with associated intrusions, has been revealed through the detailed mapping of Ian Cooper in the Nundora-Packsaddle-Milpa area. There now appear to be a number of independent extrusive volcanic centres that were active on a shallow marine shelf in late Proterozoic time. Close to each centre early pillow basalts are replaced up sequence with shallow marine to sub-aerial pyroclastic and hyaloclastic deposits, sub-aerial basaltic flows and, rarely, sub-aerial tuffs and accretionary lapilli. The sub-aerial rocks are then overlain by submarine pillow basalts. This evidence suggests the brief emergence of volcanic edifices above sea level and then submergence in a shallow marine environment. Some extrusive and tuffaceous units have become strongly differentiated towards more silicic quartzofeldspathic trachytic compositions. Beneath the volcanic piles intrusive gabbroic sills show crystal settling differentiation with some peridotitic lower sections. Above the volcanic piles dolomitic siltstones and sandstones are intruded by small plutons of syenitic and dioritic compositions that may form part of the Mt Arrowsmith Volcanics episode.

Several small granitic intrusions have now been recognised within the magnetically quiet and strongly deformed turbidite facies sequence to the east of the Koonenberry fault that has been mapped as Teltawongee beds. These rocks are fine-grained and foliated, but show country rock xenoliths. Perusal of some heavy mineral samples has indicated euhedral zircon and monazite crystals are present. Several bodies in the Williams Peak area appear to be associated with the occurrence of gold in the base of the overlying Mesozoic sequence.

Re-interpretation of the geological and geophysical features close to the Barrier Highway on Churinga and Comarto suggests that two large caldera-like ring structures may explain some of the unusual rock relationships there. Younger upper Cambrian to Devonian units are preserved within the rings, while an exposure of highly deformed older phyllite on Churinga and a nest of weakly deformed Carboniferous basic intrusions on Comarto appear related to the ring margins.

POINTERS TO FURTHER MINERAL EXPLORATION

While historical mineral occurrences and small mining operations are known throughout the Koonenberry Belt the area is very much a greenfields area for exploration. Until recently the geology was poorly understood but we are beginning to recognize the key focal points for geological investigation and mineral exploration.

The Milparinka-Mt Browne-Tibooburra region in the north is well known for its significant gold occurrence, both in quartz veins and as an alluvial component in the basal conglomeratic beds of the Mesozoic cover sequence. Smaller occurrences of gold have been worked near Williams Peak on Kayrunnera (alluvial gold in the base of the Mesozoic cover), Koonenberry Gap (carbonate-bearing quartz veins), and Cawkers Well (in quartz-chlorite-siderite veins). Anomalous gold values are also widespread in association with ankeritic carbonate in breccia and shear zones associated with the larger faults. The more quartzofeldspathic rocks derived from the differentiation of the alkaline Mt Arrowsmith Volcanics also contain anomalous gold values.

Traces of copper carbonates are often seen associated with fractures in basic volcanic rocks in the region, especially the tholeiitic volcanics within the Ponto Beds and near the Koonenberry Fault zone. Historically copper has been mined from the Grasmere and Ponto quartzose lode horizons that have been interpreted as syngenetic deposits. The oxidized zones of numerous lodes have been worked in the Wertago Copperfield. These occur within Carboniferous fault zones and along the Koonenberry Fault. There is also a spatial relationship with andesitic flows and intrusions into the Siluro-Devonian Mt Daubeny Formation red-bed sequence.

Rich silver values were obtained from the Noonthorangle Silverfield on Wertago at the turn of the century where argentiferous galena occurs in narrow quartz-siderite veins along fault zones over a deep magnetic anomaly.

The new high-resolution geophysical coverage has revealed numerous bullseye magnetic anomalies (both positive and negative) and many of these do not appear to have been adequately tested. There are also some curious magnetic anomalies and areas of disturbance of regular magnetic trends that deserve closer investigation. Large areas to the north and northeast appear to have only a shallow sediment cover and with the aid of the new generation geophysics are amenable to mineral exploration.

PROGRESS IN MAPPING

The Koonenberry region was mapped regionally at 1:250,000 scale in the 1960's. The new generation of geological mapping at 1:100,000 scale commenced in 1995 immediately following a high resolution magnetic and radiometric survey carried out under the Discovery 2000 program. At least 12 sheets at this scale contain mappable older rock units. Mapping has commenced with those sheets containing the most extensive exposure of Palaeozoic rocks.

The Bunda, Grasmere and Kayrunnera 1:100,000 geological sheets are now available in full colour. The Wonnaminta and parts of the Bancannia and Mt Arrowsmith sheets are currently being mapped and compiled. Nuchea will be mapped in the second half of this year. The Koonenberry Pre-Permian geological map at 1:250,000 scale gives an overview of the central and southern parts of the Koonenberry Belt. The Koonenberry Geological Interpretation Map at 1:250,000 scale, and the four component 1:100,000 sheets, present a compilation of current geological and geophysical knowledge of the central and southern parts of the belt.

GEOCHRONOLOGY OF WILLYAMA SUPERGROUP ROCKS BETWEEN OLARY AND BROKEN HILL, AND COMPARISON TO NORTHERN AUSTRALIA

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INTRODUCTION

Debate regarding age(s) and extent of stratigraphic coherence of the Willyama Supergroup, especially the Broken Hill Group itself, is of great relevance to regional correlation, and therefore to exploration models. Over the last few years, a large body of geochronological work has built up on the Broken Hill Domain (BHD), including more than 25 reports, abstracts and publications. These recent studies have raised contentious questions about the stratigraphic integrity of the Willyama Supergroup sequence. Ideas recently advocated include recognition of a late Archaean (~2650 Ma) basement to the Willyama Supergroup (Nutman and Ehlers, 1998a), a major thermal event at 1660-1640 Ma (Nutman and Ehlers, 1998b), and younger Proterozoic high-grade thermal events at 1500-1460 Ma, 1250 Ma. Some of these are evaluated in the light of our own new data.

Our geochronological program in the past two years has been integrated with field-based studies in both the BHD and Olary Domain (OD). Using SHRIMP U-Pb zircon techniques, its specific objectives were to (a) better quantify the basin history of the Willyama Supergroup, in particular age correlations within OD, and stratigraphic correlations between OD and BHD; (b) benchmark our new age results with those of previous workers as well as with our own previous work; (c) evaluate and test the evidence for reported Archaean basement terrain; (d) better constrain the timing of magmatic and deformational events; (e) compare Willyama Supergroup age and evolution with other Palaeoproterozoic terrains in northern Australia such as the Mount Isa Inlier.

ARCHAEAN(?) BASEMENT AT BROKEN HILL

New SHRIMP dating of zircons from layered paragneisses in the Redan Geophysical Zone provides zircon provenance age signatures typical of those found in most ca. 1700 Ma metasediments, whether from the Broken Hill Block or other Australian Palaeoproterozoic settings. Maximum ages derived from the youngest detrital zircon components are 1700-1710 Ma. This indicates that paragneisses in Redan Geophysical Zone near Farmcote are not 2654±16 Ma Archaean 'trondhjemite' (Nutman & Ehlers', 1998a preferred interpretation), but are part of a Thackaringa Group package possibly deposited about 1700-1710 Ma ago.

THACKARINGA GROUP AT BROKEN HILL, OLARY STRATIGRAPHIC EQUIVALENTS, & MAGMATIC EVENTS IN THE INTERVAL 1700-1720 Ma

Efforts to better understand Olary region geochronology follow work of Ashley et al. (1996) and have been applied to metavolcanics and immature metasediments, with 'age traverses' across six stratigraphic sections: Mulga Bore, Cathedral Rock, Mount Howden/Bimba mine, southern part of east Weekeroo Inlier, northern part of east Weekeroo Inlier, and central Weekeroo Inlier.

The 'quartzofeldspathic suite' in the OD includes clastic packages with detrital zircon ages that resemble those in the Thackaringa Group of the BHD, suggesting the same domainal provenance. In OD, the youngest zircon populations provide maximum depositional ages of 1710-1715 Ma. In addition, the OD 'quartzofeldspathic suite' and 'calcsilicate suite' contain felsic volcanic or sub-volcanic felsic rocks that directly date the stratigraphy in various parts of this region, with several ages between 1710 Ma and 1713 Ma. These volcanic rocks occur at different stratigraphic levels, and their essentially synchronous magmatic ages suggest a short depositional interval for this package. In effect, this sequence's age is tightly controlled, as its maximum (1710-1715 Ma) and minimum (~1710 Ma) ages are effectively coincident.

Quartz-albite lithologies in the Thackaringa Group (BHD) have detrital zircon populations, the youngest of which have been shown by Love (1992) and Donaghy et al. (1998) to be ca. 1710 Ma. We have obtained similar detrital zircon ages from thin-bedded quartz-albite rocks in the Himalaya Formation east of Allendale, thus substantiating a maximum age for the sequence.

Although ca. 1710 Ma detrital zircons in Thackaringa Group sediments are well known, igneous events of this vintage have not been previously recognised in the BHD. However, our new SHRIMP U-Pb zircon results from the Alma Gneiss near Broken Hill airport, give an igneous crystallisation age of 1704 ± 3 Ma (together with zircon metamorphic overgrowths formed at 1600 Ma). The age of 1704 ± 3 Ma is a minimum stratigraphic age for host Thackaringa Group. Recent tectonic argument premised on supposed 1680-1690 Ma age coherence of several BHD felsic gneisses should now be reconsidered. As the Thackaringa Group is no more than 1000-1500 metres thick and includes 1710-1700 Ma detrital zircons, the Alma Gneiss intrusion may well have been shallowly intruded, and be akin to 1700-1715 Ma felsic magmatic rocks in the Olary region. We have obtained other zircon ages that are substantially older than the previously reported age of ~ 1650 Ma (Nutman & Ehlers, 1998a; Nutman & Gibson, 1998) for a deformed, 'L' felsic intrusive sheet in the Redan area near Farmcote. Our 1704 ± 3 Ma and 1703 ± 3 Ma ages for this body are in good internal agreement and provide further evidence of this early magmatic event in the BHD.

STRATIGRAPHIC AGES IN THE BROKEN HILL GROUP, AND CORRELATIVE UNITS IN THE OLARY DOMAIN

Potosi gneiss lithotypes in the Parnell Formation (middle Broken Hill Group) and Hores Gneiss (upper Broken Hill Group) were interpreted as felsic volcanoclastic rocks with depositional ages of 1693 ± 5 and 1689 ± 5 Ma (Page & Laing, 1992). We have now substantiated the Hores Gneiss age (1686 ± 3 Ma) which, together with a new depositional age of 1691 ± 3 Ma for tuffaceous metasediments in the Allendale Metasediments, support the conclusion that the Broken Hill Group (excluding some amphibolite intrusions) is a coherent depositional entity. Suggestions that (a) the Hores Gneiss includes much younger intrusions (1640-1660 Ma old) and (b) the Broken Hill Group stratigraphy is thus split up, are at variance with our data and conclusions. We find no sustainable support for a thermal event in the BHD at 1640-1660 Ma, as advocated by Ehlers & Nutman (1997) and Nutman & Ehlers (1998b).

It has been a longstanding question as to which part of OD lithostratigraphy is correlated with the 1690 Ma-Broken Hill Group. Until now, there have been no depositional ages in upper parts of the OD lithostratigraphy. A systematic 'age' traverse in the Mount Howden region revealed a thin graphitic schist immediately above the 'Bimba' horizon. The uniform nature of the zircons in this rock and their coherent unimodal age pattern suggest tuffaceous input, preserved in a sequence starved of siliciclastic detritus. The age of 1692 ± 3 Ma is rigorously a maximum depositional age, but is presently interpreted as dating an event contemporary with deposition in this part of the OD. This age and its setting are clearly comparable with the age of 1691 ± 3 Ma for the Allendale Metasediments, thus enabling the first quantitative correlation from OD sequences to the lower Broken Hill Group. This supports the generally held stratigraphic equivalence of the 'Bimba' horizon (OD) with the Etlewood Calc-silicate Member (BHD).

Amphibolitic bodies intrude or are stratabound within the Broken Hill Group and older units in the BHD, and ages between 1670 and 1690 Ma are reported by Nutman & Gibson (1998). Our U-Pb zircon dating of another such body in the Parnell Formation north of Hores mine gives an apparent age of 1676 ± 7 Ma, but in our view this is another example where the result is better interpreted as a minimum magmatic age. A second Parnell Formation amphibolite near Allendale mine yielded only low-Th/U zircon formed during high-grade metamorphism at 1594 ± 7 Ma.

The complexity of dating high-grade gneisses affected by closely spaced events is illustrated by our age for the Rasp Ridge Gneiss of 1682 ± 3 Ma. This indicates that this magmatism postdated middle Broken Hill Group. Proposals to group most of the felsic gneisses at ~ 1690 Ma are not tenable, as we have now shown that they have real age differences. Our 1682 ± 3 Ma age agrees well with a Rasp Ridge Gneiss age of 1682 ± 7 Ma reported by Love (1992). However, Nutman and Ehlers (1998b) determined an older protolith age of 1697 ± 12 Ma, and also interpreted an age of 1658 ± 15 Ma for magmatic veinlets in the same rock. The latter age is said to support the case for a high-grade thermal event at 1640-1660 Ma, but in our view the methodology used to segregate the data and to pool the two separate ages is arguable.

SUNDOWN GROUP (BHD) AND LOWER 'PELITE SUITE' (OD)

Psammitic interbeds in the dominantly pelitic Sundown Group (BHD) and lower 'pelite suite' at Mulga Bore (OD) have provenance signatures and maximum depositional ages similar to those in Broken Hill Group clastic sediments. Major provenance patterns from late Archaean, ~ 1860 Ma, ~ 1820 Ma, ~ 1770 -1790 Ma, and ~ 1730 Ma are common, in general accord with the pattern reported by Nutman and Gibson (1998). Additionally, some BHD psammites contain minor detrital input from 1690-1700 Ma terrains, and a psammitic from the Euriowie

area and a calcareous psammite from the Monuments area include younger detrital relics closer to 1670 Ma – at present, the best maximum age for the Sundown Group.

PARAGON GROUP: BHD AND OD EQUIVALENTS

Fine-grained feldspathic beds in the Paragon Group in the northern BHD enable us to date this upper part of the Willyama Supergroup stratigraphy. Some of these feldspathic siltstones include populations of pristine, unabraded zircons that can be explained as air-fall tuffaceous input. These rocks resemble first-cycle igneous derivatives which punctuate many Mount Isa and McArthur Basin sequences, and were produced throughout late Palaeoproterozoic basin development in northern Australia. Tuffaceous siltstones in two different locations of the lower Bijerkerno Metasediments contain reworked, abraded zircons derived from commonly observed (~1780-1800 Ma, ~1850-1860 Ma) and older provenance domains. They also contain relatively pristine zircons with uniform Pb/U systematics and, from the bed in the Broken Hill block, these give a coherent age of 1656 ± 5 Ma. Rocks in the same stratigraphic position in the Euriovie Inlier give a similar maximum age. The agreement suggests that these ages are contemporary with deposition of the lower Bijerkerno Metasediments. The stratigraphic relevance of these results is emphasised by another SHRIMP age of 1642 ± 5 Ma for fine-grained feldspathic beds, interpreted as tuffaceous siltstones, in the younger Dalnit Bore Metasediments.

In the Olary Domain, 'pelite suite' rocks in a synclinal structure near Mount Howden include an albitic psammite bed containing zircon suite ages indicative of Paragon Group correlation. These zircons reveal not only the same complex provenance as seen in the older 'quartzofeldspathic suite' of the OD, but an additional younger component defined by a coherent array of detrital zircon at 1648 ± 6 Ma. This would indicate a structural discontinuity, or a disconformity of ~40 m.y. duration, or (unlikely) very slow depositional rates between this part of the section and older rocks (1692 ± 3 Ma graphitic 'tuffs') immediately above the Bimba horizon.

AGES OF DEFORMATION AND METAMORPHISM

Our efforts to refine ages for BHD deformational events have been directed towards granitoid intrusions which bracket the deformations. This enables us to possibly constrain the D₂ event between 1597 ± 3 Ma (Purnamoota road Lf gneiss) and 1596 ± 3 Ma (Cusin Creek pluton). The D₃ event can be no younger than a cross-cutting sheet of post-D₃ Mundi-Mundi granite (1591 ± 5 Ma) whilst the pre- or syn-D₃ Cusin Creek pluton provides an older age limit (1596 ± 3 Ma).

The complexity of zircon paragenesis in BHD and OD is exemplified by thin metamorphic zircon rims and discrete metamorphic zircon grains in many lithologies. Such zircons usually have distinctively high-U and low-Th/U, and almost always give metamorphic ages close to 1600 Ma, confirming approximate synchronicity of high-grade metamorphic event(s) with deformations that were apparently closely spaced in time. We find no isotopic support for any pre-1600 Ma metamorphic events, either from our results or from examination of published data. Apparent ages of 1610-1640 Ma and older, revealed in SHRIMP age profiles in Thorndale Composite Gneiss zircons are interpreted as incompletely reset protolith core ages.

NORTH AUSTRALIAN AGE CORRELATIONS

The improved geochronological framework for the Willyama Supergroup invites closer comparison with Palaeoproterozoic sequences such as the Mount Isa Inlier and McArthur Basin. The 1700-1710 Ma magmatic event, previously recognised in the OD and now in the BHD, is considered an early phase of an intracratonic rift setting for the Willyama Supergroup. This appears to be coeval with a major extensional episode (Calvert period) dated in the McArthur Basin and Lawn Hill Platform near the top of the Big Supersequence (Page et al., 2000), and it may represent a tectonic analogue of this widespread magmatic event.

Rocks of Broken Hill Group age are not widely documented in northern Australia, and this is probably accounted for by a ~20 million years erosional surface between the top of the Prize (~1690 Ma) and base of the Gun (~1670 Ma) Supersequences. It is interesting to speculate whether this same erosional / depositional break may be present in the Willyama Supergroup. In the OD, geochronological and stratigraphic evidence suggest at least two breaks, or periods of unusually retarded sedimentation: between 1710 Ma and 1690 Ma, and between 1690 Ma and 1650 Ma. In the BHD, an age gap of several million years might be present between the top of the Broken Hill Group and Sundown Group, and a gap of up to 10-20 million years between the Sundown Group and Bijerkerno Metasediments. Until there are better age constraints for the Sundown Group and basal Paragon Group, these suggestions remain as possibilities.

A readily acceptable correlation with northern Australian sequences is evident from the close age comparisons of the Bijerkerno Metasediments (1656 ± 5 Ma) and 'pelite suite' at Mount Howden (1648 ± 6 Ma) with tuff ages

(1654±5 Ma, 1656±4 Ma, 1652±7 Ma) in the Urquhart Shale – mineralised host of the Mount Isa and Hilton orebodies. Furthermore, our new age of the Dalnit Bore Metasediments (1642±5 Ma) is inseparable from a number of ca. 1640 Ma stratigraphic ages determined in the middle McArthur Group (at the HYC deposit), in the Fickling Group (Walford deposit), and in the middle McNamara Group (Riversleigh Formation).

Confirmation that the Paragon Group is stratigraphically contemporaneous with mineralised sequences in northern Australia is an important outcome of this geochronological study. Specifically, there is now a definite age correlation basis for considering a refocus of some Curnamona Province exploration efforts into the Paragon Group in BHD and equivalents in OD. This consequence and other ramifications of our ages, provide a robust geological framework against which more advanced basin analysis and metallogenic models can be examined.

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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.
- 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.
- Ehlers, K. and Nutman, A.P., 1997. Thermochronological evolution of the Willyama Complex. *Abstracts, Geodynamics and Ore Deposits Conference, Australian Geodynamics Cooperative Research Centre, Ballarat, Victoria*, 26-28.
- Love, S., 1992. Possible ages and origins for some rocks of the mid-Proterozoic Willyama Supergroup, New South Wales. Unpub. B.Sc. (Hons) thesis, Geology Department, Australian National University.
- Nutman, A.P. and Ehlers, K., 1998a. Archaean crust near Broken Hill? *Australian Journal of Earth Sciences*, 45, 687-694.
- Nutman, A.P. and Ehlers, K., 1998b. 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. and Gibson, G.M., 1998. Zircon ages from metasediments, granites and mafic intrusions: reappraisal of the Willyama Supergroup. *AGSO Record 1998/25*, p. 86-88.
- 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., Jackson, M.J. and Krassay, A.A., 2000. Constraining sequence stratigraphy in north Australian basins: SHRIMP U-Pb geochronology between Mt Isa and McArthur River. *Australian Journal of Earth Sciences*, 47.

SPECTRAL CHARACTERISATION OF REGOLITH UNITS AT BALACLAVA WEST, BROKEN HILL, NSW

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INTRODUCTION

Preliminary results demonstrating the benefits of using airborne hyperspectral data as an aid to mineralogical mapping of the regolith are very encouraging. The project area is contained within the Balaclava West 1:25,000 regolith map sheet, approximately 30 km south of Broken Hill. Hymap hyperspectral airborne data was collected over the area during April 1999. The east-west flight line passed over the area mapped during 1998 as part of a CRCLEME Honours project (Shirliff, 1998). The Honours project focussed on regolith-landform mapping, with special attention to delineation and classification of ferricretes and gypsum. The eastern half of the Balaclava area was mapped by Foster (1998), where special attention was paid to regolith carbonate accumulations. These projects provide invaluable information for ground-truthing the Hymap imagery. The spectrally-derived mineralogical classes are compared with the description and analysis of regolith materials (Shirliff, 1998, Foster 1998) and with regolith polygons derived from Foster *et al.* (2000).

GEOLOGY AND REGOLITH UNITS OF THE AREA

Balaclava West lies where the upper reaches of the Cainozoic Murray Basin palaeo-catchment overlap the southern limits of the interpreted Proterozoic Willyama Supergroup. Bedrock exposure is limited, with regolith dominating the land surface. The existing outcrop is predominantly at the western margin of the area. Lithologies consist dominantly of orthopyroxene-hornblende granulite, plagioclase-quartz-K-feldspar-biotite rich rocks, composite gneiss, quartzofeldspathic composite gneiss with migmatite and quartzofeldspathic pegmatite. Around Percy's Tank there is a sporadic outcrop of quartz-gahnite-feldspar rich rock, and in the northwest of the area an outcrop of ultramafic pyroxene-hornblende intrusive body. Schistose material consisting of biotite, muscovite and quartz is preserved in some ferruginous outcrops (Shirliff, 1998). Brown (1978) assigns these rocks to the lower most units of the Proterozoic Willyama stratigraphic succession. This incorporates them as one of the highest grade metamorphic rocks of the Broken Hill Block, well within granulite facies.

Several major prospects exist within the field area, Percy's Dam, Ten Two, Blake, and Magnetic Hill. Most of these have targeted Broken Hill lode horizon rocks, such as quartz-gahnite, garnetiferous metasediments, and Potossi Gneiss. These prospects are yet to find economically viable mineralisation.

The regolith cover at Balaclava West consists of alluvium, colluvium, aeolian sediments, duricrust (ferruginised and silicified regolith), desert loams, clays, regolith carbonate accumulations and gypsum. Their classification is given after Shirliff (1998).

The alluvium is very variable in composition in the Balaclava area. Alluvial materials include: channel sands; braided channel deposits; overbank deposits associated with proximal flood plains; and overbank deposits associated with river benches and pointbars. The colluvium occurs as: material on moderate to high rises associated with significant exposures of bedrock; material on low to high rises, with only limited exposures of bedrock; material on low foothills and slopes, where sheetwash is significant; finer material on flat to very low slopes, where sheetwash is dominant. Aeolian material includes: source bordering dunes; distal channel sands; and elongated rises. Ferruginous and siliceous indurated regolith occurs on low hills and erosional rises. Shirliff (1998) provides a detailed classification of the iron-indurated regolith. Silcretes exhibit three different morphological types: tubular/nodular; massive and columnar; or ferruginous.

HYPERSPECTRAL DATA AND PROCESSING METHODS

The Hymap data comprise 128 channels, spanning the 400 – 2400 nm wavelength range. These wavelengths are well suited for mapping the regolith, specially carbonate, sulphate and hydroxyl-bearing minerals, as well as iron-oxides and vegetation, because characteristic absorption features help the identification of these minerals. During this study the Short Wave Infrared 2 (SWIR2) spectral range was used (1950nm to 2480nm), which is most suited for identification of hydroxyl-bearing minerals, due to their well-developed absorption features in this wavelength range.

The pre-processing of data required geometrical correction of distortions due to the sensor spanning equal angles in equal time rather than equal surface areas. Calibration of data from Digital Numbers to radiance, then atmospheric correction to reflectance followed, using HYCORR software. The image was spectrally subset to the SWIR2 range and all subsequent processing was carried out on that range, using ENVI software. Volume

reduction was achieved by applying Minimum Noise Fraction (MNF) transformation (Green et al., 1988). Pixel Purity Index (PPI) was calculated to identify the spectrally most extreme materials of the scene. The Fast PPI calculation method was used, and more than 4,500 iterations achieved. The output image was thresholded to 100, considering only those pixels which have been identified as extreme more than 100 times. After visual examination of pure pixels in MNF space via an n-dimensional scattergram, a spectral library of end-members was created. Mixture Tuned Matched Filtering (MTMF) was used to create relative abundance images of each spectral endmember class.

RESULTS

The PPI analysis identified 1234 pixels as "extreme" for more than 100 times. Table 1 summarises their distribution into 12 endmember classes. The mean spectra of each group are shown in Figure 1. All spectra are offset and continuum-removed, for clarity. Mineral abundance maps are produced for each class, and interpreted in their regolith-landscape setting. Figure 2 shows two examples of abundance images, for class 3 and class 13. Much work remains to be done, including thorough examination and identification of abundance maps in relation to their regolith-landform setting. However, the preliminary results indicate that the Hymap-derived surficial units can be clearly related to existing mapped regolith polygons.

Class 1	122	Class 8	575
Class 2	21	Class 9	58
Class 3	44	Class 11	117
Class 4	49	Class 12	8
Class 5	20	Class 13	24
Class 7	146	Class 14	50

Table 1. The number of pixels identified as "extreme" for more than 100 times in each endmember class.

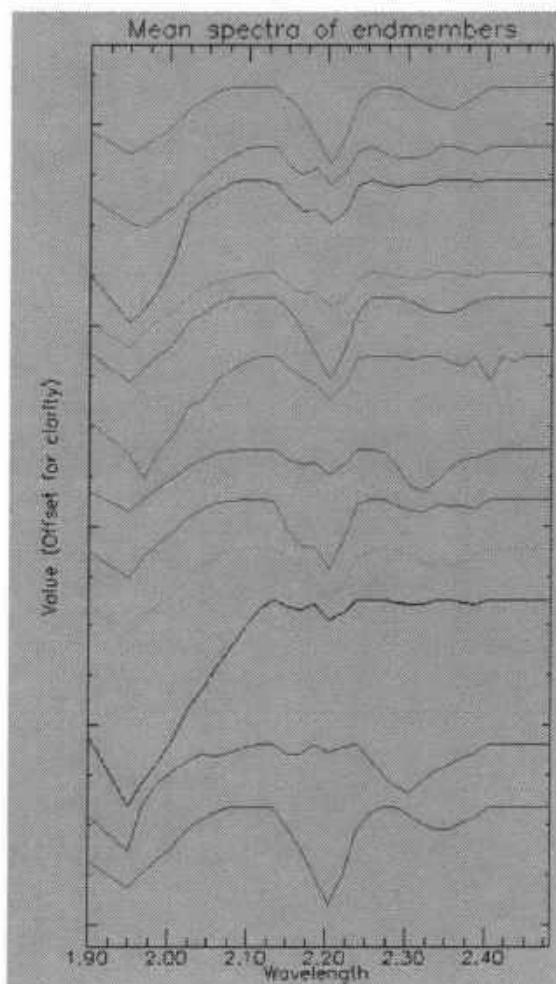


Figure 1. The mean spectra of endmember groups listed in Table 1. Class 1 is the lowermost, class 14 is the top graph. The spectra are offset and continuum-removed for clarity.

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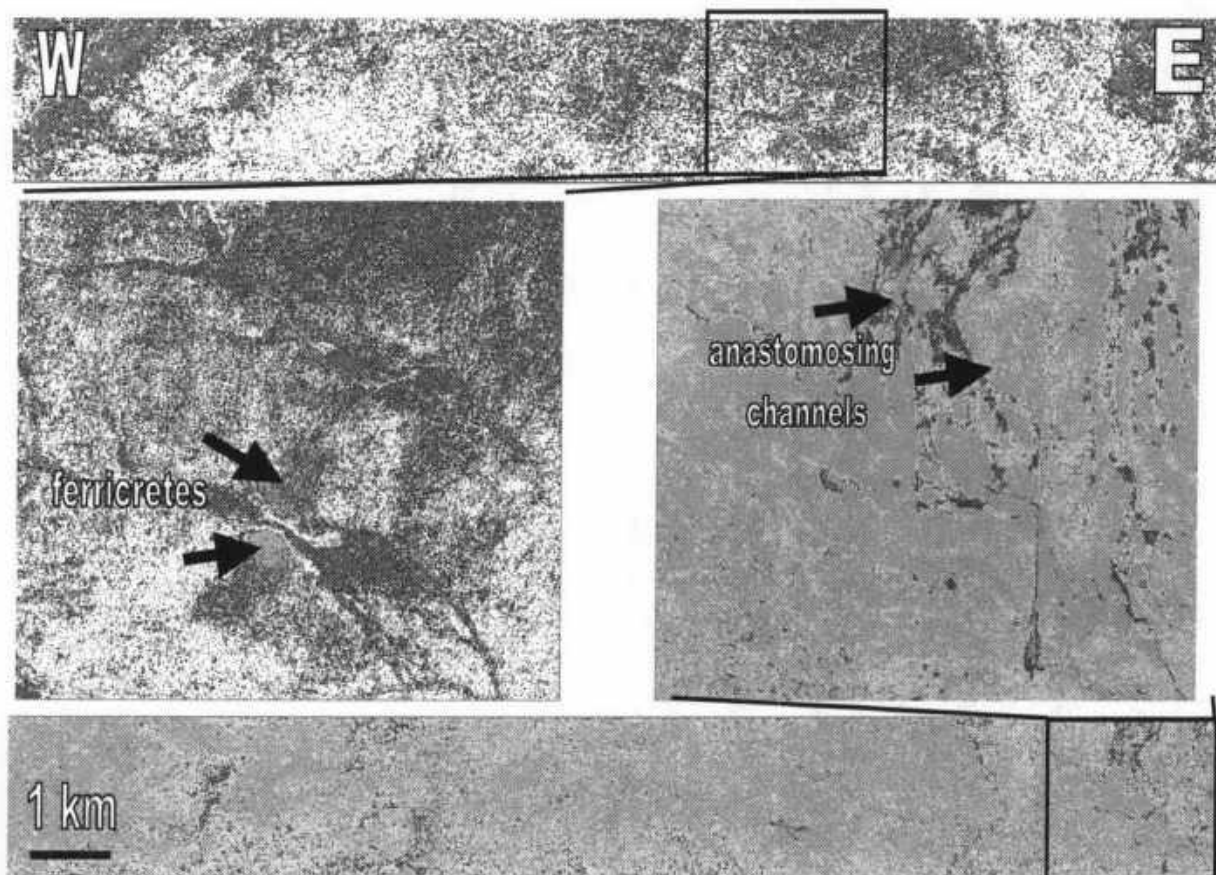


Figure 2. Abundance map of class 13 (top and middle left) and class 3 (bottom and middle right). Class 13 is interpreted as FeO abundance, in the landscape appearing as ferricrete, while class 3 interpreted as clay mineral abundance, in the landscape setting appearing as an alluvial plain dissected by shallow anastomosing river channels.

REFERENCES

- R.E. Brown, 1978: The Geology of the Balacava 1:25000 Sheet Area, Broken Hill, New South Wales. New South Wales geological Survey Report GS 1978/058 (unpublished)
- Kylie A. Foster, 1998: Regolith Geology and Geochemistry of Balacava East, Broken Hill, NSW. Honours Thesis, CRCLEME, University of Canberra
- Foster, K.A., Shirliff, G. and Hill, S.M., 2000: Balacava Regolith-Landform Map (1:25,000 scale) CRCLEME, Canberra
- Greg Shirliff, 1998: Massive Gypsum, Ferricretes and Regolith Landform Mapping of Western Balacava, Broken Hill, NSW. Honours Thesis, Department of Geology, The Australian National University.

OVERVIEW OF THE CURNAMONA PROVINCE AND ITS TECTONIC SETTING

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The **Curnamona Province** is a 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 of the province, 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 Curnamona Province is one of the most easterly preserved and outcropping Australian Precambrian crustal blocks. Its precise relationship to the Neoproterozoic continental margin, its alignment with Laurasia, and the possible intervention of the South China block between Australia and Laurasia, are still controversial.

The oldest preserved rocks are late Palaeoproterozoic metasediments of the **Willyama Supergroup**, including the Pb-Zn-Ag orebodies at Broken Hill. The total known succession is not thick in comparison to rifts and passive margin wedges; the lower part is a little older than 1.7 Ga, but its base is not seen. The absence of ophiolites, the evidence of evaporitic conditions in the lower Willyama Supergroup, and the presence of turbidites only in the upper part, suggest an epicontinental basin with restricted access to the ocean. However, 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 deformation and metamorphism in the Olarian Orogeny (~1.6 Ga). The great structural complexity of the terrain makes syndepositional structures difficult to interpret.

The tectonic context of the Curnamona Province is uncertain. Neoproterozoic sediments of the Stuart Shelf and Adelaide Geosyncline obscure boundary relationships with the mostly older Gawler Craton, whose core of late Archaean metasediments, metavolcanics and granites is flanked to the east by mid-Palaeoproterozoic sediments, tectonised and intruded by granite in the Palaeoproterozoic Kimban Orogeny. Late Archaean to late Palaeoproterozoic detrital zircons in the Willyama Supergroup suggest the eastern Gawler Craton as a source region.

Outside the Curnamona Province, the late Palaeoproterozoic to early Mesoproterozoic record is fragmentary. The shape and boundaries of the province are 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 (1.74 Ga) are variably metamorphosed, deformed, and hydrothermally altered, and host Cu mineralisation at Wallaroo-Moonta. In the Mount Lofty Ranges, sheared and retrogressed high-grade metamorphics occur as thrust sheets beneath Adelaidean cover. Limited geo-chronology suggests Olarian metamorphism, implying Willyama Supergroup precursors. 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.

The southern part of the Curnamona Province is divided into the **Broken Hill** and **Olary Domains**, reflecting differences in geological history, but new mapping to be presented at this conference suggests that the boundary between these domains is not sharply defined. In the northwestern part of the province, the **Mount Painter** and **Mount Babbage Inliers** are infolded with very thick Neoproterozoic Adelaide Geosyncline cover. Here 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 remainder of the Curnamona Province is not exposed; north of the Olary Domain, the **Benagerie Ridge** comprises Willyama Supergroup at low metamorphic grade overlain by little-deformed Mesoproterozoic felsic and mafic volcanics and sediments, known only from drillcore.

Willyama Supergroup in the Broken Hill Domain is divided into the **Thackaringa**, **Broken Hill**, **Sundown** and **Paragon Groups**. A new stratigraphic classification will be presented at this conference for the Willyama

Supergroup in the Olary Domain, reflecting uncertainty in correlation between the two domains. The Thackaringa Group is characterised by parallel-laminated, plagioclase-rich metasediments (albite generally > quartz). An origin by diagenetic alteration of Na-rich zeolites precipitated under evaporitic conditions has been suggested. Associated local facies include pelitic schist, lenticular banded iron formation and barite. In the Olary Domain, the equivalent succession 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 1.70-1.72 Ga.

Syn depositional 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 Olarian metamorphism and deformation. In the Olary Domain, outside the suggested rift, the presence of Broken Hill Group is uncertain, as will be discussed at this conference, but may be represented by the thin, sulphidic and basemetal-anomalous calc-silicate and fine-grained siliciclastics of the Bimba Formation. The Hores Gneiss at the top of the Group is a concordant marker in the Broken Hill Domain and may have a newly discovered 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. Granitic gneisses with similar age and geochemistry in the Thackaringa Group may represent sub-volcanic 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. New geochronology will be presented at this conference for equivalents in the Olary Domain.

The **Olarian Orogeny** has mostly been interpreted in terms of three main deformation phases and associated metamorphic episodes. D_1 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. F_2 folds are developed more locally at Olary but, in the Broken Hill Domain, the major arcuate NE to N-trending folds that have deformed both upright and inverted strata have traditionally be referred to D_2 . They may, however, be coextensive with and of similar orientation to D_3 structures in the Olary Domain, where F_3 folds and shear zones trend NE to E-W, and formed under lower grade conditions. If so, then temperatures remained elevated at Broken Hill where this folding is associated with high-grade metamorphism. New mapping in the Broken Hill Domain to be presented at this conference has revealed F_2 folds of similar orientation to those of the Olary Domain. Moreover, retrograde shear zones in both domains now appear to post-date the regional D_3 folding. Metamorphic grade drops from 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. Syn- to late orogenic granites in the Olary Domain include 1.63 Ga I-types and 1.59 Ga regional S-types, although their structural relationships to deformation phases are still debated.

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. In the Olary Domain, the NW vergence and decrease in intensity of both D_1 nappes and asymmetric F_3 folds suggest a foreland in the cratonic centre of the Curnamona Province. The high grade of ?Palaeoproterozoic rocks in the Mount Painter Inlier may indicate another mobile belt on the other side of this nucleus; alternatively, this metamorphism may be largely Delamerian.

During the **early Mesoproterozoic**, regional S-type granites were intruded in the Olary Domain, probably late to post- D_3 . Some of these are themselves foliated, perhaps related to retrograde shear zones. The Mundi Mundi Granite in the Broken Hill Domain appears post-tectonic. Much of the Curnamona Province was then uplifted and unroofed; pebbly sandstone was deposited and felsic and mafic volcanics were extruded on the Benagerie Ridge.

In the Mount Painter Inlier, the extremely thick Freeling Heights Quartzite was deposited, 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, possibly similar to the retrograde shears in the Willyama Supergroup, which could be late Olarian or younger (e.g. related to the Musgravian Orogeny).

Sedimentation in the **Adelaide Geosyncline** comprises five rift cycles, beginning at ~0.83 Ga with the early Willouran **Arkaroola Subgroup** (Flinders Ranges) and equivalent **Poolamacca Group** north of Broken Hill. Associated mafic activity includes intrusion of the NW-trending Gairdner Dyke Swarm (NE Gawler Craton) and Little Broken Hill Gabbro (NSW), and extrusion of the Beda, Wootana and Wilangee Volcanics that overlie basal Adelaidean transgressive sediments. The second rift cycle is represented by the late Willouran 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 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 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 0.78 Ga Boucaut Volcanics south of Olary underlie the basal sandstone, and may represent initiation of the third rift phase. The rest of the Burra Group comprises siltstone, dolomite, sedimentary magnesite and feldspathic sandstone forming 6 or 7 transgressive-regressive sequences, with 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 north and **Normanville Group** in the south). 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 deposited extremely rapidly. Coeval redbeds in the north 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 eastern 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 Palaeozoic, 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 Palaeozoic mobile zones that were uplifted, because Palaeozoic reverse faults were appropriately orientated 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.

EXPLORATION FOR BROKEN HILL TYPE MINERALISATION, SOUTHERN CURNAMONA PROVINCE

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On a regional scale, Broken Hill Type mineralisation within the Southern Curnamona Province is concentrated within a sequence of pelitic metasediment above a regionally pronounced magnetic gradient of magnetite bearing quartzofeldspathic rock. Field mapping at Mutooroo suggests that this contact is an original unconformity, interpreted as the onset of a rift / flood event. This fundamental break conforms to Leyh and Conor's (Leyh and Conor, 2000) recent separation of the Upper and Lower Willyama Supergroups.

Mineralisation is enhanced in areas of the pelite sequence proximal to major crustal sutures that may have acted as mantle tapping feeders with associated volcanism during rift development and subsequent compressional tectonism. Magnetic depth slicing highlights strong regional NE and conjugate NW trends, which appear to control localisation of BHT mineralisation throughout the Curnamona.

In the field BHT mineralisation or 'lode' is identified through the key alteration markers of garnet, gahnite, Mn-Fe oxide and sporadic primary and secondary Pb-Zn ores. At Mutooroo a number of lode horizons have been identified through a systematic programme of 1:500 scale mapping and rock-chip geochemistry. Collectively the mapped lodes have been found to occur over a wide stratigraphic width and extend over three kilometres in strike, with an inferred extension of the 'lode corridor' a further 7km under shallow cover. Rock-chip geochemistry returned Zn (gahnite) up to 15.8% (best Zn after sphalerite up to 1%), Pb 6.3% and Ag 31g/t.

Lode horizons are structurally configured, occurring as stacked en-echelon pods, slightly oblique to the regional meta-fabric. Generally the best lodes are formed where these shear controlled openings intersect a reactive host such as a psammite or calcsilicate interbed within the pelite sequence. At Mutooroo our western lodes are hosted by a prominent psammite, which displays all the classic BHT alteration effects and is dominantly a zinc lode. Further east, along the shear opening trend, the BHT system is developed up sequence, is Pb dominated and hosted in calcsilicate lithologies. This trend bears remarkable similarities to the Broken Hill Ore Body.

First pass RC and diamond drilling of four lode horizons at Mutooroo has confirmed that the outcropping lodes are part of a large sulphidic system. BHT alteration envelopes encompassing primary Pb-Zn cores form stacked en-echelon arrays in the subsurface and confirm a gahnite to sphalerite transition, most likely controlled by local P-T stability fields. Limited outcrop coupled with structural complexities necessitate that the next phase of drilling will rely heavily on latest MMR and EM processing technologies for target selection.

REFERENCES

Leyh, W.R., & Conor, C.H.H., 2000 Stratigraphically controlled metallogenic zonation associated with the regional redox boundary of the Willyama Supergroup. *Mesa Journal* 16.

TIME-SPACE FRAMEWORK OF CU-AU(-MO) AND REGIONAL ALTERATION SYSTEMS IN THE CURNAMONA PROVINCE

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INTRODUCTION

The Broken Hill Domain and adjacent Olary Domain in the Curnamona Province experienced broadly similar lithostratigraphic, magmatic and tectonic evolution during the Palaeoproterozoic and Mesoproterozoic. Although both domains host representatives of the major mineral deposit styles in the province, the Olary Domain contains the greater share of known Cu-Au(-Mo) mineralisation, whereas Pb-Zn-Ag resources discovered to date are located primarily in the Broken Hill Domain. Robust and predictive exploration models for Cu-Au and Pb-Zn-Ag ore systems in the Curnamona Province will build on a framework of quantitative information on the timing of hydrothermal events relative to tectonism and magmatism, the geometry of fluid flow pathways, and fluid and host rock physico-chemical properties. Here, we present a summary of geochronological, stable isotopic and preliminary fluid inclusion constraints on the timing, character and distribution of fluids responsible for Cu-Au(-Mo) mineralisation and regional Na-Ca-Fe alteration, and conclude with comments on the significance of the results for exploration models. Reviews of the regional geology and metallogenesis of the Olary Domain by Ashley (2000) and Ashley et al. (1998) provide a background to our results.

CU-AU(-MO) MINERALISATION AND ALTERATION

Vein, breccia and replacement style Cu-Au(-Mo) mineralisation at the Kalkaroo, Portia, Waukaloo, Mundi Mundi, and other similar prospects in the Olary Domain occur as stratabound zones, predominantly in albitic and calc-albitic metasedimentary rocks of the 'upper albite' (UA) unit within the 'quartzofeldspathic suite' (QFS). In places, Cu-Au(-Mo) mineralisation and associated potassic $\pm$ sodic alteration extends stratigraphically upwards across the calcsilicate $\pm$ carbonate-rich 'Bimba formation' and into the biotite $\pm$ graphite-bearing lower 'pelite suite' (PS), resulting in altered pelites locally resembling the UA (e.g. at Kalkaroo). The spatial association of sulfide mineralisation with the regional redox interface beneath the PS has long been recognised and targeted by explorationists (Cook & Ashley, 1992; Skirrow & Ashley, 1998; Leyh & Connor, 2000; Ashley, 2000), although the depth extent of Cu-Au(-Mo) mineralisation in structurally-controlled zones *below* this interface has yet to be evaluated. Indeed, gold and minor Cu-Mo mineralisation at the White Dam prospect occurs at a stratigraphic position different to that of the Kalkaroo and many of the other Cu-Au(-Mo) systems. Additionally, the Copper Blow Cu-Au deposit in the Broken Hill Domain occurs within the Thackaringa Group, which is equivalent to the QFS. A spectrum of deposit styles from iron oxide poor Au(-Cu-Mo) to Cu-Au(-Mo) associated with disseminated to massive magnetite are present in the Curnamona Province (Skirrow & Ashley, 1998).

Relative timing of Cu-Au(-Mo) introduction varies from pre- or syn-peak metamorphic (pre- or syn-D2?) at the White Dam Au(-Cu-Mo) prospect, through syn- to post-peak metamorphic at Kalkaroo, Waukaloo, Mundi Mundi, Lawsons, Wilkins, Dome Rock, Green & Gold, Copper Blow and Walparuta. Subsequent generally weaker deformation events and associated lower-temperature hydrothermal effects (e.g. chloritisation, carbonate veining) have overprinted and locally redistributed mineralisation to varying degrees (see below). At White Dam, recrystallised chalcopyrite and deformed molybdenite in high-grade hypogene gold zones are localised in strongly shortened Na-plagioclase - quartz - biotite vein-like bodies with biotitic selvages that cross-cut banded quartz - feldspar - biotite gneiss. The high-grade tectonic fabric (S2?) and sulfidic quartzofeldspathic veins are postdated by medium-grade mylonite zones in which magnetite - albite were stable. All of these fabrics are overprinted by localised cataclastic-pseudotachylite in some shear zones, and retrograde muscovite, low-grade shearing and folding to form schist zones.

In iron-oxide associated Cu-Au(-Mo) deposits, syn- to late-diagenetic(?) regional albitisation $\pm$ magnetite alteration of host rocks (see below) was followed by three principal syn- to post-peak metamorphic hydrothermal assemblages.

1. *Iron-calcic assemblages*: The earliest and highest temperature mineralisation, which contains chalcopyrite - pyrite $\pm$ molybdenite, is associated with veins and replacements of magnetite - actinolite - K-feldspar -

quartz $\pm$ albite $\pm$ titanite $\pm$ allanite (e.g. deeper zones at Kalkaroo, & BWM1A) and magnetite – actinolite – albite – titanite (e.g. Waukaloo). At Dome Rock, Lawsons and Wilkins prospects chalcopyrite is accompanied by actinolite – magnetite – pyrrhotite $\pm$ pyrite, whereas sulfides in the Green & Gold prospect occur within a magnetite – actinolite – biotite – garnet – staurolite post-peak metamorphic shear zone. These assemblages in places overprinted metamorphic clinopyroxene. New oxygen isotope geothermometry for quartz-amphibole-magnetite at Kalkaroo and Waukaloo yields temperatures of ~ 420 – 450°C . Preliminary fluid inclusion data for Kalkaroo corroborate these temperatures, and indicate involvement of hypersaline Na-Ca-K and possibly $\text{CO}_2 \pm \text{N}_2$ rich fluids.

2. **Potassic assemblages:** Major deposition of chalcopyrite, Au and molybdenite occurred in association with biotite – quartz $\pm$ K-feldspar potassic alteration, and with biotite – albite (e.g. non-magnetic zones at Kalkaroo), that overprinted the magnetite $\pm$ amphibole veins and/or formed in zones above and lateral to this iron-calcic metasomatism. Feldspars are commonly red with hematite inclusions ('red-rock'), particularly in systems of the Benagerie Ridge (Portia, Kalkaroo, BWM1A, ETM5A), although specular hematite is rare in the systems studied. Hydrothermal carbonate deposition commenced late in the potassic alteration stage. At the Mundi Mundi prospect, chalcopyrite, gold and molybdenite occur in magnetite-rich K-feldspar – quartz $\pm$ biotite $\pm$ muscovite veins and disseminations. This hydrothermal magnetite with associated sulfides predates or grew synchronously with the bedding-parallel cleavage, and was overprinted by a crenulation cleavage. At Copper Blow, chalcopyrite, pyrite and trace pyrrhotite and molybdenite were introduced with massive to disseminated magnetite – biotite $\pm$ garnet during shearing (late-D3?). Similarly, in the Walparuta prospect magnetite – biotite – albite $\pm$ barite filled the matrix of syntectonic (D3?) breccia with chalcopyrite – pyrite – bornite.
3. **Carbonate – chlorite assemblages:** Late-stage carbonate replacements were accompanied by minor to locally significant chalcopyrite-pyrite, extensive chloritisation, and quartz, fluorite, hematite and rutile development, commonly in association with localised deformation features such as extensional fractures. Oxygen isotope geothermometry of quartz-chlorite yields isotopic temperatures of ~ 300 – 420°C . The carbonate-chlorite assemblages may have formed as early as the Mesoproterozoic or as late as the Cambro-Ordovician.

RE-OS DIRECT DATING OF MINERALISATION

Rhenium-osmium (Re-Os) isotopic dating of sulfides allows direct determination of mineralisation ages, as compared with the indirect age constraints afforded by dating of alteration minerals. Recent improvements in the Re-Os method now allow precision rivalling that of the more mature U-Pb dating methods (e.g. Stein et al., 1998). Molybdenite is the mineral of choice, due to its unsurpassed ability as a single-mineral Re-Os geochronometer. Molybdenite samples from three prospects in the Portia area (supplied by G. Teale), Kalkaroo, White Dam and Waukaloo yielded 9 Re-Os ages ranging from ~ 1632 to ~ 1612 Ma (Suzuki et al., in prep.). Six of the ages from three prospects are in the range 1616–1612 Ma. The consistency of the results is matched by the very high precision (0.04–0.5%) obtained on individual Re-Os ages, and excellent reproducibility in replicate analyses (0.07–0.4%). These represent some of the most precise ages on Precambrian mineralisation reported in the literature. The data strongly suggest that resetting or post-crystallisation Re loss or Os gain in the molybdenites were insignificant. The results imply Mo and initial Cu-Au introduction before the peak of regional metamorphism at 1600 ± 8 Ma (Page & Laing, 1992; Page et al., 2000), although earlier high grade metamorphic events have also been postulated (Donaghy et al., 1998; Gibson, 1998; Nutman & Ehlers, 1998). However, consideration of overall errors of 0.5–1.0% in the absolute ages, arising in part from uncertainties in the decay constant for ^{187}Re , suggests that a range in timing from pre-peak to post-peak metamorphic introduction of Cu-Au-Mo remains plausible. A minimum age of ~ 1500 Ma is indicated by ^{40}Ar – ^{39}Ar data for muscovite in the Mundi Mundi prospect (Skirrow et al., 1999).

TIMING OF REGIONAL ALTERATION

Mainly stratabound Na $\pm$ Fe alteration is present in the Thackaringa Group in the Broken Hill Domain and within quartzofeldspathic to calcisilicate-bearing metasedimentary and ~ 1715 – 1705 Ma felsic meta-igneous rocks of the Olary Domain. Textural evidence in low grade metasedimentary rocks of the Benagerie Ridge bracket the timing of this early regional Na-silicate $\pm$ Fe-oxide alteration between diagenetic formation of carbonate $\pm$ evaporite(?) minerals (i.e. postdating 'Moonta biscuits') and metamorphic recrystallisation to albite $\pm$ magnetite during D1 and D2.

Syntectonic Na $\pm$ Ca $\pm$ Fe metasomatism in the Olary Domain overprinted the early stratabound sodic alteration, and was localised by fabrics related to shearing and folding during mainly the D3 regional deformation event. The geometries and PT conditions of formation of the D3 structures appear to be similar to those documented in the Broken Hill Domain (Gibson, 1998), where the D3 event is constrained between 1591 ± 5 Ma and 1596 ± 3 Ma.

Ma (Page et al., 2000). Syntectonic alteration styles include calcsilicate-matrix breccias (Yang & Ashley, 1994), vein networks, brecciated ironstones, and intensely 'albitised' zones affecting diverse lithologies, with assemblages including Na-plagioclase, clinopyroxene, clinoamphibole, quartz, magnetite, hematite, garnet and titanite. Garnet-epidote metasomatic zones (Kent et al., in prep.), and albitisation of andalusite porphyroblasts (B. Davies, pers. comm., 1999) may have also been coeval with these styles of alteration. Our calculated oxygen isotopic temperatures of ~450-550°C in calcsilicate-bearing assemblages are consistent with fluid inclusion and mineral stability constraints (Yang & Ashley, 1994).

SHRIMP U-Pb dating of titanite in four spatially distinct occurrences of syntectonic alteration in the Olary Domain yielded ages in the range 1588-1583 Ma, with ~0.5% errors. Two titanite samples are from calcsilicate-matrix breccias, one from amphibole-quartz veining, and the fourth from pervasively albitised granite at Tonga Hill. Consideration of titanite closure temperatures for U-Pb, and titanite formation temperatures, implies that the ages are minima but are probably close to crystallisation ages. Conversely, the age of peak metamorphism (1600 ± 8 Ma; Page & Laing, 1992) is a likely maximum for this alteration, based on the post-peak metamorphic textures, fabrics and formation conditions. A Sm-Nd age of 1575 ± 26 Ma for garnet-epidote regional alteration (Kent et al., in prep.) is compatible with our timing constraints for Na $\pm$ Ca $\pm$ Fe alteration. A Pb-Pb step-leach preliminary age of 1660 ± 33 Ma reported earlier for one of the titanite samples (Skirrow et al., 1999) is now understood to represent mixed age populations.

ORIGINS OF FLUIDS

Mineral oxygen and hydrogen and whole rock oxygen isotope analyses were performed to examine possible roles of magmatic versus metamorphic or other processes in the mineralising and regional alteration systems, and to constrain temperatures. This represents the first comprehensive stable isotope study for the Olary Domain since Bierlein et al. (1996) reported carbonate isotopic compositions and $\delta^{18}\text{O}$ for 18 quartz samples from epigenetic sulfide veins. Our calculated $\delta^{18}\text{O}$ compositions of syntectonic regional alteration fluids are mainly in the range 8-11‰ (n=25; calculated at ~450-500°C). Fluids involved in Cu-Au-Mo mineralisation have significantly lower $\delta^{18}\text{O}$ values of 4.2-8.5‰ (n=12; calculated at ~300-450°C). There is no distinction between calculated δD for fluids in regional alteration and Cu-Au-Mo mineralisation (-44 to -67‰; n=14).

Syntectonic regional alteration is interpreted as the product of Na-Ca-Fe-rich late-metamorphic fluids, sourced within siliciclastic, felsic igneous, calcsilicate and possibly evaporite-mineral bearing rocks of the Willyama Supergroup. Input of magmatic fluid was probably minimal, but cannot be ruled out. In contrast, we infer from oxygen and hydrogen isotope compositions that fluids involved in Cu-Au(-Mo) mineralisation may have contained a significant component of magmatic water (based on reference compositions of Taylor, 1996).

CONCLUSIONS AND EXPLORATION IMPLICATIONS

- Cu-Au(-Mo) introduction in the epigenetic Fe-oxide associated systems may have commenced during the period ~1612-1632 Ma, based on high-precision Re-Os dating. This timing would have overlapped with possibly the earlier stages of the Olarian orogeny as marked by granitoid emplacement (e.g. at 1616 ± 9 Ma, Fanning et al., 1998). However, improvement in the accuracy of Re-Os dating, and further age dating and characterisation of ~1620-1580 Ma S-type and/or I-type and ~1630-1640 Ma I-type granites (Ashley et al., 1998; Wyborn et al., 1998), are required to fully reconcile our results on the temporal relationships between mineralisation and magmatism.
- Regional-scale flow of ~450-550°C Na-Ca-Fe metamorphic brines between ~1595 Ma and ~1583 Ma was controlled principally by D3 structures.
- The regional alteration event temporally overlaps with magmatism of the Hiltaba Suite - Gawler Range Volcanics and Cu-U-Au mineralisation (Olympic Dam) in the Gawler Craton, and is within error of the age of volcanism on the Benagerie Ridge (Fanning et al., 1998).
- Syntectonic Na-Ca-Fe regional alteration is prominent in the southern, higher metamorphic grade parts of the Olary Domain, whereas Cu-Au(-Mo) mineralisation and associated Fe-oxide and potassic alteration are best developed in the lower metamorphic grade, northern Olary - Benagerie Ridge.
- The White Dam Au(-Cu-Mo) mineralisation may be a high-temperature style associated with quartzofeldspathic veins in a high-grade metamorphic area.
- Although the Cu-Au-Mo-As-F-LREE geochemical signature and stable isotope compositions of proximal alteration minerals in the Fe-oxide associated systems are consistent with magmatic fluid input, possible 'causative' magmatism has yet to be identified.
- Shear/fault zones active during D3 and transgressing the regional redox interface between strongly and weakly magnetic domains (Leyh & Conor, 2000) may be prospective for epigenetic Cu-Au.

- Zoning within some Cu-Au systems in the Olary Domain from lower and/or inner magnetite-amphibole-bearing assemblages to upper and/or outer biotite±K-feldspar±albite assemblages may provide vectors to the centres of mineralisation.

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REFERENCES

- Ashley, P.M., Conor, C.H.H. & Skirrow, R.G., 1998. Geology of the Olary Domain, Curnamona Province, South Australia. Field guidebook to Broken Hill Exploration Initiative excursion, 13-15 October, 1998. *Primary Industries and Resources South Australia, Report Book 99/12*, 53 pp.
- Ashley, 2000. Review of the geology and metallogenesis of the Olary Domain, South Australia. *AGSO Record*, in press.
- Bierlein, F.P., Ashley, P.M., & Seccombe, P.K., 1996. Origin of hydrothermal Cu-Zn-Pb mineralisation in the Olary Block, South Australia: evidence from fluid inclusions and sulfur isotopes. *Precambrian Research*, 79, 281-305.
- Cook, N.D.J. & 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.
- Fanning, M., Ashley, P.M., Cook, N., Teale, G. and Conor, C.H.H., 1998. A geochronological perspective of crustal evolution in the Curnamona Province. *AGSO Record*, 1998/25, 30-35.
- Gibson, G., 1998. Regional Structure in the Willyama Supergroup and its relevance to mineral exploration in the Broken Hill Inlier. *AGSO Record*, 1998/25, 38-40.
- Kent, A.J.R., Ashley, P.M. & Fanning, C.M., in prep. Metasomatic alteration associated with regional metamorphism: an example from the Willyama Supergroup, South Australia. Submitted to *Lithos*.
- Leyh, W.R. & Conor, C.H.H., 2000. Stratigraphically controlled metallogenic zonation associated with the regional redox boundary of the Willyama Supergroup - economic implications for the southern Curnamona Province. *MESA Journal*, 16, 39-47.
- 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.
- Page, R.W., Stevens, B.P.J. & Gibson, G.M., 2000. New SHRIMP zircon results from Broken Hill: towards robust stratigraphic and event timing. *AGSO Record*, in press.
- Page, R.W., Conor, C.H.H. & Sun, S.-S., 1998. Geochronology of metasedimentary and metavolcanic successions in the Olary Domain and comparisons to Broken Hill. *AGSO Record*, 1998/25, 89-93.
- Skirrow, R.G. & Ashley, P.M., 1998. Copper-gold mineral systems and regional alteration, Curnamona Craton. *AGSO Record*, 1998/25, 104-108.
- Skirrow, R.G., Maas, R. and Ashley, P.M., 1999. New age constraints for Cu-Au mineralisation and regional alteration, Olary – Broken Hill region. *AGSO Research Newsletter*, 31, p. 22-25.
- Stein, H.J., Sundblad, K., Markey, R.J., Morgan, J.W. & Motuza, G., 1998. Re-Os ages for Archean molybdenite and pyrite, Kuittila-Kivisuo, Finland and Proterozoic molybdenite, Kabeliai, Lithuania: testing the chronometer in a metamorphic and metasomatic setting. *Mineralium Deposita*, 33, 329-345.
- Suzuki, K., Skirrow, R.G. & Tatsumi, Y., in prep. High-resolution rhenium-osmium dating of molybdenite in copper-gold deposits of the Broken Hill – Olary region, Australia.
- Taylor, B.E., 1996. Magmatic volatiles: Isotopic variations of C, H and S. *Reviews in Mineralogy*, 16, 185-226.
- Yang, K. & 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.

EVALUATING MODELS FOR TECTONIC DEVELOPMENT OF THE WILLYAMA SUPERGROUP

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There has emerged two very different general concepts for the early history of the Willyama Supergroup. The concept contributed to by several groups and published by Willis et al. (1983) (the "**Stratigraphic Model**") was of an intact sedimentary-volcanic sequence deformed and metamorphosed after deposition ceased, with relatively minor igneous intrusion. Quartzo-feldspathic gneisses and albitic rocks were considered to be volcanic or volcanically-derived. Amphibolites comprised both volcanics and contemporaneous intrusions. Progressive modifications to the above concept (Stevens 1998) include interpretation of the Rasp Ridge and Alma Gneisses as sub-volcanic sills, interpretation of albite-rich rocks as altered sediments with or without tuffaceous component, and interpretation of amphibolites as sills and dykes (possibly without extrusive equivalents) intruded during Broken Hill Group time.

The alternative view (Nutman and Ehlers 1998, Gibson 1998, Nutman and Gibson 1998, Donaghy et al. 1998) (the "**Thrust and Intrusion Model**") is that a pseudo-stratigraphy comprised metasedimentary units separated by thrusts, and that quartzo-feldspathic gneisses and amphibolites were all syn-deformation intrusions. An extreme version of this view concluded that some apparent quartzofeldspathic gneisses and pelites are really mylonites of indeterminate origin (White et al. 1995). Followers of this model (e.g. Gibson 1998) concluded from the presence or absence of a series of schistositys, that the Alma, Rasp Ridge and Hores Gneisses were intrusions emplaced during or perhaps before D2, but after D1. Similarly Gibson (1998) concluded that the Paragon Group is either in tectonic contact with the rest of the Willyama Supergroup, or was deposited unconformably on it after D1. The amphibolites were also interpreted as post-D1 intrusions.

Some of the conflicts between the above models can be evaluated on the basis of field criteria, textural data and new geochronological data.

THE STRATIGRAPHIC SEQUENCE

Relative younging from the Thackaringa Group up to the Paragon Group was interpreted from sedimentary younging data, which correspond in a general sense with decrease in metamorphic grade. This younging is now confirmed by geochronology (Page et al. this volume). From the Alma Gneiss to the Dalnit Bore Metasediments, the only unit out of sequence is the Rasp Ridge Gneiss. This was probably a sub-volcanic intrusion, emplaced into albitic metasediments of the Himalaya Formation.

In the Olary Block, relative stratigraphy has also been validated by zircon geochronology, and correlations tentatively made with the Broken Hill stratigraphy are strengthened by the geochronology. There are local differences, but equivalents of the Thackaringa, Broken Hill, Sundown and Paragon Groups exist in the Olary Block, in the same stratigraphic order.

Those who postulate thrusts must now explain why younger rocks sit on older rocks throughout the sequence. Thrusts tend to place older rocks on top of younger rocks.

The contacts between stratigraphic units are complexly folded. If these contacts are thrusts, they must have developed before folding. Pre-folding thrusts consist of flats and ramps. If there are ramps, the thrusts will cut up sequence and provide a variety of neighbours for any given stratigraphic unit. This will be reflected on maps. But on the Broken Hill maps there is consistency. For example Broken Hill Group is consistently found adjacent to Thackaringa Group (older) and Sundown Group (younger). So, if thrusts exist between stratigraphic units, they have no ramps, just flats extending for hundreds of folded kilometres. I suggest such thrusts do not exist.

Additional argument for the lack of thrusts between the Thackaringa, Broken Hill, Sundown and Paragon Groups, is the transitional nature of the metasediments near the contacts. The lowest part of the Broken Hill Group is rich in feldspathic psammite, similar to Thackaringa Group, and these change upwards into the feldspar-poor pelite-rich units typical of the Broken Hill and Sundown Groups. The boundary between the Broken Hill and Sundown Groups is difficult to identify where the Hores Gneiss is absent, due to the very similar nature of the metasediments in the two groups. In the basal part of the Paragon Group there is interlayering of distinctive Paragon Group chiasolite schist and pelitic metasediment resembling that in the

underlying Sundown Group. In the Euriowie Block the transition from Sundown Group to Paragon Group is gradational.

INTRUSIVE ROCKS AND DEFORMATION

The stratigraphic sequence from the Thackaringa Group to the Paragon Group contains no angular unconformities, precluding any high grade deformation in the time interval from about 1720 Ma to 1640 Ma. Page et al. (this volume) have dated the Alma Gneiss at 1704 ± 3 Ma and the Rasp Ridge Gneiss at 1682 ± 3 Ma. These rocks were emplaced while deposition of the stratigraphic sequence was taking place.

Hores Gneiss (1686 ± 3 Ma) retains volcanic textures, and contains inclusions entrained as unconsolidated sediment. Its distribution pattern and geochemistry are compatible with a volcanic or volcanoclastic origin, but not with an intrusive origin. Its contacts are parallel to bedding in the adjacent metasediments.

No geochronological study has detected zircons with metamorphic characteristics (overgrowths on older grains, low Th/U), older than about 1600 Ma. Deformation events before this date have mostly been inferred from the presence of pre-1600 Ma "granites". There was no high grade deformation before 1600 Ma.

Amphibolites have provided dates in the range 1690-1670 Ma. These rocks are abundant in the sequence up to the top of the Broken Hill Group, but are absent above this. This strongly suggests they are older than the Sundown Group. They were syn-depositional, not syn-deformational.

YO-YO TECTONICS

Granulite grade metamorphism experienced by the Willyama Supergroup requires a depth of burial of about 20 km. Proponents of the Thrust and Intrusion model have interpreted granulite grade deformations at and before 1690 Ma (D1?), at about 1650 Ma (D2) and at 1600-1590 Ma (D3?). This requires the Thackaringa Group to be buried to 20 km and deformed at granulite grade (D1?) before 1690 ± 11 Ma, to be raised to the surface, still flat lying, and overlain conformably by Allendale Metasediments (1695 ± 5 Ma), Parnell Formation (1693 ± 5 Ma) and Hores Gneiss (1686 ± 3 Ma), followed conformably by Sundown Group. At about 1650 Ma the sequence was required to sink again to 20 km below the surface to be deformed at granulite facies (D2?). Again the sequence was exhumed, still flat-lying, to be conformably overlain by the Paragon Group between 1656 ± 5 Ma and 1642 ± 5 Ma. By 1600-1590 Ma the sequence was again buried and deformed (D3?). This is the event which produced all of the metamorphic zircons, and is considered to be "peak" metamorphic conditions. Parts of the Paragon Group attained sillimanite grade. But all of the structural/metamorphic studies indicate that D3 was lower grade than D1 and D2, so how could the 1600-1590 Ma event be D3? Also, the coincidence of three deformations, separated by exhumations, producing virtually the same PT conditions, stretches credibility.

GENUINE THRUSTS IN THE WILLYAMA SUPERGROUP

From the above, it is clear there are no large-scale **pre-folding** thrusts separating whole stratigraphic units. But there is mapped evidence for large thrusts contemporaneous with early folding, and there are undoubtedly thrusts associated with later fold events. These later thrusts may be locally parallel to previously-folded bedding, but elsewhere transgress bedding and stratigraphy.

The Bijerkerno Syncline sits on the upper limb of an older refolded anticline, above a folded thrust (fig. 1). Graphitic sillimanite (after chistolite) schist of Cartwrights Creek Metasediments is dragged into the thrust, and a sill-like porphyritic leucogranite in or near the thrust, has been deformed at least twice.

The core of the Allendale Fold in the northern Broken Hill Block is occupied by one or two limbs of Hores Gneiss over most of a strike length of 25 km. This requires some detachment of Hores Gneiss from the Sundown Group in this structure (not elsewhere), and most likely involved gliding of Hores Gneiss on one limb over Hores Gneiss on the other limb.

In the Nine Mile area west of Broken Hill the distribution of stratigraphic units can only be explained by the presence of an extensive discontinuity. This is at an acute angle stratigraphy and may be a D2 thrust.

TECTONIC MODEL - CONCLUSIONS

The Willyama Supergroup preserves a depositional sequence from about 1720 Ma to 1640 Ma, which may contain non-depositional intervals, but contains no angular unconformity. There are no pre-folding thrusts separating stratigraphic units. No substantial deformation and certainly no granulite metamorphism could have occurred during this time period. The Hores Gneiss was undoubtedly a volcanic or volcanoclastic unit. The Alma and Rasp Ridge Gneisses were most probably syn-sedimentary intrusions, and certainly predate the first deformation, which occurred at about 1600 Ma. Most of the amphibolites were sills and dykes emplaced during Broken Hill Group time.

Reliance on the presence or absence of schistosity to determine the relative ages of rocks is fraught with danger in a multiply-deformed terrain. It cannot be assumed that a rock will preserve a schistosity from every deformation it has undergone, and it is too easy to mis-correlate schistosity from one rock to another. At Broken Hill, Gibson's (1998) conclusions from schistosity history are in direct conflict with relict textures and with mapped relationships between metasediments and meta-igneous rocks.

Similarly, reliance on geochronology is dangerous where the geochronology conflicts with field and map data. Conclusions of Nutman and Ehlers (1998) conflict with field data, but data from Page et al. (this volume) do not.

FUTURE RESEARCH - DEPOSITIONAL HISTORY

With evidence firming for preservation of a largely sedimentary sequence, the way is clear to resume study of depositional history. The evidence so far points to alternating lacustrine/sabha and marine sedimentation in the Thackaringa Group, and open marine shelf sedimentation in the Broken Hill and Sundown Groups, with intervals of explosive volcanism in the Olary area during Thackaringa Group time and in the Broken Hill Block during Broken Hill Group time. Increased water depth during Broken Hill Group time relates to rifting and emplacement of tholeiitic sills and dykes, while Sundown Group represents sag phase sedimentation.

Cartwrights Creek Metasediments began with slow deposition of anoxic, deep, black mud (now chert), followed by deep water evaporite (King Gunnia Calc-Silicate Member) and either tempestite or distal turbidite (graphitic fine psammite). Bijerkerno Metasediments largely represent fine sandy turbidites, changing upward to distal muddy turbidites of Dalnit Bore Metasediments. The basal beds of Bijerkerno Metasediments are tuffaceous, indicating that volcanism and associated tectonic disturbance might have led to renewal of the sediment supply.

Much of the 30 m.y. time interval between the Hores Gneiss and basal Bijerkerno Metasediments could be accounted for by very slow deposition in lower Cartwrights Creek Metasediments, and possibly a hiatus at the top of Cartwrights Creek Metasediments. Both the base and top of Cartwrights Creek Metasediments may represent marine transgression events with associated deepening and depositional breaks.

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REFERENCES

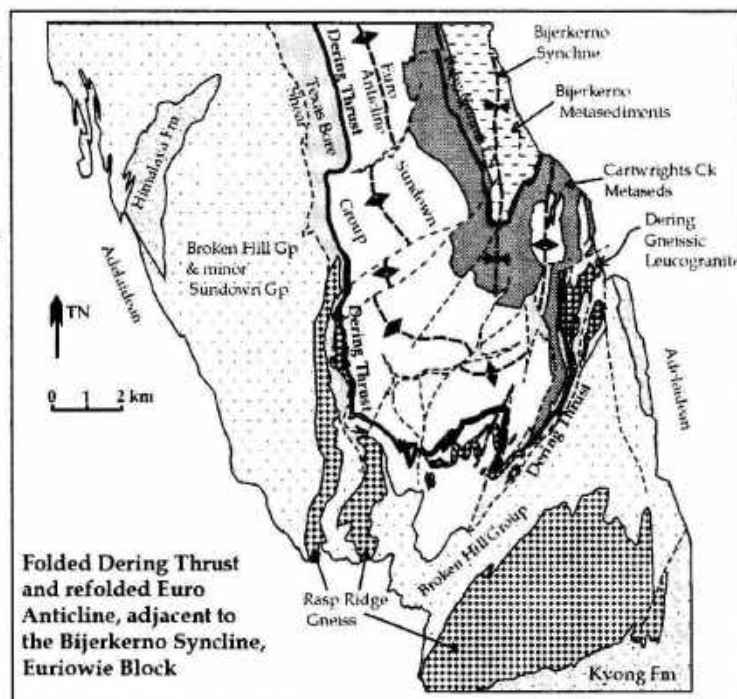
- Donaghy, T., Hall, M., Gibson, G., & Nutman, A., 1998. The age of deposition and first deformation of the Palaeoproterozoic Willyama Supergroup, Broken Hill Australia. *Geological Society of Australia, Abstracts* 49, 118.
- Gibson, G. 1998. Regional structure in the Willyama Supergroup and its relevance to mineral exploration in the Broken Hill Inlier. *Broken Hill Exploration Initiative, Abstracts, AGSO Record 1998/25*, 38-40.
- 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. & Gibson, G.M. 1998. Zircon ages from metasediments, granites and mafic intrusions: reappraisal of the Willyama Supergroup. *Broken Hill Exploration Initiative, Abstracts, AGSO Record 1998/25*, 86-88.
- Stevens, B.P.J. 1998. The origins of Broken Hill rock types and their relevance to mineralisation. *Broken Hill Exploration Initiative, Abstracts, AGSO Record 1998/25*, 109-114.
- 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. *Institute of Mining and Metallurgy, Transactions* 104, B1-B17.

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.

PREFERRED INTERPRETATION	BROKEN HILL BLOCK-EURIOWIE BLOCK	OLARY BLOCK
(Relatively) distal turbidites	PARAGON GROUP Dallwitz Bore Metasediments < 1642 ± 5	Upper PELITE SUITE 1648 ± 6
(Relatively) proximal turbidites	Bijerkerno Metasediments < 1656 ± 5, 1650-1660	
Time break (transgression)	King Gumia CS Member	
Deep, anoxic mud, with thin carbonate (evaporitic?) - starved basin	Cartwrights Creek Metasediments	Lower PELITE SUITE
Transgression	SUNDOWN GROUP < 1690	1692 ± 3
Marine shelf (distal delta)	Hores Gneiss 1686 ± 3	BIMBA SUITE
Volcaniclastics from explosive volcanism. Dolerite sills	Silver King Fm	
Marine shelf (distal delta)	Freyers Metasediments < 1780	
Volcaniclastics and dolerite sills or basalt flows.	Parnell Formation 1693 ± 5, > 1676 ± 7	CALC-SILICATE SUITE
Marine shelf with thin evaporitic carbonate, minor ashfalls	Alendale Metasediments 1695 ±	1715 ± 3 < 1717 ± 4
	Entlewood CS Member	
Na-alteration in evaporitic lakes/playas. Sub-volcanic granite.	Rasp Ridge Himalaya Fm Gneiss 1682 ± 3 < 1700 > 1690 ± 11	QUARTZO-FELDSPATHIC SUITE 1712 ± 2 > 1701 ± 8 > 1703 ± 6 > 1717 ± 14 > 1711 ± 2
Marine transgression.	Cues Formation	1699 ± 10 1710 1713 ± 2 1710 ± 3
	Alders Tank Formation	
Na-alteration in evaporitic lakes/playas. Sub-volcanic granite.	Alma Gneiss 1704 ± 3	COMPOSITE GNEISS SUITE
	Lady Brassey Formation < 1710-1740	
Deltaic to lacustrine, feldspathic sediments. Redan-Mulculca Na-altered and carbonate-bearing sediments, evaporitic environment.	Thorndale Composite Gneiss	
	Clevedale Migmatite	
	REDAN SUB-BLOCK Farmcote Gneiss > 1704 ± 3 < 1705 ± 5	
	Mulculca Formation	
	Ednas Gneiss	
	Redan Gneiss	

Figure 1: Stratigraphy, selected geochronology (from Page, Fanning, Nutman, Donaghy) and depositional interpretation.

Figure 2. Example of a folded thrust inferred from lithological mapping and stratigraphic interpretation. The Dering Thrust is localised in graphitic sillimanite schist of the Cartwrights Creek Metasediments. The normal stratigraphic sequence is disrupted. The Dering Gneissic Leucogranite closely follows the folded thrust.



ORTHO- AND GEOPHYSICAL IMAGERY; APPLICATION TO GEOLOGICAL MAPPING IN THE OLARY DOMAIN

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In 1995, AGSO & PIRSA (formerly MESA) provided funding to fly a 100m line spaced, N-S traversing airborne survey collecting radiometric and aeromagnetic data across the southern part of the Curnamona and northern part of the Olary 1:250 000 map sheets. Whilst the geophysical data is spatially accurate to 1m, it has been difficult to reliably relate to surface topography and surface geology due to lateral distortions in aerial photographs and poor spatially located geological maps. Overlays of the various datasets frequently display this discrepancy in accuracy.

Early in 2000, PIRSA acquired an orthoimage dataset from Kevron which covers the Olary Domain. The orthoimage dataset is derived from a set of 1:85 000 air photos by scanning, rectification, and merging to produce a near seamless product. At 1:25 000 scale, the map scale spatial accuracy is quoted as 0.5mm which equates to 12m on the ground. Ground truthing using differential GPS has indicated an accuracy of better than 5m. The orthoimages allow accurate plotting of aeromagnetic, radiometric and surface geology data relative to aerial photography

Although the images are recent acquisitions, existing geological mapping illustrates how the orthoimagery can be used as either stand alone base maps, or in conjunction with other data sets. As stand alone base maps, the data forms accurate images to map on, either as a hard copy, or as digital files which can be used in the field in devices such as palm top computers. When used in conjunction with geophysical data it is possible to map by overlaying a slightly transparent geophysical layer directly over the orthoimage. The orthoimages act as accurate base maps where specific radiometric and magnetic signatures can be tied to individual points on the ground. Larger areas of alike radiometric and magnetic signatures often represent individual lithologies. Polygons can then be drawn following along the boundaries.

In regions where some research has been done, it has been found that radiometric images created from different combinations of radioactive element concentrations can highlight individual lithologies. For example, in the Weekeroo Inliers, U Th, and K have been used semi quantitatively to discern between regional granites, altered older granites, pelitic rocks, albitic rocks and mafic units. Further work is in progress on quantification of individual lithologies and it is hoped in the future to have radiometric data to characterise most lithologies that are present in the Olary Domain.

Combining orthoimages and geophysical data also aids in mapping alteration zones, particularly where K, U or Th has been selectively enriched or depleted relative to one another. Magnetic trends that follow and cross cut lithologies can also be accurately mapped. However, these interpretations depend on some form of initial ground truthing where a correlation between a radiometric signature and a certain lithology can be made.

Detailed geological mapping still requires fieldwork because the orthoimages and geophysical datasets do not have the resolution of aerial photographs (the Curnamona aeromagnetic data has a theoretical resolution of 7m and radiometrics have a resolution of only 70m). Nevertheless, the digital nature and spatial accuracy of the Curnamona orthoimage data set is proving to be a valuable tool for regional geological mapping of the Olary region.

GEOCHEMICAL MAPPING OF ELEMENT DISTRIBUTION IN THE REGOLITH AT PORTIA AND NORTH PORTIA PROSPECTS, BENAGERIE RIDGE MAGNETIC COMPLEX, CURNAMONA, SA.

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In areas where topography is subdued or when the bedrock occurs as subcrop, three-dimensional (3D) visualization of geochemical data provide ways to delineate the overall element distribution patterns with respect to both the surficial materials and the stratigraphic units at depth. There are approximately 50 to 70 m of Quaternary and Tertiary sediments overlying the Proterozoic basement rock at Portia and North Portia prospects. The Namba Formation (dark-, olive-grey clay and pink sediments) makes up the bulk of the Tertiary sediments and is underlain by kaolinite-rich Portia Unit (light grey clay with basal sandy unit). The Proterozoic bedrock lithology units consist of scapolitic albitite footwall, various banded sulphide-, carbonate-, biotite-, illite- and albite-rich mineralized sequences, and a carbonaceous phyllite (both pyritic and non-pyritic) hanging-wall. All the different albitite lithologies weather to form kaolinite- and quartz-rich saprolite.

The 3D map utilizes geochemical data obtained from 160 air-core holes across the North Portia prospect and the software *Environmental Visualization Systems* (EVSTM) was used to produce the geochemical maps. Mapping geochemical indices is preferred over mapping individual elements because some groups of elements have similar distribution in the regolith and can be mapped together as a single variable and produced onto a single image. Nevertheless, the most important advantage of mapping indices is that fundamental geochemical characteristics of the stratigraphic units are enhanced. A rational and systematic way of classifying elements into respective indices is to employ the results from factor analysis (extracted using principal component methods). Five indices were extracted and are summarized in Table 1. The distribution of the geochemical 'plume' in the stratigraphic units could be delineated by only retaining the 'anomalous' values of the indices. The break of slope on a cumulative frequency curve is taken here to separate background from anomalous population. In addition, most indices are log-transformed to attempt to normalize the population distribution and reduce the range.

The Namba index (X_{Namba}) comprises six major elements and is calculated using the formula $[\log((0.1\text{Fe} + \text{Ca} + \text{Na} + \text{K} + \text{Mn} + \text{Mg}) / 60)]$. The values of the X_{Namba} range from 1.3 to 3.5. The surface Quaternary sediments host anomalous X_{Namba} values (> 3) owing to the presence of high Ca content associated with abundant calcite and gypsum. The X_{Namba} values decreases from the upper Namba Formation down to the Portia Unit and the saprolite. The latter are kaolinite-rich and hence have low Mg, Ca, Mn and Na contents.

The North Portia mineralization index (X_{min}) comprises the three elements Au, Cu and Mo and is calculated using the formula $[\log(10\text{Au} + 0.2\text{Cu} + \text{Mo})]$ (see Figure 1). The X_{min} ranges from 0.5 to 4 and values from 2 to 4 represent the anomalous population depicting mineralization, which occurs in a linear south-southeast trend along the strike of the banded pyritic albitite. The Portia Unit is generally absent or thin (1 to 3 m) on the subsurface ridge, where the saprolite-hosted mineralization occurs. Dispersion of the elements from the saprolite into the Tertiary sediments is limited to the base of lower Namba Formation and does not extend into the overlying middle Namba Formation.

The carbonaceous phyllite mineralization index (X_{phyllite}) uses the three elements As, Pb and V based on factor analysis and is calculated using the formula $[\log(\text{As} + \text{Pb} + \text{V})]$. The X_{phyllite} ranges from 1 to 4, and values 2.8 to 4 represent the anomalous population hosted in the pyritic carbonaceous phyllite. This index may not strictly depict the occurrence of pyritic carbonaceous phyllite because high V content (up to 1270 ppm) could occur in the saprolite unrelated to phyllite lithology. In addition, anomalous X_{phyllite} may overlap with anomalous X_{min} when Cu mineralization occurs in the banded albitite. In this case, high X_{phyllite} is caused by elevated As values (arsenopyrite) associated with chalcopyrite (with rare enargite).

Pyrite is a common gangue sulphide in the varying mineralised albitite sequence throughout the Benagerie Ridge Magnetic Complex. Ferruginous saprolite is formed upon weathering of pyritic albitite and carbonaceous phyllite. The Tertiary and Quaternary sediments host a few percent Fe_2O_3 . Hence, plotting Fe distribution alone

does not allow differentiation between Fe-hosted by pyrite and Fe-hosted by oxides and oxyhydroxides. Both Ni and Co are only known to be hosted in pyrite as reported by Teale (1999), and form one of the element groups determined by factor analysis. Hence, it is possible to map the occurrence of pyrite by using Ni and Co as an index (X_{pyrite}), which is calculated using the formula $[\text{Ni} + \text{Co}]$.

The Portia index X_{Portia} is the only index that consists of a single element (Au), also defined using factor analysis. Gold at Portia predominantly occurs with no statistically significant association with other elements at the Tertiary-Proterozoic unconformity and in the Proterozoic saprolite.

Table 1. Table showing the indices and their formulas used in producing the 3D images.

Index Name	Index Formula	Remarks
Namba (X_{Namba})	$\log [(0.1\text{Fe}+\text{Ca}+\text{Na}+\text{K}+\text{Mn}+\text{Mg})/60]$	Major elements essential in the minerals that make up the Namba Formation.
North Portia mineralization (X_{min})	$\log (10\text{Au}+0.2\text{Cu}+\text{Mo})$	Cu Mineralization at North Portia with varying amounts of Au and Mo.
Carbonaceous Phyllite Mineralization (X_{phyllite})	$\log (\text{As}+\text{Pb}+\text{V})$	As, Pb and V found to be in anomalous concentrations in the pyritic carbonaceous phyllite.
Pyritic Index (X_{pyrite})	Co+Ni	Co and Ni are essentially hosted in pyrite.
Portia Index	Au	Au at Portia prospect occurs at the Tertiary-Proterozoic unconformity and saprolite.

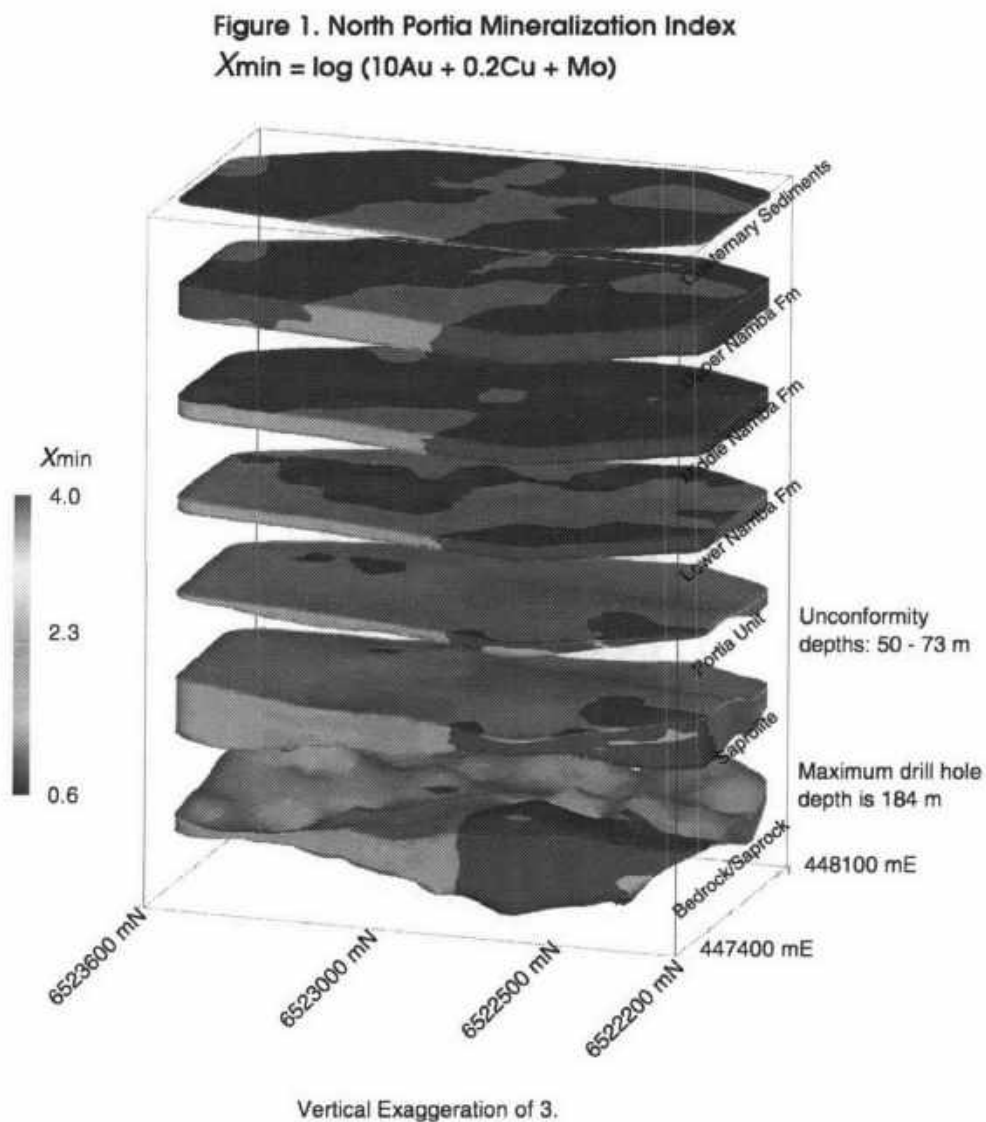
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REFERENCE

Teale, G. (1999). Mineralisation at the Benagerie Ridge. Part II. Stratigraphic subdivision, sediment provenance, petrography observations, mineral chemistry, mineralisation and vein paragenesis, U-Pb age dating, gold and silver studies, comparison with other Proterozoic provinces. *Confidential report for Pasminco Exploration. Vol. 2.* Pp. 180-273.

Figure 1. Diagram showing element distribution throughout the Proterozoic saprolite and the overlying sediments at North Portia. V/H = 3/1.



MINERALISATION ASSOCIATED WITH THE BENAGERIE RIDGE MAGNETIC COMPLEX, SOUTH AUSTRALIA.

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The Benagerie Ridge Magnetic Complex (BRMC) lies approximately 125 km WNW of Broken Hill and is one of a number of similar complexes in the region (eg Lake Charles and Eurinilla Magnetic Complexes). Intensive mineral exploration activity over the last five years, including the drilling of approximately 1600 drillholes, has led to the discovery of a number of mineralisation styles ranging in age from ~1700 Ma (syngenetic to diagenetic Pb-Zn) through to Tertiary (eg Au in palaeosols, roll front uranium). The geology and stratigraphy of the BRMC and the Benagerie Ridge, including the intrusive and extrusive activity, can now be discussed with some authority.

The sequence on the BRMC has been dated at 1702 ± 6 Ma (Teale and Fanning, this volume) and can be subdivided into a minimum of seven units commencing with an albitised footwall (unit 1) and capped by a strongly carbonaceous phyllite (unit 7). The "mineralised units" in between the above can be up to 200m in total thickness and are composed of variably altered, meta-evaporitic shales and carbonates. Crosscutting domains of invasive albitisation often destroy many of the original chemical and mineralogical features of the units.

The earliest mineralisation is considered to be ~1680 – 1700Ma in age and is composed of 1) Ag-Pb-Zn mineralisation in biotite-rich phyllites and 2) Ag-Pb-Zn in carbonaceous phyllites. Cu-As in carbonaceous phyllites may be associated, however it is considered that this mineralisation may be a distal associate of the younger Cu-Au-Mo (North Portia type) mineralisation. The Ag-Pb-Zn is present in fine grained, bedding parallel layers and is associated with an increase in fine grained, bedded pyrite. Carbonate, biotite (Mn and F-rich), feldspars, fluorite and chlorite are ubiquitous associates of the sulphide mineralisation, with sphalerite also present in carbonate nodules. The Ag-Pb-Zn bearing biotite phyllites grade laterally (from south to north) into barren carbonaceous phyllites suggesting a more silty initial component in the biotite phyllites.

The North Portia Cu-Au (-Mo) mineralisation has been dated at ~1605 Ma and develops in albitised meta-sediments, with invasive albitisation often pushing well up into the hangingwall carbonaceous phyllites (unit 7). The mineralisation comprises both a lower domain of predominantly replacement Cu-Au within carbonates and carbonate-rich meta-sediments and overlying vein infill style Cu-Au developed in brittle, "cherty" albitites and K-feldspar rock. Some early replacement molybdenite mineralisation may be associated with the albitisation event dated at ~1630 Ma (Teale and Fanning, this volume). Within the North Portia system, (~1605 Ma) molybdenite is also early and Mo vein mineralisation is often cut by later developed Cu-Au vein and replacement mineralisation. The timing and phases of mineralisation are outlined in Table 1, below.

The North Portia vein and replacement system exhibits a zoning upwards from its structural/stratigraphic base. Early "calcic" veins (tremolite – calcite – quartz – sphene $\pm$ biotite) give way to biotite – k-feldspar veins (quartz – calcite – biotite – k-feldspar – cpy – py – monazite) which become progressively more hematite-rich. In the upper parts of the system barren calcite – hematite veins are present, with barren k-feldspar $\pm$ biotite veins developed in the footwall albitites.

Carbonates in the North Portia system become progressively more Fe and Mn- rich from the structural/stratigraphic base of the mineralisation to the top. This carbonate zoning may be of use in exploring for North Portia style mineralisation and will assist in verifying where in the hydrothermal system a particular site/sample is. Gold fineness increases overall from the base to the top of the system due to the precipitation of hessite (Ag_2Te). Tourmaline becomes more vanadium rich towards the top of the system (eg Portia) with V_2O_3 and Cr_2O_3 sometimes up to 7% combined. It would appear that vanadium in the ore fluid increases with time. The bonanza gold grades observed at Portia, associated with vanadium-rich gangue (and sideritic carbonate?) could be compared to bonanza grade gold (with roscoelite mineralisation) which sits above or adjacent to porphyry systems. SHRIMP U – Pb zircon age dating of granitic intrusives from the Benagerie Ridge precludes these as a source of metals. Highly altered and fractionated dioritic intrusives near to the BRMC may be, in part, responsible for mineralisation.

Table 1. Timing and Phases of Mineralisation, North Portia – Portia areas, BRMC.

<u>Mineralisation</u>	<u>Age</u>	<u>Comment</u>
Phase 1	1680-1700 Ma (D ₁ , M ₁)	Diagenetic to D ₁ (?) framboidal pyrite; Sphalerite ± galena ± REE – bearing phases; early albitisation
Phase 2	1640-1680 Ma (?)	Early bedding parallel pyrrhotite + cpy ± bornite ± REE phases
Phase 3	1640-1660 (?) (D ₂ , M ₂ ?)	Pyrite ± magnetite ± hematite; replaces phase 2
Phase 4a	~1630 Ma	Invasive albitisation; Monazite abundant at (Replacement MoS ₂ albitisation “front”; possible pyrite-monazite with albitisation) veins; albite – quartz – monazite veins; replacement MoS ₂ (± biotite)
4b	~1630 Ma	Breakdown of Cl and F – bearing phases during albitisation and removal of Ag – Pb (- Cl – F) and other metals from albitised lithotypes.
Phase 5a	~1605 Ma	MoS ₂ in veins and replacement domains; (Calcic vein type) (“calcic” veins) structurally and stratigraphically low in system. Allanite and sphene as gangue phases.
5b	~1605 Ma	Development of hematite ± mt – calcite (Biotite - Kspar – Fe veins, Cu-Au in crosscutting veins, Cu-Au -type) replacing meta carbonate/evaporite beds, breccia zones, additional MoS ₂ in calcite ± cpy veins, monazite abundant.
5c	~1605 Ma	Cu-Au (-F-Bi-Te-Hg-Ag-Ba) introduction; (F-rich type) can crosscut or replace “older” phases. Reactivation of older min.; REE- fluorcarbonates peak;
5d	~1605 Ma	Replacement of higher T. gangue by(lower T- addition) chlorite, talc – calcite, siderite – Fe chlorite; upgrading of existing mineralisation.
5e	~1605 Ma	Zeolite – pyrite veining
Phase 6	<1605 Ma (pre – Delamerian)	Late fault breccias; hematite – calcite – fluorite – barite – galena ± sphalerite ± MoS ₂ ; reactivation and micro shearing. Probably generated outside of the Nth Portia Hydrothermal system.
Phase 7	~500 Ma	Remobilisation of the above; crustiform galena – calcite ± marcasite ± sphalerite veins; Bi – Te – Au – Ag veins in Adelaidean; calcite – cpy veins, calcite – cpy infills.

Away from the North Portia area bonanza gold grades have been recorded in a structurally/stratigraphically high position at the Shylock Prospect (eg 5m @ 356g/t gold in drillhole BEN 677) and breccia style Cu-Mo(-Au) mineralisation has been noted well within the core of the BRMC in footwall albitites at the South Nerissa Prospect. In the latter area primary bornite has been observed.

Marcasite – galena – carbonate ± sphalerite ± cpy veins developed during the Delamerian tectonothermal event and are of only minor interest. On the Benagerie Ridge these veins have been observed in Willyama Supergroup sediments, Mesoproterozoic granites, Cambrian sediments and Adelaidean sediments. They can be distinguished from older vein types on textural and isotopic grounds.

Eluvial gold in Tertiary palaeosols is present in a number of areas, the best known being Portia. At Portia a thin (0.2-1.5m) palaeosol, known as the "light grey clay" hosts coarse gold, with grains up to 1cm in size present. Angular fragments of quartz in the palaeosol contain sulphide inclusions, but no gold has been observed in the quartz.

The BRMC hosts numerous styles of mineralisation over a strike length of ~40km. Exploration has been difficult due to the presence of Tertiary cover and deep weathering of basement rocks. Structural complexity, predominantly due to faulting, has to be addressed when drilling. Exploration activity is continuing on the BRMC.

REFERENCES

Teale G.S. and Fanning C.M. 2000: The timing of Cu –Au mineralisation in the Curnamona Province. *AGSO Record*, in press.

THE TIMING OF CU-AU MINERALISATION IN THE CURNAMONA PROVINCE

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Copper-gold-molybdenite mineralisation in the Curnamona Province (CP) occurs principally (but not only) in Willyama Supergroup metasediments and volcanics and shares many similarities with other Palaeoproterozoic iron oxide associated Cu-Au(-Mo) deposits. The age of the Willyama Supergroup is established at around 1700 Ma (Page and Laing, 1992; Ashley et al., 1996; Ashley et al., 1998; Nutman and Ehlers, 1998). On the Benagerie Ridge a population of simple, zoned igneous zircons from a thin felsic tuff marker bed have a SHRIMP U-Pb age of 1702 ± 6 Ma, confirming earlier and current ages for the middle Formations of the Supergroup.

An exhaustive petrological study of in excess of 2000 polished thin sections, has enabled the selection of critical samples for *in situ* SHRIMP age determinations. The mineral phases chosen for such *in situ* robust U-Pb analyses, monazite rutile and sphene have clear, specific and direct relationships to mineralising events. These relationships are preserved in the polished thin sections and back scattered SEM imaging has been used to characterise the internal structure of all grains prior to analysis. Samples were selected from Cu-U-REE $\pm$ Au $\pm$ Mo $\pm$ Co mineralisation from the Mount Painter Inlier (Gunsight prospect and Parabarana Copper prospect) and from Cu-Au-Mo $\pm$ Pb $\pm$ Zn prospects in the Olary-Benagerie Ridge region (North Portia, Portia, Lorenzo, Shylock, Ram Dam, Polygonum Dam prospects). Although not reported here, we have also analysed *in situ* a number of key mineralised occurrences from the Broken Hill area.

Within the CP, one of the major conundrums has been the timing of albitisation and specifically its relationship, if any, to Cu-Au(-Mo) mineralisation. Albite gneisses and/or well bedded albitites can be observed throughout the CP occurring in all outcropping domains as well as under cover on the Benagerie Ridge. This latter area, with its low metamorphic grade ($\sim 400^\circ\text{C} - 450^\circ\text{C}$; 2Kb, PH_2O), is ideal for the study of the albitisation process and its relationship to Cu - Au (- Mo) mineralisation (eg North Portia) The following key observations can be made:

- There is an early albitisation and K-feldspar enrichment event that occurred over a period of time from diagenesis through to the earliest metamorphic event. Evaporitic minerals and possible early formed zeolite minerals provided sodium and potassium during dehydration and destruction of water soluble sodium carbonates.
- There is an invasive albitisation event that is post metamorphic. Apart from albite this alteration also contains abundant to minor F-phlogopite (generally altered to chlorite), fluorite, carbonates (including ankerite), magnetite $\pm$ hematite, REE-fluorcarbonates and monazite. Brecciation is common.
- Deeper zones of this alteration system can contain actinolite, hedenbergite, grossular-andradite garnet and epidote (as seen along and adjacent to the western bounding fault of the Benagerie Ridge).
- Two tectonothermal events, each with a distinct fabric, occurred prior to the invasive albitisation event (possibly equating to the early thermal and deformational events discussed by Nutman and Ehlers (1998), at ~ 1690 - 1680 Ma and 1660 - 1640 Ma). The albitisation is distinct, containing Mn - calcite rhombs, and albite replaces all pre-existing silicates. Garnet, for example, is totally pseudomorphed by albite.
- Cu-Au mineralisation post dates albitisation, with structural preparation of the albitites being one of the parameters for the deposition of mineralisation. An early introduction of molybdenite may have been synchronous with this albitisation event.

Monazite formed during the invasive albitisation event occurs generally as tabular to lenticular, "spongy" hydrothermal grains. Such fragile grains have been analysed *in situ* by SHRIMP II and give the timing of albitisation at ~ 1630 Ma. Albite-quartz-monazite veins occurring in the albitic footwall of the Portia Prospect also have a SHRIMP II U-Pb monazite age of ~ 1630 Ma, confirming the timing of this post metamorphic invasive albitisation.

Copper-gold mineralisation at the North Portia Prospect has been the subject of intensive exploration and study by the Pasminco-Werrie Gold Joint Venture over the last few years (Teale, this volume). Monazite occurs as a significant gangue phase and is present in bedding parallel replacement mineralisation as well as in cross-cutting infill sulphide veins. The monazite can contain inclusions of chalcopyrite and be included in chalcopyrite. Detailed *in situ* SHRIMP II dating of these monazites gives an age of ~1605 Ma, although some grains are complex and a subordinate number of areas record an older age of ~1690 Ma. This older age is not as well defined and most probably reflects inheritance associated with an earlier phase of fluid activity which crystallised monazite, during the time of the major ~1700 Ma magmatism in the CP (Fanning et al., 1998). Dating of rutiles from mineralised veins is ongoing with SHRIMP U-Pb rutile ages of ~1600 Ma being obtained when the grains are found to contain significant uranium.

Samples from the Ram Dam and Polygonum Dam prospects (RDD1-297 m and PO17-412.4 m) have experienced higher metamorphic grades than those from the Benagerie Ridge, reaching low to middle amphibolite facies grade. At Polygonum Dam a boudinaged (quartz-magnetite-pyrrhotite-pyrite-chalcopyrite-allanite-monzazite) copper-rich vein with a reaction aureole dominated by Mn-rich garnet was investigated as observations indicated a pre-tectonic origin. The monazite does not appear to be internally complex, but can be seen to rim magnetite. As with other samples analysed in this study a number of areas record discordant older $^{207}\text{Pb}/^{206}\text{Pb}$ ages ranging from ~2300 Ma to ~1810 Ma and three analyses at ~1550 Ma, not necessarily interpreted as reflecting significant geological events. The remaining analyses can be subdivided into an older group at ~1705 Ma (9 analyses) with a second group at ~1640 Ma (8 analyses) reflecting known tectonothermal/magmatic events within the CP (Fanning et al., 1998; Nutman and Ehlers, 1998). The ~1700 Ma event is well documented as the age of the host sequence, as evidenced by the zircon dating of a felsic tuff horizon from the Benagerie Ridge (see above). Intrusives around this age have also been recorded (Fanning et al., 1998). A series of magmatic events punctuate the earliest Mesoproterozoic of the CP in the Olary region with ages of ~1640 Ma and ~1630 Ma (summarised by Fanning et al., 1998) while Nutman and Ehlers (1998) record a deformational/thermal event at ~1640-1660 Ma in the Broken Hill region.

At the Ram Dam prospect additional data is required however ages of ~1670 Ma, ~1630 Ma and ~1600 Ma have been obtained and these are consistent with other events recorded by both U-Pb zircon and U-Pb monazite systems in the CP.

The sequence which hosts the Gunsight Cu-U-Co-REE-Fe-F deposit (Mt. Painter Inlier) has conventional U-Pb zircon age of 1575 ± 14 Ma (see Drexel, 1993). This sequence is highly deformed and in part mylonitic. It consists of sulphidic biotite – chlorite – quartz schists and mineralised LREE – enriched iron formation which are intercalated with metavolcanics, calc – silicates, cordierite – bearing meta-pelites and tourmaline – rich gneiss. The latter overlies the Cu – Co – U – REE mineralisation. Monazite grains associated with mineralisation have been recrystallised and now yield Delamerian ages. In the Lower Adelaidean sequence flanking the Mt. Painter Inlier Cu-Au-Mo mineralisation has been superimposed upon existing stratabound copper mineralisation. This mineralisation is possibly related to Delamerian to post Delamerian granitoids of the region. On the southern flank of the CP the Delamerian Anabama Granite and adjacent sediments host low grade Cu – Mo (-Au) mineralisation (Robertson et. al., 1998).

In summary, Cu-Au mineralisation in the CP is younger than the associated sequences which host the mineralisation. Early, but minor, Cu-Au-Fe-REE mineralisation in the Polygonum Dam area predates a deformational event and is probably ~1640 Ma in age. On the Benagerie Ridge Cu-Au-Mo mineralisation has been dated at ~1605 Ma, which postdates the major albitisation event which occurred at ~1630 Ma. Cu-U-REE-Co $\pm$ Mo $\pm$ Au mineralisation in the north-west of the CP occurs in rocks with 1), an age of ~1575 Ma (Gunsight Prospect), 2), in a sequence similar to that at North Portia (Parabarana Copper prospect) or 3), in Lower Adelaidean metasediments (e.g. Yudnamutana area). In the stable cratonic central domain of the CP (i.e. the northern Olary-Benagerie Ridge domain) it is considered that much of the known Cu-Au(-Mo) mineralisation (e.g. Kalkaroo, Waukaloo) shares a similar age to the North Portia mineralisation. Continued investigations are required to unravel the obvious complexities associated with Cu-Au mineralisation in the CP.

REFERENCES

- Ashley P.M., Cook N.D.F., & 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., Connor C.H.H., & Skirrow R.G. 1998: Geology of the Olary Domain, Curnamona Province, South Australia. Field guidebook to Broken Hill Exploration Initiative excursion, 13-15 October, 1998. South Australian Department of Primary Industries and Resources, Report Book, 99/12, 53 pp.
- Drexel, J.F., Preiss, W.V. and Parker, A.J., 1993: The geology of South Australia. Volume 1 The Precambrian. *South Australia Geological Survey. Bulletin*, 54.
- Fanning C.M., Ashley P.M., Cook N.D.F., Teale G & Connor C.H.H. 1998: A geochronological perspective of Crustal Evolution in the Curnamona Province. *AGSO Record* 1998/25, 30-35.
- 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.
- Robertson R.S., Preiss W.V., Crooks A.F., Hill P.W., and Sheard M.J. 1998: Review of the Proterozoic geology and mineral potential of the Curnamona Province in South Australia. *AGSO Journal of Australian Geology and Geophysics*, 17, 169-182.
- Skirrow R.G. & Ashley P.M. 1998: Copper-Gold mineral systems and regional alteration, Curnamona Craton. *AGSO Record*, 1998/25, 104-108.
- Teale G.S. 2000: Mineralisation associated with the Benagerie Ridge Magnetic Complex, South Australia. *AGSO Record*, in press.

Pb-Pb STEPWISE LEACHING (PbSL): A NEW GEOCHRONOLOGICAL TOOL FOR HIGH-GRADE POLYMETAMORPHIC TERRANES

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OVERVIEW

This abstract summarizes progress in, and briefly outlines the implications of, an isotopic investigation performed on Proterozoic staurolite and garnet porphyroblasts, using the new Pb-Pb step leaching method. Staurolite and garnet are important phases in areas of medium to high-grade metamorphism. Temperatures experienced by metamorphic rocks in such conditions commonly exceed 600 °C, leaving U-Pb, Pb-Pb and Th-Pb as the only applicable geochronometers. Pb-Pb dating of individual metamorphic minerals directly associated with distinctive metamorphic grades has proved to be a powerful tool for deciphering the history of metamorphic activity within a polymetamorphic terrane. Unfortunately, such isotopic dating in metamorphic terranes has often been treated with scepticism due to the following potential obstacles to accurate and precise thermochronometry of rock-forming minerals:

1. Low parent/daughter ratios, which limit the isotopic spread obtained on $^{207}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$ diagrams
2. Sensitivity of the (U-Th)Pb-Pb systems to post-intrusive disturbance (i.e. hydrothermal alteration, thermal overprinting)
3. Uncertainties in the closure temperatures of (U-Th)Pb-Pb systems in minerals
4. Frequent presence of U-and/or Th-rich inclusions (zircon, monazite) in the host phase, which can greatly influence its radiogenic Pb budget and apparent age.

In this study we explore the feasibility of the PbSL as a new and reliable silicate digestion technique for Pb-Pb isotope studies of metamorphic minerals.

GEOLOGICAL SETTING

Staurolite and garnet are metamorphic indicator minerals widely used by petrologists, and which occur within a limited range of thermal stability in most metapelites. The selected sampling area, located around the old Southern Cross mine site, is part of the palaeoproterozoic sequences that comprise the Willyama Supergroup at Broken Hill. This province is suggested to have undergone at least three high-grade metamorphic episodes. From structural and regional criteria, based on the geological framework provided by Wilson and Powell (1998), staurolite crystals whose metamorphic paragenesis was associated specifically with the D3/M3 event were studied. The staurolite crystals were collected from a 'high-strain' retrograde shear zone. The garnets are from rocks sampled just outside the system of conjugate shears, and from structural constraints, these must have grown during either D1 or D3. Quantitative P-T estimates by Wilson and Powell (1998), for the D3 equilibrium paragenesis (garnet-staurolite $\pm$ chloritoid $\pm$ chlorite) provide temperature estimates of about 600 °C and pressure in the range 4-6 kbars. From the sparse geochronological data available an estimated maximum age of approximately 1700 Ma has been proposed for the deposition of the Willyama Supergroup. There is, however, no general consensus on the interpretation of the available geochronological data associated with later events. Most of the geochronological studies published so far report age-data based on SHRIMP U-Pb chronology of accessory phases (i.e. zircon, monazite) rather than targeting metamorphic minerals directly correlated with petrologically deduced P-T paths. Therefore the reconstruction of the P-T-t evolutionary path is often far from obvious and may lead to errors in interpretation and therefore models of formation of polymetamorphic terranes.

BACKGROUND

PbSL is a new silicate digestion technique based on sequential acid treatment which allows the selective recovery of radiogenic and common Pb components from a mineral, making single-phase Pb-Pb dating possible (e.g. Frei & Kamber, 1995). The potential of the step leaching technique to enhance the spread in $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ ratios, allows age determinations to be undertaken on a wide range of minerals, particularly those in which U/Pb ratios are generally unfavourable for conventional U/Pb dating. For example, in our experiments an extremely large spread in isotopic ratios is obtained during the step leaching of garnet. One additional advantage of the PbSL approach is an ability to clearly delineate the possible influence of sub-microscopic inclusions (i.e. monazite or zircon), and to determine whether or not these have undergone isotopic equilibration with their host. This is achieved by the comparison of stepwise leaching spectra in the uranogenic vs thorogenic Pb isotope diagrams, which provide a monitor of primary variations in U/Th ratio. A linear arrangement of PbSL data points

in both diagrams might be expected if the mineral under investigation was compositionally homogeneous and unaffected by later disturbance. Alternatively, multiple arrays in the thorogenic diagram may result from bulk mixing of Pb from different phases. Thus, if a linear array is obtained in the $^{207}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$ diagram, it becomes possible via the thorogenic Pb plot to identify leaching steps carrying an isotopic signature from inclusions. In this study a clear example is provided by the staurolite data. The sample studied contains microscopic inclusions (approx. 5 μm) of opaque phases, which suggest that this sample could have a complex history.

ANALYTICAL METHODS AND RESULTS

Our PbSL experiments followed those of Frei and Kamber (1995). Table 1 summarizes the experimental parameters as well as the Pb isotope results, obtained using a Nu plasma multi-collector ICP-MS with thallium internal standard normalization. The Pb isotopic-progressions of successive leach steps are plotted in conventional uranogenic ($^{207}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$) and thorogenic ($^{208}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$) Pb diagrams in Figure 1. PbSL derived $^{208}\text{Pb}/^{206}\text{Pb}$ trends together with optical observations, reveal that staurolite hosts μ -size inclusions of an opaque phase; the garnet is essentially inclusion-free. The slope defined by our data yields apparent $^{207}\text{Pb}/^{206}\text{Pb}$ isochron ages of 1323 ± 11 Ma and 874 ± 34 Ma (two age components in the staurolite), and 1638 ± 67 Ma (garnet). All experiments recorded leach spectra with progressively increasing radiogenic Pb recovered with subsequent leach steps of increasing acid strength and duration.

The ability of PbSL to distinguish between radiogenic Pb in a host phase versus an included phase is readily apparent from the considerable scatter of data points depicted in plotting thorogenic vs uranogenic Pb ratios obtained from the staurolite aliquots (Figure 1). The influence of a variety of microscopic solid inclusions (hematite, and another Th-bearing but unidentified mineral) is clearly documented. All step leach spectra of staurolite are disturbed (i.e. the individual step leaching data have a large scatter around the reference line, which represent the locus of points of a compositionally homogeneous mineral). The chaotic arrangements of thorogenic steps in staurolite indicate at least two-component mixing of common and radiogenic Pb reservoirs within this mineral. The scatter observed is attributable to sample heterogeneity possibly as represented by the inclusions. The dual well-correlated trends defined by the staurolite data points on the $^{208}\text{Pb}/^{206}\text{Pb}$ and $^{207}\text{Pb}/^{206}\text{Pb}$ diagram are interpreted as reflecting the Pb contributions from two distinct mineral phases. The first two steps of each aliquot appear to be dominated by Pb components released from the host staurolite. In the last two fractions the Pb budget appears to be dominated by micro-inclusions. Thus, the stepwise leaching experiment reveals two Pb sources. As a result both ages could potentially record geochronological information, an aspect which is currently under investigation.

Conversely, a quasi-linear behaviour of uranogenic vs thorogenic $^{208}\text{Pb}/^{206}\text{Pb}$ is observed for the garnet, implying the virtual absence of (or totally equilibrated) submicroscopic inclusions (Figure 2). The linearity exhibited by leach steps in the garnet on both diagrams ($^{208}\text{Pb}/^{206}\text{Pb}$ and $^{207}\text{Pb}/^{206}\text{Pb}$) clearly indicate proportional release of uranogenic and thorogenic Pb and is interpreted as Pb contributed from a single mineral phase. Thus, the isochron extrapolated from the conventional $^{207}\text{Pb}/^{206}\text{Pb}$ diagram should reflect the genuine age of the garnet formation. Furthermore we can speculate a prograde growth-age for garnet and staurolite. Interpretation of these results as the age of mineral growth is justified because the 1110 and 1070 $^{\circ}\text{C}$ closure temperatures for Pb in the dated phases (Dahl, 1997) respectively, far exceed the T_{max} at the Southern Cross locality (600 $^{\circ}\text{C}$; Wilson and Powell, 1999). Provided our ages are accepted, the sequential leaching experiments permit a spatio-temporal characterization of the D3/M3 event. The age defined by the staurolite data could be interpreted as dating the cessation of high P-T shearing in the Southern Cross region. The age obtained from garnet, 1638 ± 67 Ma is in good agreement with a 1613 ± 4 Ma age obtained from monazite (SHRIMP U-Pb; Venn, 1997), hosted in a granitoid body in the Mt. Robe region, NW Broken Hill, and interpreted as an episode of regional granitic magmatism.

CONCLUSION

The power of our integrated approach, using the new PbSL-technique, coupled with MC-ICPMS Pb isotope determinations is illustrated in this report. Our study demonstrates:

1. The precision of these PbSL ages almost rivals that of U-Pb methods, primarily as a result of the wide spread in Pb-isotopic ratios produced during acid-leach steps.
2. PbSL techniques yield relatively accurate ages for the host phases despite the presence of Pb from other reservoirs, the latter also revealed using this approach. Furthermore we promote PbSL as a valuable tool in the interpretation of polymetamorphic and deformational terranes.

REFERENCES

- Dahl Peter S. 1997. A crystal-chemical basis for Pb retention and fission-track annealing systematics in U-bearing minerals, with implications for geochronology, *Earth And Planetary Science Letters*, (150)3-4 pp. 277-290
- Frei, R and Kamber, B.S. 1995. Single mineral Pb-Pb dating. *Earth and Planetary Science Letters*, 129, pp.261-268
- Venn,C. 1997. Evidence for extended thermal activity in Broken Hill. New geochronological constraints using SHRIMP U-Pb ages. *Geological Society of Australia, Abstracts No. 46*, pp 43
- Wilson C.J.L. and Powell R. 1998. Strain localisation and high-grade metamorphism at Broken Hill, Australia: a view from the Southern Cross area. *Tectonophysics* (in press.)

Table 1. Pb-Pb isotope and acid leach data

Sample	Code	Step	Acid	Time	206/204	207/204	208/204
Staurolite 1	St.1-1	1	HBr (0.6 N)	2 h	18.808	15.574	40.297
Staurolite 1	St.1-2	2	HCl (6 N)	6h	27.186	16.157	51.212
Staurolite 1	St.1-3	3	HF 48%-HNO3	48 h	91.684	22.009	67.297
Staurolite 1	St.1-4	4	HF 48%-HNO3	48 h	81.247	21.108	63.436
Staurolite 2	St.2-3	3	HF 48%-HNO3	48 h	124.436	25.216	64.612
Staurolite 2	St.2-4	4	HF 48%-HNO3	48 h	56.458	18.982	51.096
Staurolite 3	St.3-1	1	HCl (1 N)	2h	34.797	16.665	57.806
Staurolite 3	St.3-2	2	HCl (6 N)-HNO3	6 h	20.706	15.71	43.07
Staurolite 3	St.3-3	3	HF 48%-HNO3	48 h	68.3	20.026	60.113
Staurolite 3	St.3-4	4	HF 48%-HNO3	48 h	51.05	18.539	49.333
Garnet 1	Grt1,1	1	HBr (0.6N)	2 h	19.722	15.782	38.299
Garnet 2	Grt2,1	2	HBr (10.8N)	14 h	143.64	29.236	199.688
Garnet 2	Grt2,2	3	HNO3 (14.5N)	24 h	992.309	115.667	1378.265
Garnet 3	Grt3,1	2	HBr (9N)	14 h	62.378	19.923	90.756
Garnet 3	Grt3,2	3	HNO3 (14.5N)	24 h	1204.659	134.181	1683.448

Figure 1. Left side: Thorogenic Pb-discrimination plot showing staurolite, zircon and monazite trends. Right side: uraniumogenic Pb diagram illustrating the entire 'staurolite' dataset and the two more realistic isochrons extracted from this array based on the evidence for inclusions.

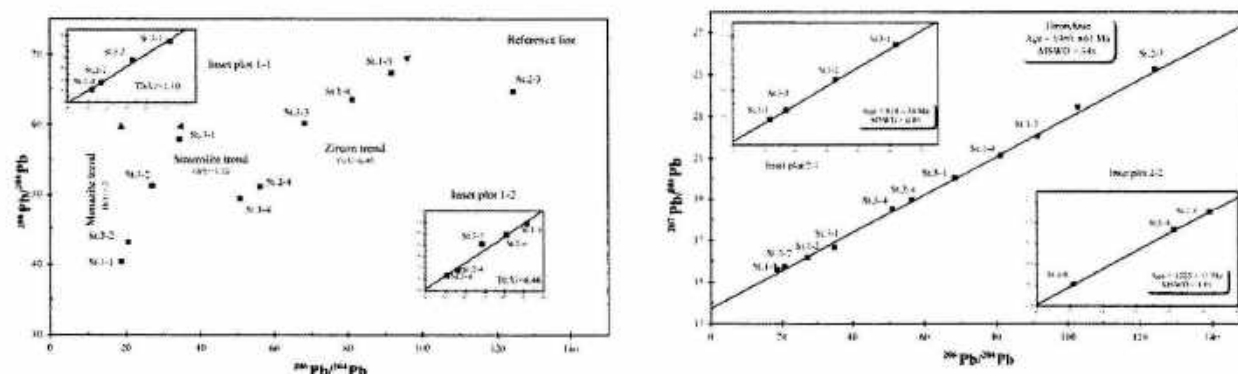
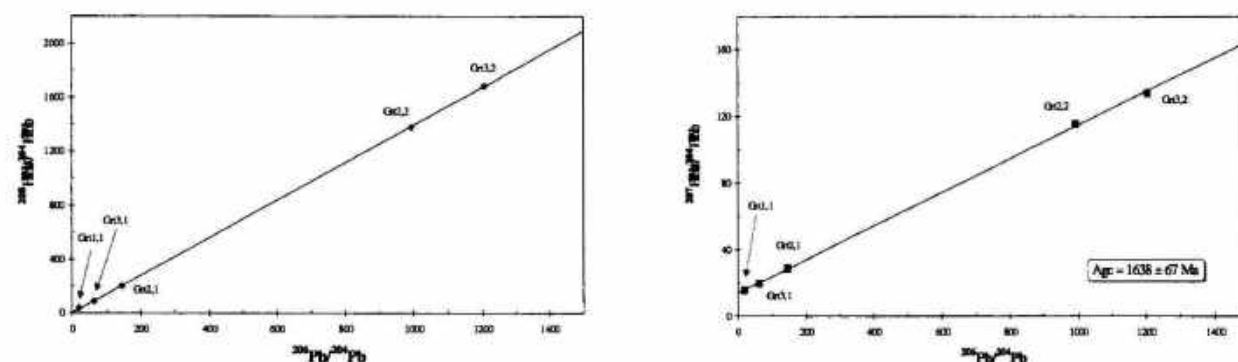


Figure 2. Left side: Thorogenic Pb-discrimination plot showing excellent correlation for all the garnet-leacheates, implying virtual absence of inclusions. Right side: isochron defining consistent age of 1638 ± 67 Ma.



STRUCTURES IN THE BROKEN HILL OREBODIES

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INTRODUCTION

This paper describes some of the significant deposit-scale folds, shears and faults that have affected the Palaeoproterozoic Broken Hill lead-zinc-silver deposit. The research is based on field observation, underground geological mapping and a compilation of data that has been gathered since the 1890's for various mining-related purposes. The discussion focuses on the central part of the mining field, within the urban area of the City of Broken Hill, comprising the former mining leases (ML) 10 to 15 and 39. This area has been largely neglected in modern geological studies due to poor underground access and the extensive open cut mining that has destroyed the upper mine levels. For convenience, the names of former mines and mining leases will be used throughout this paper as a means of referring to regions within the centre of the mining field.

ORE LENS GEOMETRY

All of the nine main Broken Hill ore bodies are strongly linear, approximately parallel in strike and roughly lenticular in cross section. The linearity of the main orebodies and related mineralised zones, and the great strike length of the two main orebodies produces a series of 'ribbons' of mineralisation that extend over 8.5 kilometres. 2 Lens (2L) and 3 Lens (3L) are the most continuous orebodies and possess three dimensional geometry's that are reminiscent of convoluted ribbons. 3L is continuous for the entire length of the area. 2L has a strike length of 8.5 kilometres but is structurally dismembered and thinned in the central part of the field, where only small mining tonnages were present.

Between ML 11 and 14 (the central part of the field), the plunge of 2L and 3L undulates around the horizontal to shallow southwest and shallow northeast. From near the boundary with ML 15 the orebodies plunge to the northeast at around 40° but this progressively steepens, reaching 70° in ML 15, until the orebodies are displaced at depth, in a reverse sense, by the Thompson Shear. On their re-emergence to the northeast of the Thompson Shear, in ML 16 and 39, the steep northeasterly plunge remains. To the southwest of ML10, 3L and 2L have an apparent southwesterly plunge (approximately 20° to 50°) which persists throughout the South and Pasminco mines at the southwestern end of the field. The orebodies thus define two boomerang shapes in longitudinal section, the apices of which occur in ML's 12, 13 and 14, where the deposit outcropped.

The main lenses are structurally terminated at depth by the Globe-Vauxhall Shear at the northeastern end of the deposit. The continuation of 3L has been located beyond the shear (the "2K" zone) but this zone of mineralisation is terminated by the Western Shear. Beyond this structure, the size and extent of the Broken Hill orebodies is unknown.

STRUCTURES WITHIN THE OREBODIES

The structures most apparent within the orebodies are a set of asymmetric, tight to isoclinal, apparently *en echelon* folds with wavelengths in the order of 50-75 metres (D2). They are variably attenuated and dislocated and host large masses of ore. The folds within the orebodies plunge southwest, to the south of ML 12 and plunge to the northeast from ML14. The southwesterly plunging D2 fold geometry that becomes established in the orebodies in ML 11 and 10 persists to the southwest into the Pasminco Mine. In the intermediate region, occupied by part of ML 12, ML 13 and part of ML 14, the folds undulate around the horizontal. The folding event is the earliest deformation to have significant geometrical effects in the orebodies.

The common limbs of folds are the locus of shearing. Broad shear planes are focussed in the attenuated limb regions of the earlier folds and they are often occupied by relatively thin sheets of ore. Shearing dislocates and offsets fold hinges in a sinistral, west block up sense, preserving them as complex lenticular ore masses. Two generations of shearing are apparent; a higher grade sillimanite, biotite, pyroxene, pyroxenoid generating event associated with transposition and some mesoscopic folding (D3A) and an overprinting quartz-sericite-biotite-amphibole generating event (D3B). Both generations of shearing are confined to the same planar zones. Several multi-planed fault systems dislocate the folded and sheared orebodies in the ML 15, and 16 area and further to the northeast in the North Mine (D4).

The axial traces of the early folds and the strike of the earlier (D3A) shears (and possibly the D3B shears) are curved within ML's 10 to 16, swinging through an arc of approximately 50 degrees from southwest (ML 10) to northeast (ML 16, 30 and beyond). The curvature of the strike of the structures is also seen in the orebodies and the surrounding stratigraphy, which vary in strike in a similar manner. Such curvature in both fold traces and the shears that dislocate them is difficult to explain unless the mining field has been refolded after the event that produced the D2 and D3 deformations. The change in the strike of the structures and the orebodies occurs in the same region of the deposit where the plunge reversal occurs and the pivot point of the change is in the same area.

The trend of the strike of the orebodies and early structural elements is disrupted in the ML15, 16 and 39 by a complex planar set of faults, generally known as the British Fault (D4). This brittle structure is not curved in the same way as the orebodies and the folds and shears within them and so is interpreted to be later, or at least approximately synchronous with the development of the curvature. Dolerite dykes intrude the orebodies in a number of northwesterly trending planes throughout the Line of Lode. In the central region of the field, they are focussed in a narrow belt near the southwestern part of ML 12 and in ML 13. The point at which these dykes cross the strike trend of the deposit also approximates the pivot points of the strike swing in the orebodies, early shears and fold axial traces; the reversal in plunge of D2 folds, and the apex of the plunge reversal of the deposit.

THE BHP AND CENTRAL MINES

The former BHP Mine (ML 11, 12 and 13) occupied the region of the plunge culmination; the place where mineralisation came closest to surface and where the manganiferous ironstone outcrops occurred. The geometry of 3L is variable through ML's 11 to 13, being dominated by a complex tight to isoclinal fold pair (BHP Synform and the BHP Antiform) and the effects of sinistral shears that have extensively modified the fold geometry's. The fold pair are tight to isoclinal in style and have a variable, undulating plunge throughout the BHP Mine. 3L lies within the hinge regions of both folds for much of ML's 11, 12 and 13, progressively migrating from the antiform hinge to the synform hinge in ML's 11 and 12. For much of ML 12 and 13 the orebody lies in the complex synform hinge.

The orebody is drawn out and structurally thinned in the fold limbs where shearing was most strongly focussed. It is therefore a tightly convoluted orebody consisting of linear pipe-like masses of sulphides and silicate-carbonate gangue (preserved fold hinges) linked by thin 'sheets' of sheared mineralisation (attenuated fold limbs).

The BHP fold pair are shallow southwesterly plunging in ML 10 and the southeastern part of ML 11. The plunge reverses midway through ML 11 before returning to a shallow southwestern plunge again near the boundary of ML 12. From ML 12 to the northeastern end of ML 13, the folds are shallow southwest to horizontal in plunge. It was the zone of undulating, near horizontal plunge in ML 12 that formed the central arch of the deposit and which brought the mineralisation closest to the palaeosurface, within reach of the surface weathering processes.

The BHP Synform, located on the southeastern side of the deposit, was best developed in the region near the boundary of ML's 11 and 12. 2L mineralisation was restricted to a thin, dismembered segment preserved within the keel of the synform and formed a vertical to steeply dipping shoot within the fold keel.

A narrow 'sheet' of sheared mineralisation projected upwards from the common limb area and it is mainly this material, with a small component of antiformal hinge ore that outcropped in ML 12, producing the prominent coronadite outcrop of the original "broken hill". This fold hinge only reached the surface over a maximum strike length of approximately 720 metres in ML's 12 and 13.

THE BLOCK 14 MINE (ML 14)

3L is the only significant orebody to occur in ML 14, where it is expressed as high grade rhodonite-bustamite mineralisation containing large masses of sulphide-poor rhodonite-bustamite. The size of the orebody increases through ML 14 and into ML15, to reach its greatest size near the northeastern boundary of the former ML. The development of rhodonite-bustamite is also greatest in this region. 2L does not outcrop in this area and is thin and attenuated throughout.

The geometry of 3L is simple in ML 14, lacking the convolutions and intense shearing of the BHP Antiform and BHP Synform to the southwest. The geometry of the orebody is mainly controlled by a single broad, tight antiform which comes into prominence in the northeast of ML 13 and then persists into ML 15. The relationship between this structure and the BHP Antiform is unclear at present and for convenience it is referred to here as

the British Antiform. A complementary tight to isoclinal synform lies to the south of and parallel to the British Antiform and is referred to here as the British Synform. The synform is poorly developed and is highly modified by shearing along the southeastern margin of the orebody. Shearing is particularly focussed in the common limb of the two folds. The axes of the British Antiform and British Synform are generally horizontal but undulate in plunge from shallow southwest to shallow northeast. From near the boundary with ML 15, the plunge becomes progressively steeper to the northeast until the orebody is truncated at depth by the Thompson Shear.

3L mineralisation is mostly focussed in the northwestern limb of the British Antiform in the southwest of ML 14 but gradually migrates across the fold hinge to the northeast, crossing the hinge in the region of the ML 14-15 boundary. 3L is thus "draped" across the hinge of the antiform, while defining both the southern and northern limbs of the fold. As it approaches the northeastern boundary of ML 14, the main mass of 3L enters the hinge of the British Synform, just south of the position where the Thompson Shear truncates it. 2L mineralisation is only preserved on the 1 Level of the British Mine within the keel of the British Synform and is sheared out at depth by the Thompson Shear on the northeastern boundary of the mine. The hinge of the British Antiform remains at depth throughout ML 14 and 15.

THE BRITISH AND JUNCTION MINES (ML 15, 16 AND 39)

As in ML 14, the British Synform and the British Antiform are a major controlling factor on the orebody geometry in ML's 15, 16 and 39. However, the folds progressively steepen in plunge to the northeast of ML 14, reaching 40° in the centre of ML 15 and 60 degrees at the northeastern boundary of ML 16. The increased plunge of the orebodies results in a rapid decrease in the occurrence of lode rocks and mineralisation at surface.

Midway through ML 15, two shear/fault structures known as the Thompson Shear (D3A) and the British Fault (D4) develop and they have a significant effect on the geometry of 3L and 2L; producing a sharp northerly change in the strike of the lodes which commences on ML 15.

The Thompson Shear, which is a broad tabular, slightly sinuous, steep easterly dipping structure comes into prominence on the southeastern side of the orebodies in ML 14 and persists well into the North Mine area (northeast of ML 16 and 39). It intersects the folded geometry of the orebodies at a low angle (approximately 30 degrees) and produces a 300 metre, northeasterly (sinistral) horizontal offset in 3L and 2L, where they lie within the hinges of the British Antiform and Synform. The northeast block is displaced approximately 350 metres vertically, in a reversed sense. A dislocated block of rhodonite-rich 3L ore, variably referred to as the British Orebody (Boots 1972) or the British Shoot (Henderson, 1953) and probably consisting of a dislocated segment of the British Synform contained in this shear zone was mined as a separate orebody.

Subsequent development of the easterly dipping (65° to 85°) British Fault produced 100 metres of apparent strike slip offset in the Thompson Shear and may have produced some vertical displacement as well. Yet, while the multiple planes of this fault may have produced significant reversed, northeast block up movement between the North Mine area and the Central Region (BHP-Block 14 area), the majority of the structural attenuation and offset in 3L and 2L was present before the fault developed.

STRUCTURE OF ML 16 AND THE SOUTHWESTERN NORTH MINE

Isoclinal folds dominate the geometry of 2L and 3L northeast of the Thompson Shear. However the fold geometry's are suppressed and the orebodies have a strongly lenticular shape which has been described as a flat sheet by workers such as Hobbs (1966). Folds become more evident below the North Mine 12 Level and are particularly well developed between the 23 and 27 Levels and in the Fitzpatrick Orebody on the 36 Level. Intense shearing destroys all fold geometry below the 29 Level to the 34 Level and at depth below the 36 Level.

The orebody geometry that is observed in outcrop and in the upper levels of the North Mine is controlled by transposed isoclinal folds which represent the direct continuation of those that occur in ML 15 southwest of the Thompson Shear. A similar fold geometry is evident in the shear bounded fold structures that occur at depth in the British Mine.

The reversed movement of the Thompson Shear resulted in 3L and 2L being uplifted in the Browne Shaft-North Mine area (ML 39), relative to the southwestern block and therefore brought closer to the surface than they were in the Block 14 and British Mine areas.

CLOSING STATEMENT

Previous workers have identified a single fold pair, known as the Eastern Syncline and the Western Anticline, that were interpreted to extend the entire length of the Broken Hill deposit (eg. Gustafson et al, 1950; Laing et al, 1978). The present work does not support this interpretation but instead shows that there is a series of asymmetric folds throughout the length of the deposit. The results of the present work more closely resembles the structural interpretation of Lewis et al (1965) who also recognised the multiple fold pattern in the South Mine. It is suggested that cross sectional interpretations of the orebodies can give the impression that only a single antiform-synform pair are present in the Broken Hill orebodies. However from surface maps and geological plans constructed from mine level mapping reveal the true complexity of the structures within the orebodies.

Also, previous workers have interpreted a single shear structure; the Main Shear, extending for the entire length of the deposit and marking its southern side (eg. Andrews 1922; Gustafson et al, 1950). This interpretation is overly simplistic and there is a complex shear array throughout the Line of Lode, the geometry of which appears to be controlled in part by the geometry of the pre-existing folds developed within ore and the wall rocks.

REFERENCES

- Andrews, E C, 1922. The Geology of the Broken Hill District. *New South Wales Geological Survey Memoir 8*. 432 pp, (Department of Mines: Sydney).
- Boots, M K, 1972. *The Textural, Mineralogical and Chemical Effects of Retrograde Metamorphism on the Main Lode Horizon, Broken Hill, NSW*, PhD Thesis (unpublished), University of New South Wales.
- Gustafson, J K, Burrell, H C and Garretty, M D, 1950. The Geology of the Broken Hill Ore Deposit, Broken Hill, NSW, Australia, *Bulletin of the Geological Society of America*, 61:1369-1438.
- Henderson, Q J, 1953. North Broken Hill Mine. In Edwards A B, (Ed.), *Geology of Australian Ore Deposits*, pp 627-649, 5th Empire Mining and Metallurgical Congress, Australia and New Zealand (The Office of the Congress and the Australasian Institute of Mining and Metallurgy: Melbourne).
- Hobbs, B E, 1966. The Structural Environment of the Northern Part of the Broken Hill Orebody. *Journal of the Geological Society of Australia*, 13:315-338.
- King, H F. and O'Driscoll, E S, 1953. The Broken Hill Lode. in *Geology of Australian Ore Deposits*. Fifth Empire Mining and Metallurgical Congress- Australia and New Zealand (Ed: A B Edwards), Volume 1, pp. 578-600 (The Office of the Congress and the Australasian Institute of Mining and Metallurgy: Melbourne).
- Laing, W P, Marjoribanks, R W, and Rutland, R W R, 1978. Structure of The Broken Hill Mine Area and its Significance for the Genesis of the Orebodies, *Economic Geology*, 73:1112-1136.
- Lewis, B R, Forward, P S and Roberts, J B, 1965. Geology of the Broken Hill Lode, Re- interpreted in *Geology of Australian Ore Deposits*, Eighth Commonwealth Mining and Metallurgical Congress-Australia and New Zealand, (Ed: J McAndrew), pp. 319-332, (The Office of the Congress and the Australasian Institute of Mining and Metallurgy: Melbourne).

COPPER-GOLD SYSTEMS IN THE WILLYAMA SUPERGROUP OF THE BROKEN HILL DOMAIN, CURNAMONA PROVINCE

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Two copper-gold systems with economic potential are recognised in the Proterozoic Willyama Supergroup of the Broken Hill domain (Broken Hill, Euriowie and eastern Olary Blocks in New South Wales):

- ◊ *Epigenetic syn- to late-tectonic stratabound (to transgressive) Fe-Cu-Au* and
- ◊ *Epigenetic structurally-controlled post-tectonic vein Cu-Au/ Au.*

Both systems post-date peak high-grade metamorphism and are related to probable D3 tectonism at about 1590-1580 Ma (early Mesoproterozoic, late Olarian Orogeny), and ~450 Ma (Ordovician, Delamerian Orogeny), respectively. Both types are compatible with descriptive metallogenic deposit classes recognised by the Geological Survey of NSW (Barnes 1988a, b, Burton (1994, in prep.).

The Mesoproterozoic *epigenetic syn- to late-tectonic stratabound (-transgressive) Fe-Cu-Au* system generates mineralisation with affinities to recent discoveries in the Olary Block (eg Portia, Kalkaroo) (cf Skirrow and Ashley 1998). Major characteristics of the type are:

- ◊ Cu-Au (Mo, Co, As, Ag, $\pm$ U, $\pm$ REE) metals signature;
- ◊ Vein, breccia and stockwork forms;
- ◊ Structural control in shears and dilational settings;
- ◊ Moderate-high to moderate-low temperature K-Fe alteration (especially magnetite/ hematite, with variable biotite, feldspar, chlorite, sericite);
- ◊ Syn- to early post-tectonic timing for the alteration and Cu-Au veining (~1590-1580 Ma) (ie interpreted syn- to post-D3 deformation; cf Skirrow et al 2000).

The mineralisation favours magnetite/ hematite ironstones and iron formations of various types as suitable rheological and reductant hosts within the sequence. They include related syn-tectonic early alteration ironstones (eg Copper Blow), possible pre-metamorphic stratabound ironstones (eg some "Great Eastern type" deposits), stratabound magnetite-bearing metasediments or albitites (eg Grid 4 or Mundi Mundi Prospect; cf Skirrow et al 1999), and syn-sedimentary bedded iron formation ("Sisters type" deposits). Deposits of the type are prospective for Cu, Au and/or Cu-Au.

The stratabound Cu-Au mineralisation displays syn- to late tectonic K-Fe ($\pm$ Na) high-temperature alteration (magnetite/ hematite, K $\pm$ Fe silicates, Fe-Na-Ca silicates, $\pm$ Cu-Au), and/or syn- to late-tectonic K-Fe lower temperature alteration (hematite/ magnetite, chlorite-sericite, $\pm$ Cu-Au). The latter style of alteration and mineralisation dominates in the Broken Hill and Euriowie Blocks in brittle-ductile to brittle regimes (later and/or distal to fluid sources), and the former style is common in the Olary Block in brittle-ductile regimes (earlier and/or proximal). Both styles typically generate enhanced magnetic signatures, although hematitic alteration with minimal magnetic signature is also known.

The stratabound Cu-Au mineralisation is concomitant with significant regional tectono-thermal events in the Curnamona Province, including post-peak metamorphism deformation (interpreted to be D3) and associated moderate-grade metamorphism, regional felsic magmatism (Benagerie Ridge volcanics and probable associated intrusives at ~1590-1580 Ma), and regional alteration events at ~1580-1590 Ma (cf Skirrow et al 2000). Fluid sources are interpreted to be tectonothermal, including probable magmatic hydrothermal and metamorphic components, with the former significant in the Olary Block and the latter more dominant in the Broken Hill domain.

There is potential in the Broken Hill domain for economic stratabound Cu-Au deposits and the region is significantly under-explored for this deposit type. Magnetic features indicative of late magnetite (K-Fe $\pm$ Cu-Au mineralisation?) alteration are widely evident in magnetic data from the eastern Olary Block in NSW (Mundi Mundi Plain area, overprinting early stratigraphically-controlled albite-magnetite alteration), and in parts of the Broken Hill and Euriowie Blocks (eg anomalies similar to Copper Blow). Conceptual targets related to key structures active during alteration and mineralisation, favourable dilational sites, and favourable hosts ($\pm$ magnetic features) are also apparent, permitting targeting of weakly- to non-magnetic (hematitic) targets.

The stratabound Cu-Au mineralisation displays some features similar to the worldwide hydrothermal Fe oxide-Cu-Au ($\pm$ U, Ag, REE) class (eg Ernest Henry, Olympic Dam, La Candelaria) (cf Conor 1996). These include metals signature, association with Fe oxide ($\pm$ K, Na, Ca) alteration, structural control, and geological setting.

The *epigenetic structurally-controlled post-tectonic vein Cu-Au/ Au* deposit type is widely known from the Broken Hill and Olary domains, with characteristics of veins in late brittle dilational structures (Barnes 1988a, b, Burton 1994, in prep., Ashley et al 1998). They have simple quartz-sulfide ($\pm$ carbonate) assemblages as vein and vein breccia infill, associated restricted chlorite-sericite ($\pm$ silica) alteration, and post-tectonic, post-Adelaidean timing (Delamerian). The post-tectonic Cu-Au/ Au veins are unlikely to develop significant Cu resources, but their potential for Au is good and significantly under-tested. Extensive vein systems of the type have variable but common high gold grades (> 10 gpt Au), and most are not systematically drilled.

The potential for gold in the Broken Hill domain extends to Broken Hill type Pb-Zn-Ag deposits (review in Webster 1991). The Broken Hill Main Lode is a major Au producer (>700 koz) from a grade of ~ 0.2 gpt Au in the sulfide lodes. Significantly anomalous zones (>1 gpt Au) also occur on the orebody margins and in host garnetites and siliceous lodes, as metals remobilised from the sulfides or externally introduced to the system, during post-sulfide orebody tectonism and metasomatism.

Mineral deposits of all types, and the Broken Hill domain in general, are inadequately sampled for Au, and the real potential for gold-only mineralisation in the domain is poorly known.

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REFERENCES

- Ashley, P.M., Conor, C.H.H., Skirrow, R.G., 1998. Geology of the Olary Domain, Curnamona Province, South Australia. Field Guidebook to BHEI excursion, 13-15 October 1998. *Report and CD - Primary Industries and Resources SA*.
- Barnes, R.G., 1988a. Metallogenic studies of the Broken Hill and Euriowie Blocks, New South Wales. 1. Styles of mineralisation in the Broken Hill Block. *Geological Survey of New South Wales, Bulletin 32(1,2)*, 1-116.
- Barnes, R.G., 1988b. Metallogenic studies of the Broken Hill and Euriowie Blocks, New South Wales. 2. Mineral Deposits of the southwestern Broken Hill Block. *Geological Survey of New South Wales, Bulletin 32(1,2)*, 117-250.
- Burton, G.R., 1994. Metallogenic studies of the Broken Hill and Euriowie Blocks, New South Wales. 3. Mineral Deposits of the South-Eastern Broken Hill Block. *Geological Survey of New South Wales, Bulletin 32(3)*.
- Burton, G.R., in prep. Metallogenic studies of the Broken Hill and Euriowie Blocks, New South Wales. 4. Mineral Deposits of the Euriowie Block (including the northernmost Broken Hill Block and Poolamacca Inlier. *Geological Survey of New South Wales, Bulletin 32(4)* (in prep.).
- Conor C.H.H., 1996. Curnamona, Moonta and Cloncurry: Common styles of alteration and mineralisation linked by the Diamantina Orogen. In Preiss WV (compiler): Resources '96 Convention Abstracts. *Department of Mines and Energy, South Australia*.
- Skirrow, R.G. and Ashley P.M., 1998. Copper-gold mineral systems and regional alteration, Curnamona Craton. *Broken Hill Exploration Initiative - Abstracts from 1998 Annual Meeting. AGSO Record 1998/025*, 104-108.
- Skirrow, R.G., Ashley, P.M., Conor, C., McNaughton, N. and Katz Suzuki, 2000. Metallogenic framework for Cu-Au and regional alteration systems of the Curnamona Province: Geological, Re-Os and U-Pb age dating, and stable isotopic constraints. *Broken Hill Exploration Initiative. Abstracts from 2000 Annual Meeting, Broken Hill, May 2000*.
- Skirrow R.G., Maas, R. and Ashley P.M., 1999. New age constraints for Cu-Au(-Mo) mineralisation and regional alteration in the Olary-Broken Hill region. *AGSO Research Newsletter 31*.
- Willis, I.L., 2000a. Copper-Gold Systems in the Willyama Supergroup, Broken Hill Domain, NSW. *Geological Survey of New South Wales, Report GS 2000/085*.
- Willis, I.L., 2000b. Field notes on copper-gold mineralization in the Willyama Supergroup of the Broken Hill domain, NSW. *Geological Survey of New South Wales, Report GS 2000/086*.
- Webster A.E., 1991. The search for gold in the Broken Hill Mine Sequence. *James Cook University, Department of Geology (unpublished manuscript)*.