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Predictive Mineral Discovery Cooperative Research Centre

Extended Abstracts from the April 2006 Conference

A.C. Barnicoat and R.J. Korsch (Editors)

Record
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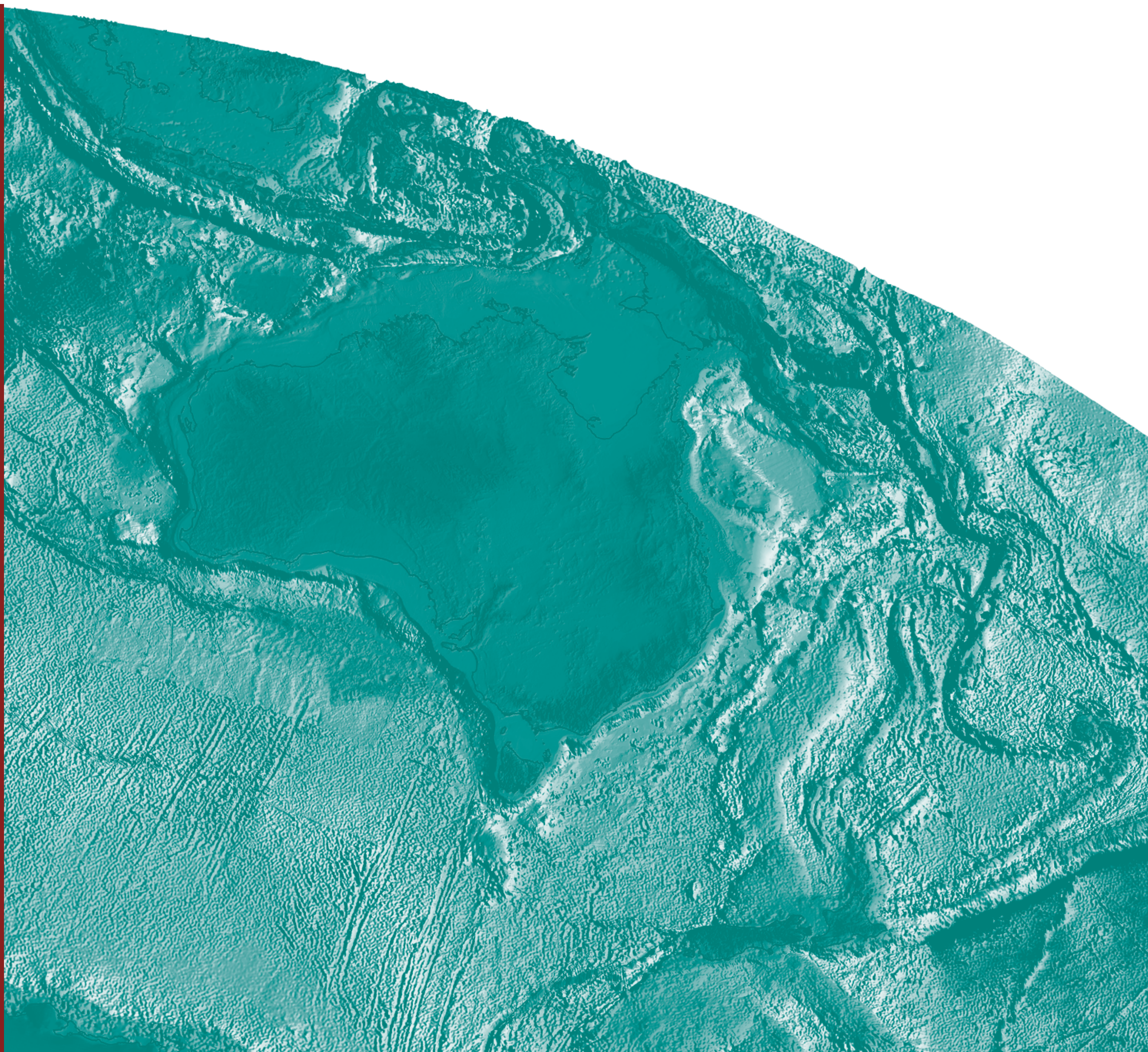

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Preface

The Predictive Mineral discovery Cooperative Research Centre (pmd*CRC) was established under the auspices of the Commonwealth Government's Cooperative Research Centres Program in 2001. The purpose of the pmd*CRC is to generate a fundamental shift in mineral exploration practice and cost-effectiveness by developing a vastly improved understanding of mineralising processes and a four dimensional understanding of the evolution of the geology of mineralised terranes.

Specific objectives of the pmd*CRC are to:
Contribute to the resolution of the key areas of uncertainty in current models for the formation of major economic mineral deposit types within mineralised terranes that have a high exploration priority.
Build 3D and 4D images and histories of well known mineralised systems.
Create a computational environment to simulate the 4D evolution of mineral systems with the goal of developing predictive capabilities for the location and quality of superior ore deposits.
Transfer these concepts, skills and technologies into the mineral exploration industry to assure a long-term competitive advantage to the industry.

The partners in the pmd*CRC are
CSIRO Division of Exploration and Mining
Geoscience Australia
James Cook University
Monash University
University of Melbourne, and
University of Western Australia.

The pmd*CRC is currently sponsored by 19 mineral exploration companies and state geological surveys.

This volume contains extended abstracts for oral presentations at the pmd*CRC's conference 'Science at the Sharp End' held on 19-20 April 2006.

For further information on the pmd*CRC, visit the website at www.pmdcrc.com.au.

Regional scale architecture – 3D maps, models and minefields

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3D Maps of the Mount Isa Inlier – why?

Exploration for new mineral deposits partly involves understanding what the sources of metals were, how they were being transported and why and where they concentrated in spatially limited volumes within the crust. The pmd*CRC's '5 Questions' methodology, based on the systems approach often seen in the petroleum industry necessitates an understanding of the structure or architecture of a terrane as part of the context for the plumbing system that links more or less deep sources of fluids and metals to depositional sites to form orebodies in the upper crust.

By building 3D maps, we enhance our knowledge about the geometry or architecture of the system, i.e. the fluid flow pathway as well as the potential geological controls on where deposit may form. In a few words, building 3D architectural maps of a terrane allows for integration and reconciliation of our knowledge, pin points the areas where knowledge is missing or still highly interpretive and also provides the framework within which proposed mineralising processes can be tested.

This part of the I7 project proposes to reconcile the different maps that have been built over the years, including some unpublished work resulting from research undertaken through the Australian Geodynamics CRC, to test our understanding of the architecture of the Mount Isa Inlier and provide the geometrical framework for fluid flow modelling at the scale of the terrane or at least mineral province. At the same time, integrating current research results of other projects modules in to this architecture may help to test proposed interpretations. This is particularly the case with the I7 research concerning the east-west correlation across the Inlier, which has so far successfully been carried out in 2D (maps and cross-sections).

How do we build the 3D maps – Minefields!?

The 3D maps presented are built following the flowchart developed by Henson (2006) at Geoscience Australia (Figure 1). It should be noted, however, that most of the modelling (i.e. knowledge and data integration) is being done during the cross sections and solid geology building phase. The cross sections are east-west and are built with a constant spacing of 10km. Figure. 2 shows the distribution of the sections as well as the areas where 3D maps are or have been built over the Mount Isa Inlier. Each cross section was tested against 2.5D forward modelling of the magnetics. This essentially constrains the dip of the major faults and structures. Worming of both the gravity and magnetics dataset was also used to qualitatively constrain the direction of dip of the major faults.

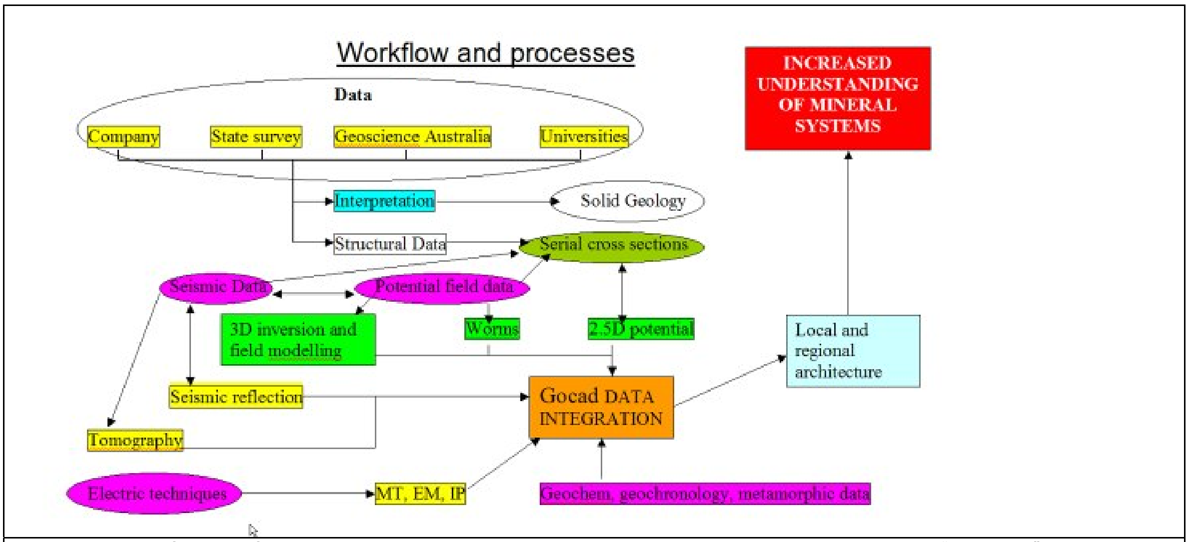

Figure 1: Modified workflow and data integration during 3D maps building (Henson, 2006). The “modelling” or integration involves rationalising the solid geology and the serial cross sections. Geophysical datasets are used to constrain the geometries produced in the third dimension.

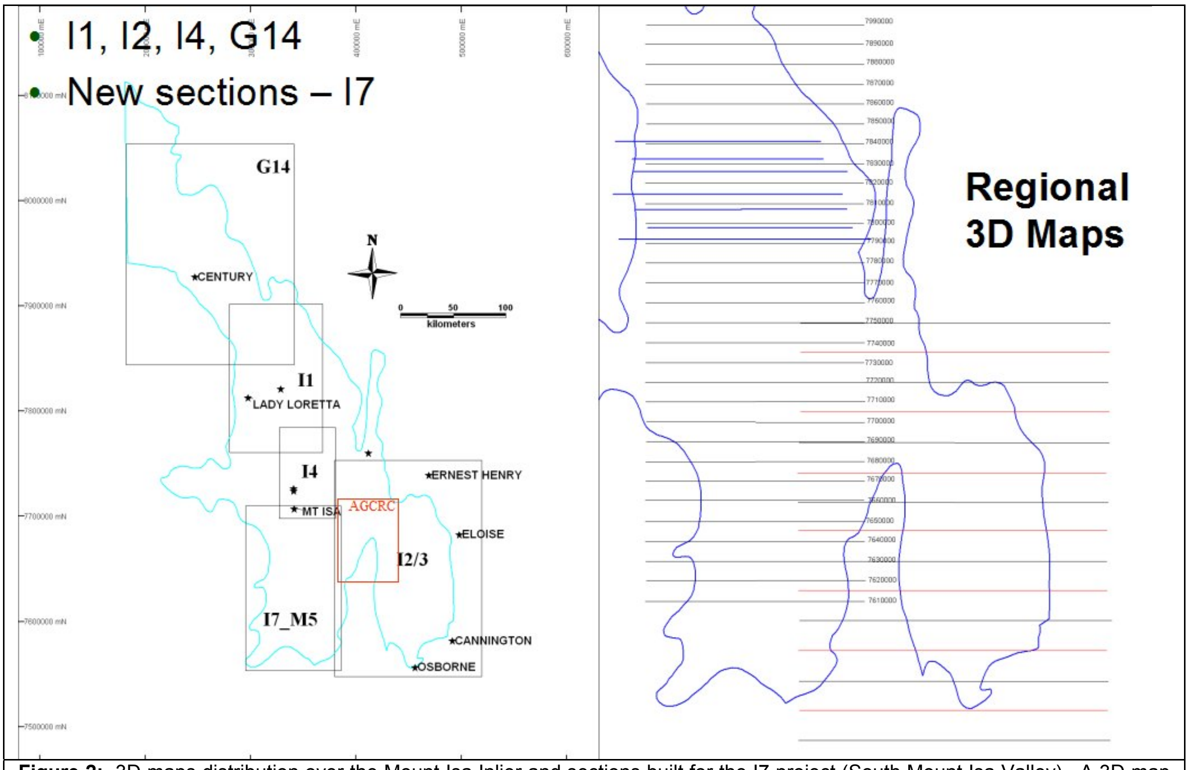

Figure 2: 3D maps distribution over the Mount Isa Inlier and sections built for the I7 project (South Mount Isa Valley). A 3D map of the Mitakoodi culmination built during the Australian Geodynamics CRC is being contributed to the project (in red; O’Dea *et al.* 2006).

Results so far…

Figures 3 and 4 show the current state of the model. The main outcome so far is to confirm how complicated and deep the plumbing systems could have been at the time of mineralisation. This may vary with differing metal systems and should be tested through simple (but realistic) numerical models at varying scales (mine to regional).

The 3D map also shows that the early basin architecture (basement geometries at time of deposition) is still controlling the present day geometries, even after deformation during the Isan orogeny (Betts et al., 2004 and references therein). There is no obvious detachment between basement and hosted basins, including in the Eastern Succession, which may have experienced larger scale horizontal translation with shortening and thrusting.

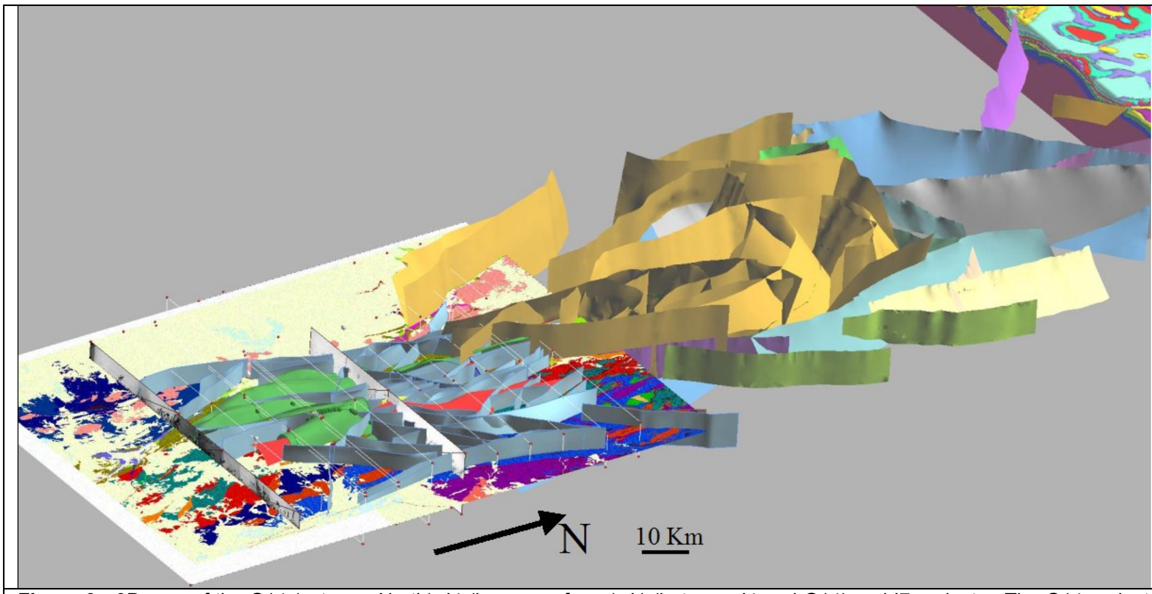

Figure 3: 3D map of the G14 (extreme North), I4 (brown surfaces), I1 (between I4 and G14) and I7 projects. The G14 project is developed within the pmd*CRC on a 1:1 collaboration with Zinifex. The G14 map was built using 3D Geomodeller. At the southern end of this image, the geological map shows the extent of the "in-progress" I7 3D map. The section spacing is also visible.

What is next?

Building 3D maps should be done with a purpose, for example, as a test for some of our interpretations, or as a tool to help with integration of varied datasets to produce a framework for further modelling and hypotheses testing (e.g. coupled fluid and mechanical modelling to distinguish between prospective and non-prospective areas – i.e. was the plumbing system developed enough to produce mineralised systems).

In the short term, the models will be rationalised with the results of the east-west correlation group in order to test in 3D the proposed basinal/rifting histories and resulting basins architectures.
The following surfaces will be specifically mapped in 3D:

- Base of the Leichhardt Superbasin Rift (Mt Guide Quartzite/Myally/Eastern Creek Volcanics)
- Base Leichhardt Superbasin Sag Phase (Quilalar Formation)
- Base Calvert Superbasin Rift (Bigie/Prize/ Fiery Creek Volcanics)
- Base Calvert Superbasin Sag (Gun)
- Isa Superbasin (base River)
- Base South Nicholson / Roper Group
- Base Cover (Cambrian)
- Base post-Palaeozoic/Recent

Note that this list also includes potential aquifers and seals at time of mineralisation (Mt Guide Quartzite and Bigie and equivalent formations.
Lastly, most 3D maps are highly interpretive and more constraints have to be built into them. There is a definite need for more geophysical modelling, for example, geologically and petrophysically constrained inversions and fault dip sensitivity analysis versus magnetics.

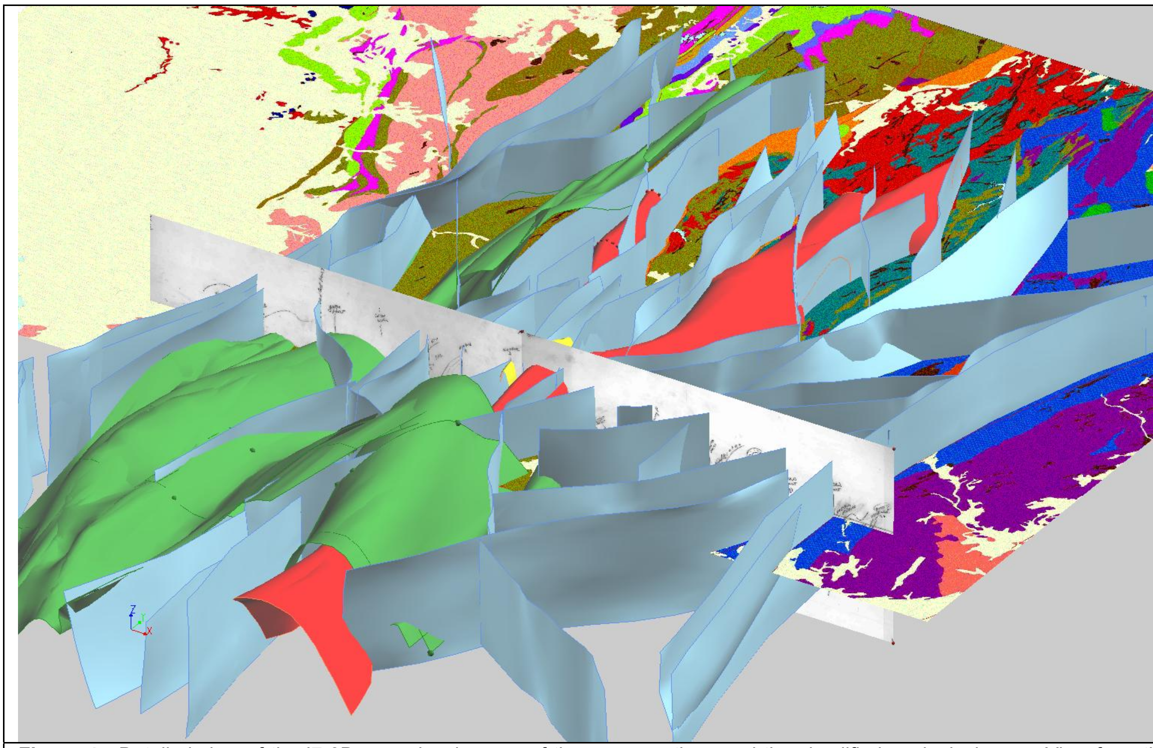

Figure 4: Detailed view of the I7 3D map showing one of the cross-sections and the simplified geological map. View from the southeast.

Acknowledgements

We would like to thank the Geological survey of Queensland and particularly Laurie Hutton for his comments/suggestions about some of the interpretations. Lawrence Leader was instrumental during the modelling of the Lawn Hill platform (G14 project).

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Science, the 5 Questions and Exploration

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Background

The pmd*CRC has followed the Australian Geodynamics CRC in using the ‘5 Questions’ as a background for understanding mineral systems. These questions, concerning the geodynamic setting, architecture, fluid reservoirs, flow paths and drivers, and processes of transport and deposition, provide a cross-disciplinary, cross-scale framework that ensures consideration is given to the context of a mineral system as well as its more obvious manifestations of alteration and mineralisation. Answers to the five questions can provide understanding that informs the exploration process at a range of scales. In selecting an appropriate province in order to explore for some form of gold system, for example, the answers to questions on the geodynamics and architecture are going to be of much more relevance than those on deposition. Conversely, in the search for a new ore shoot on an existing property where the presence of a successful system is proven, answers about geodynamics will be irrelevant but those about (detailed) architecture and deposition will be of paramount importance.

The mineral systems paradigm, exemplified by the ‘5 questions’, provides a means of moving beyond the source-transport-trap-paradigm that has been ported in a somewhat careless fashion from hydrocarbon exploration. The source transport-trap model has a number of weaknesses:
It ignores the geodynamic and geological context of ore formation in its bald form,
It conflates the sources off fluids, metals and sulphur, often resulting in an unsuccessful focus on metal sources alone,
It implicitly links fluid flow pathways and drivers, and
It perpetuates the vision of ores being ‘trapped’, though in the case of ore systems orders of magnitude more material flushes through than is retained at the depositional site.
Of course a thorough application of source-transport-trap could circumvent all of these objections, but the ‘5 questions’ enforce consideration of these issues and so provide, in my view, a far superior structure within which to analyses mineral systems.

Although the ‘5 questions’ facilitate describing mineral systems, do they provide a means by which we can explain (and hopefully predict) ***giant*** mineral systems? The remainder of this paper is devoted to showing how the origin of giant deposits can be related to the ‘5 questions’.

Some Fundamental Relationships

Phillips (1990, 1991) has shown that the rate of mineral deposition is given by the expression

$$\boxed{\text{Rate of mineral deposition}} \;\boxed{=}\; \boxed{\text{Fluid velocity} \cdot \text{Rate of change of solubility with P, T, C} \cdot \text{Gradient of P, T, X}} \qquad (1)$$

This expression shows that maximising (i) fluid flow velocity, (ii) the pressure (P), temperature (T), and composition (C) where the largest changes in solubility occur and (iii) temperature, pressure and compositional gradients will maximise the rate of mineral deposition.

A second expression

$$\text{Fluid velocity} = \frac{k\rho g}{\mu}\ \text{Gradient in hydraulic potential} \qquad (2)$$

relates the fluid flow velocity to the permeability (k), fluid density (ρ), gravity (g), fluid viscosity (μ) and the gradient in hydraulic potential.

A third relationship is needed to complete the analysis:

$$\text{Total quantity of mineral deposited} = \int \text{Rate of mineral deposition. } dt \qquad (3)$$

The amount of mineral deposited is, from expressions (1), (2) and (3), proportional to:
Gradient in hydraulic potential

- Time
- Permeability
- Rate of change in solubility with P, T & C
- Spatial gradients of P, T & C (strictly ∇P, ∇T, ∇C).

The amount of mineral deposited is also inversely proportional to:

- Fluid viscosity.

These parameters are formally independent of one another and are, in addition, independent of any specific processes. This has the benefit of removing bias as to critical parameters from any analysis.

How do the parameters derived from this perspective relate to the '5 questions'?

5 questions and the Fundamental Relationship

The '5 questions' each feed in to the key parameters listed in the previous section (Figure 1). This shows that there is a clear mapping between the 5 questions and the parameters derived from the fundamental relationship. A further consideration of these links reveals that the most fundamental controls are exerted by the geodynamic setting and the architecture. The former controls, very largely, the available fluid reservoirs and the pathways and drivers available to allow the tapping of the reservoirs. The geodynamic setting also controls the location of the maximum rates of change in solubility with respect to P, T and C, and in combination with the architecture defines the spatial gradients in P, T and C. The structural and stratigraphic architecture also defines the distribution of permeability.

Using the Analysis

This analysis of the origin of giant ore systems yields a clear rationalisation for many observations. For example, think about the role of pressure gradients, which can be critical for gold deposition in certain environments, as phase separation may be driven by them. Under certain conditions, $\partial Au/\partial P$ (rate of change of gold solubility with pressure) will be high (see Figure 2). When is ∇P (the gradient in pressure) high too? This might be due to fluid release from a magmas body, which will be a transient event, or perhaps more typically, this will be when either an overpressured (sealed) compartment is breached by faulting, or during dilation due to deformation. In either of the later two cases, fluid flow will lead to both a diminution in the pressure gradient and the (re)sealing of the system. ∇P will only have been high when fluid flow velocities were high for a short period of time. Repetition of the deformation event is thus important for attaining high time-integrated values of ∇P and fluid velocity. Such circumstances are especially common when basement structures are present and can be reactivated more readily than new structures can form.

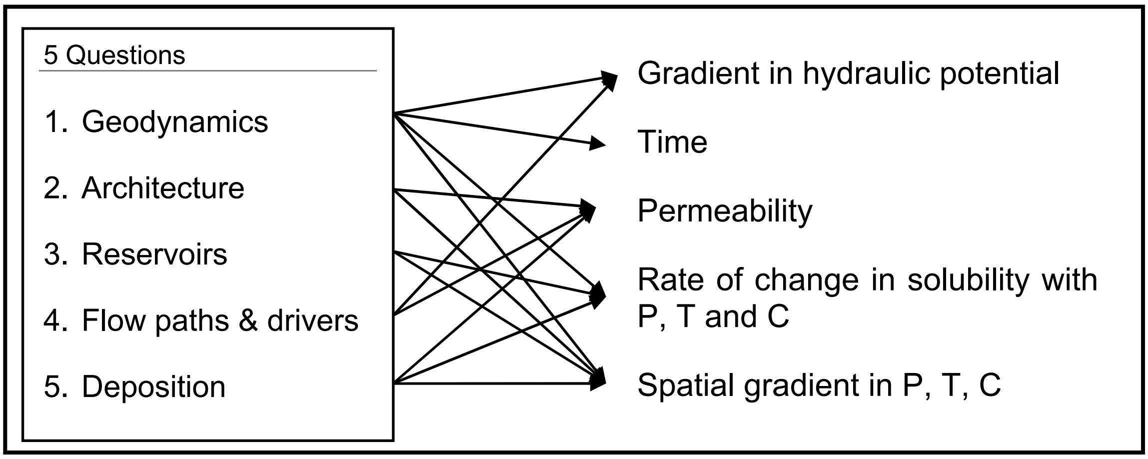

Figure 1: The relationship between the 5 questions and the parameters derived from the fundamental relationship.

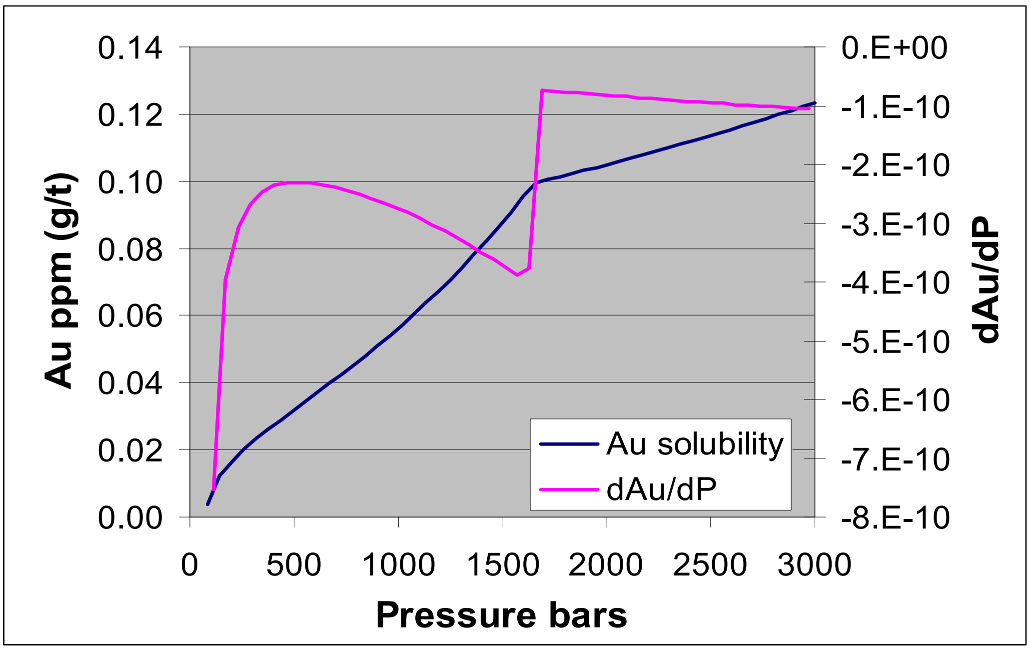

Figure 2: Gold solubility as a function of pressure at 300°in a CO_2-bearing solution with pH controlled by k-feldspar-muscovite-quartz, total S = 0.01m and with redox fixed just below haematite-magnetite. A gas phase separates at about 1600 bars, leading to a decrease in solubility and a change in ∂Au/∂P.

The perspective presented here has a number of advantages. It is phenomenological rather than process based and hence not tied to any specific depositional mechanism. For example, gradients in chemistry may be due to the mixing of fluids, or alternatively to passage from one host lithology into another. Numerical models, especially those simulating chemistry (see Cleverley et al., 2006), may be interrogated to determine the relative magnitudes of different gradients and hence used to evaluate the distribution and controls of such parameters (Figure 3).

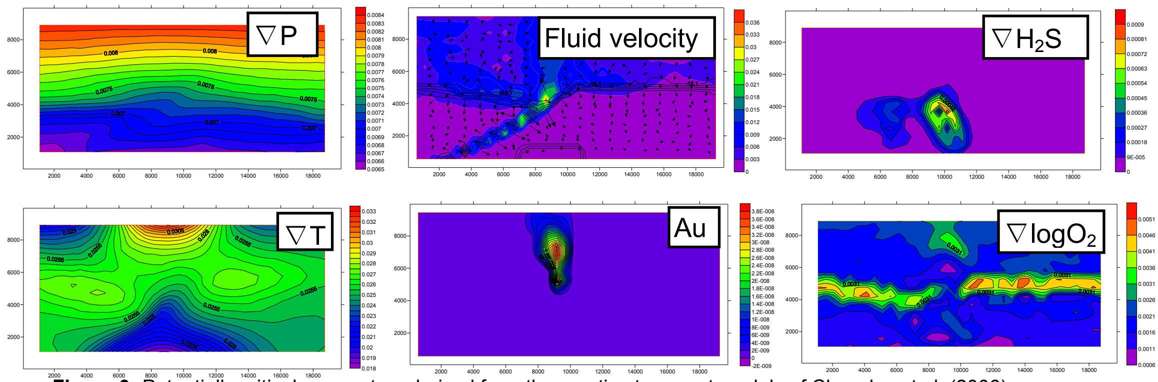

Figure 3: Potentially critical parameters derived from the reactive transport models of Cleverley et al. (2006).

Finally, the independent parameter set this view of mineral systems yields should be well-suited to the development of effective exploration risk analysis.

Acknowledgements

Mark Duffett (NTGS) asked the question about how we could explain giant mineral systems, and this sparked the train of thought that lead to this paper. I owe a great debt to Bruce Hobbs for providing the intellectual framework I have exploited, to John Walshe, Alison Ord, Heather Sheldon, Paul Roberts, and Greg Hall and Scott Halley (of the late, lamented Placer Dome) for conversations on related topics, and to everyone in the pmd*CRC for the observations and ideas I have used.

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Concepts to targets: a scale integrated mineral systems study of the Laverton region, Yilgarn Craton WA.

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Introduction

The general mineral exploration industry perception regarding the prospectivity of the Yilgarn Craton is that the next world-class ore deposit is likely to be undercover and at depth. To be successful undercover and at depth, the explorationist need targets (not just anomalies), and these are most effectively defined by the integration of multiple datasets and the identification of targets based on a number of supporting criteria (Bavinton, 2004).

The Y4 project of the *pmd**CRC has been developing a scale-integrated understanding based on many criteria that are characteristic of the Yilgarn's orogenic gold mineral systems. We have integrated a number of concepts across the scales (mantle lithosphere of the craton to specific ore shoots in the deposits) using the "five CRC questions", and generated targets at a range of equivalent scales in anticipation of an improved predictability for mineral discovery.

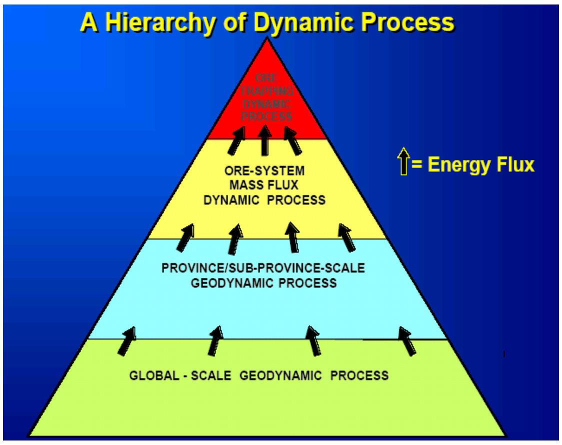

Figure 1: Conceptual view of the hierarchy of dynamic processes operating at a range of scales in the formation of an ore body (after Hronksy, 2004).

Mineral deposits are the focus of large mass and energy transport systems (Hronsky, 2004). They sit atop a pyramid whose geometry is defined by the size of the system's footprint. At the base lie the processes operating at the global scale (e.g., secular change, plate reorganisation, climate, etc), and in the intermediate position lie the processes operating at the province (e.g., delamination, regional tectonic drivers, etc), sub-province (e.g., major fluid pathways), district to camp scales (e.g., subsidiary structures, specific alteration gradients), and finally to the deposit (Figure 1). Fortunately, the larger and more energetic systems have large footprints and these generally equate to bigger ore deposits. This means that the signatures of the system are large and more easily imaged or detected. Despite being able to recognise parts of the system (e.g., breaks in

* The paper is presented as a Y4 team effort and is ordered alphabetically accordingly

Moho tomography), the precise genetic links with mineralisation (apex of the pyramid) remain unclear.

The challenge for the explorer in undercover areas is two fold. Firstly, they must be in the right ground and, secondly, they need to identify prospective drilling targets in a cost effective manner (Harmen, 2004). In this paper we present an integrated view of the orogenic gold mineral system by transforming a series of concepts and hypotheses into targets at a range of scales. From this approach we not only better understand the system in general, but can and do make specific predictions of likely targets in the Laverton area (Figure 2). We suggest that these 'learnings' can be applied to other orogenic gold systems in other terranes.

The following sections will consider a series of concepts and accompanying targets for the orogenic gold mineral system from the two 'ends' of the system's triangle of scale (Figure 1); the lithospheric-province scale at the base and the deposit to specific ore shoot scale at the apex. Between these end-members is the camp or district scale, and it is here that we are relatively data poor and most uncertain about prediction and targeting. The concepts presented here are drawn from Yilgarn papers presented in this volume (Goleby et al., 2006; Henson et al. , 2006; Sheldon et al. , 2006; Chopping et al. , 2006; Miller, 2006; Neumayr et al. , 2006; and Cleverley et al. , 2006) and integrated across scale into a series of targets.

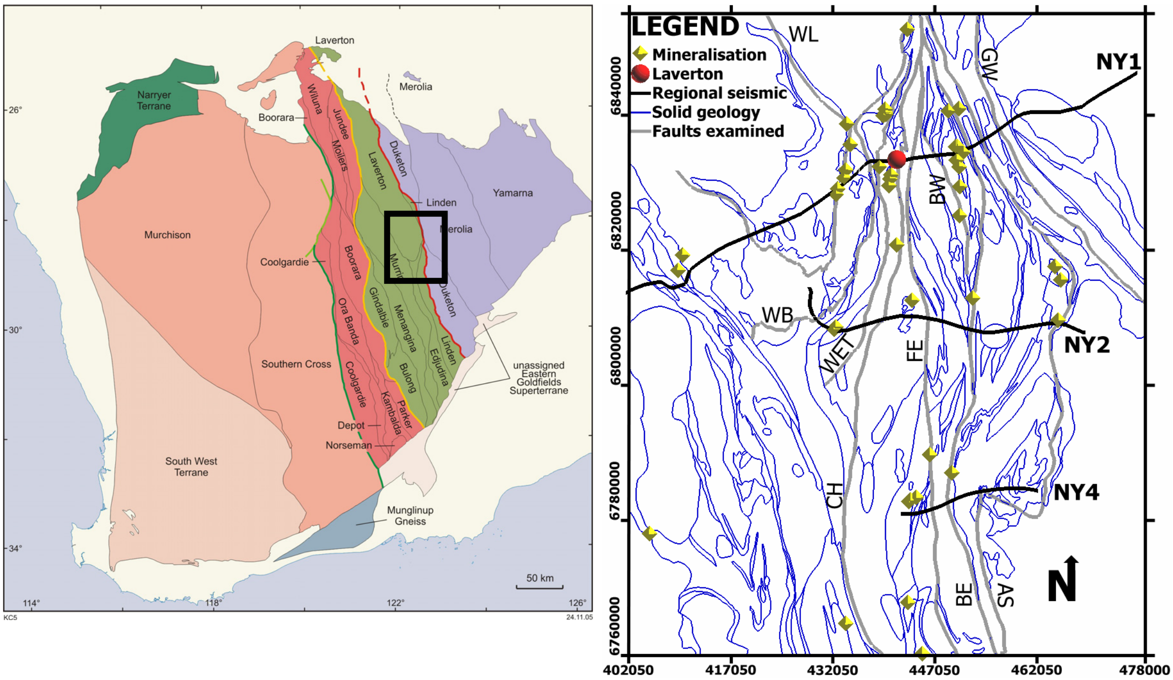

Figure 2: Map of terranes of Yilgarn Craton with Laverton Region shown in the box. Solid geology, mineralisation and regional seismic traverses in the Laverton region. Solid geology after Henson et al (2006). Laverton township is indicated by the filled circle. Coordinates are GDA94, zone 51. Faults: WL – Wallaby Low-Angle Shear, WB – Wallaby Basin, WET – Wallaby East Thrust, CH – Childe Harold, FE – Far East, BW – Barnicoat (West), BE – Barnicoat (East), AS – Apollo Shear, GW – Granite Well

Concepts to targets at the lithospheric and province scales

The Yilgarn Craton has world-class real estate, but a quick glance at a map shows that mineralisation (especially the world-class deposits) is not evenly distributed. There are first-order controls of the fecundity across the craton and these are expressed as very broad signatures. Goldfarb et al. (2004) recently suggested that due to the extreme variability of gold deposits (in detail), observations at the orogen-scale, both lithosphere- and terrane-wide, may be the most useful approach for determining where global giants are likely to be located and also, importantly, where they are likely to be absent.

The province-scale controls are evidenced by signatures in a variety of datasets, such as age of host rock, mantle separation age (T_{DM}), presence of deep crustal-penetrating structures, magmatic type, edges and breaks in mantle shear-wave velocity tomograms, and crustal velocity differences. These datasets are signatures of the largest part of the system and they can be used to infer large-scale geodynamic processes that may account for the special endowment of the Yilgarn Craton.

At the scale of the Yilgarn Craton and its lithosphere, 'targeting' is essentially a 'terrane' selection process. Decisions need to be made about which provinces or terranes of the craton should be targeted. These decisions are linked to a model which may have particular geodynamic settings and specific time periods. The giant deposits in the Archaean across the globe are mostly clustered in greenstone rocks aged between 2720 Ma and 2550 Ma (Groves et al. 2005) and in belts that have relatively juvenile crust (Kerrich et al., 2000), and this time interval marks a global period of new crustal generation. Geochronological maps of the Yilgarn show that the eastern third contains the vast majority of greenstone belts of this age. Maps of the age of mantle separation or crustal maturity show discrete domains across the Yilgarn Craton (Cassidy et al., 2005). The eastern Yilgarn Craton is characterised by relatively younger T_{DM} ages than the Youanmi Terrane (Southern Cross) to the west. These younger T_{DM} ages are indicative of younger crust formation in an active and evolving arc to back-arc system (Cassidy et al., 2006). These data indicate that on a first-order control (crustal age), the most permissive ground for large gold deposits in the Yilgarn Craton is likely to be in the east.

Tomographic images of the lithosphere of the Yilgarn Craton can be interpreted in terms of features and signatures of the largest geodynamic processes (Goleby et al., 2006). The shape and distribution of the 4.8 $km.s^{-1}$ isosurface of the shear-wave velocity in the mantle lithosphere could reflect a relict slab that delaminated and terminated High-Ca magmatism at around 2660 Ma. The slab has a variety of steps, holes and edges whose position, when projected vertically, correlate approximately with the distribution of Archaean (?) and Early Proterozoic mantle-derived magmas such as kimberlites, lamprophyres and carbonatites (see Goleby et al., this volume). An improved 'fit' of these mantle-tracing magmas and the tomographic volume is achieved by adjusting for the late Proterozoic collision of the Albany-Fraser Orogen and the Yilgarn Craton (Goleby et al., 2006). The adjustment is made on the assumption that this Late Proterozoic collision shifted the crust to the northwest by around 100 km from the mantle lithosphere. Once 'adjusted' for this post-Archaean orogenesis, the alignment of the large gold camps and edges (e.g., Kalgoorlie, Laverton) in the tomography are remarkable.

The Laverton region of the eastern Yilgarn is located above a step or boundary in the tomographic volume (Goleby et al., 2006). Lamprophyres, syenites, Mafic-type granites, and carbonatites are present, and these mantle-sourced magmas are a signature of a connection with large-scale mantle processes. A caveat to this relationship is the fact that some of these magmatic rocks have intruded the region as late as ca. 0.85 Ga, questioning the validity for an orogenic 'adjustment' at 1.3-1.1 Ga.

If tomographic steps and associated mantle-derived magmatism are a proxy for locating large deposits, then consideration of other edges and large (high-level) 'worm' anomalies is warranted. The newly discovered Tropicana prospect, which is delivering exciting gold intercepts (Flint, 2006), is located along the major north-south edge of the adjusted tomographic volume.

Extending this concept along the tomographic edge, the country undercover to the east of Yamarna is a new target. The ages of the greenstones are mostly unknown, but the available TDM data for the granites in the area are in the favourable age range of 2.9 Ga to 3.0 Ga (see next section).

Concepts to targets at the sub-province (terrane?) scale

There are second-order provincial controls of the fecundity of one terrane in comparison to another within the eastern Yilgarn Craton. The provincial-scale controls are evidenced in a variety of datasets such as: geological and stratigraphic maps, details in the Sm-Nd isotope maps, presence of 'Late Basins' (Hall, 2005), metamorphic grade (Binns et al., 1976), deep-penetrating shear zones (Goleby et al., 2004), regional domes and anticlinoria (Henson et al., 2005).

Despite many of the terranes of the eastern Yilgarn having the preferred greenstone ages (Cassidy et al., 2006), gold is not equally distributed. An empirical observation highlighted recently by Cassidy et al. (2005) showed that gold is co-located with komatiites. In contrast, although the central Kurnalpi Terrane contains greenstones of the 'right' age range (2.72-2.65 Ga), it contains few komatiites and significant gold mineralisation has yet to be found. This terrane also coincides with a belt of the youngest TDM ages (most juvenile crust), and hosts VHMS deposits (such as Teutonic Bore). Significant province-scale processes are mapped by the metallogenic differences and the Sm-Nd isotope data, despite the 'right' age range for the host rocks. We are presently unsure of reasons for the relationships between komatiites, crustal contamination (TDM), and endowment of gold, nickel, or base metals.

In terms of targeting and area selection, the province-scale datasets of the eastern Yilgarn can be used to quickly focus on regions with TDM ages of 2.9 Ga to 3.0 Ga. These areas include the Kalgoorlie, the far eastern Kurnalpi, and the Burtville Terranes (Cassidy et al., 2006). In addition, the region around Laverton has all of the key attributes for targeting at a province scale, including:

- known large deposits,
- greenstone rocks in the age range (2.72 Ga to 2.65 Ga),
- komatiites,
- mantle-sourced magmas (from 2.66 Ga to <1.0 Ga),
- TDM model ages of (2.90 Ga to 3.00 Ga),
- significant Late Basins (Wallaby and Granny Smith),
- gradients of metamorphic grade indicative of uplift,
- deep-crustal penetrating shear zones (deep fluid pathways?), and
- regional domes.

These areas have greenstones of the 'right' age range, and are located in a region that has had connection to the mantle. Late Basins are relatively thick and the regions where they are thickest are where most of the large deposits are (Bryan Krapĕz, pers. comm., 2005). Hall (2005) stated that all the large gold camps in the Eastern Yilgarn (and elsewhere) are within 1 km of the Late Basin unconformity. In Hall's model, the Late Basins are thought to have provided a basinal fluid and/or operated as a seal to fluid flow and facilitated focussing. These hypotheses have been tested with numerical modelling (Sheldon et al., 2006). Much of the Laverton region is located within this structural-stratigraphic window in three dimensions (see Henson et al., 2006). Many gold camps appear to be hosted by terranes that have undergone rapid uplift and exhumation (Goldfarb et al., 2004). The high-grade metamorphic zones adjacent to regional (granite-cored?) domes (Binns et al., 1976; Ben Goscombe unpublished data) and the rapid drop to lower grades into the surrounding greenstones likely reflects the exhumation and uplift of the evolving orogen. Many of the Late Basins have maximum depositional ages within error of one another and are within error of the age of intruding mantle-derived magmas. These data suggest that exhumation was rapid, the depositional products were the Late Basins themselves, and that the controlling architecture for the entire orogenic gold system was established in extension and that this was earlier than the gold.

Crustal-penetrating shear zones are mapped in deep seismic reflection profiles and are thought to play a role as deep sourced fluid pathways (see Goleby et al., 2006). The known crustal-penetrating shear zones of the Eastern Yilgarn are the Ida Fault System, unnamed structures beneath the Ockerburry Fault System, the Laverton Tectonic Zone (LTZ), and the Yamarna Fault System. The Kalgoorlie Terrane, which is known for the giant Golden Mile deposit as well as many other large deposits, lies between the Ida and Ockerburry Fault Systems. The Yamarna Fault System has been suggested previously as prospective, although other supporting fundamental data are lacking, such as the age of the greenstones. The Laverton region is host to a surface expression of a true crustal-penetrating structure (LTZ), and this is an area worthy of selection and targeting (see also Henson et al., 2006). The deep-sourced fluids likely used these fluid pathways and were further focussed into interlinked dome-like, low-angle shear zones (Henson et al., 2005). This combined geometry is critical in focusing upward moving fluids and subsequent distribution of fluids into the overlying complexly deformed greenstones.

In combination, the above concepts suggest that the Laverton region of the eastern Kurnalpi Terrane is prospective. The region hosts more than 15 Moz Au in just two deposits (Sunrise Dam and Wallaby), so this is true elephant country. Two common questions all of us ask are “why are they there”, and more importantly “where is the next one”? The above conceptual discussion has partly answered the first question. The second question is one of targeting that is best examined at two smaller scales:

- in the mine and near mine environment, and secondly,
- in the Laverton region.

To answer the regional question we will extend our understanding and concepts from the data-rich mine and near mine environment to be predictive for the region. Integration with the understanding and concepts from the broader-scale analysis places the region and its deposits in its geological context. The next section will consider the mine and near mine concepts and predictions for targeting and then follow with a section that makes predictions from this understanding to the camp as a whole.

Concepts to targets at the deposit scale

Miller (2005, 2006) described a structural history of stress switching for the Wallaby and Sunrise Dam deposit and linked this to the regional structural study by Blewett et al. (2004). In both studies it was noted that mineralisation was likely coincident with switches in the palaeostress field. Miller (2006) calculated a stress field based on meso- and micro-scale structural elements at Wallaby (and an equivalent one at Sunrise Dam) with a dominant NNW-oriented contraction at gold deposition time. Warren Potma (unpublished *pmd**CRC work) undertook numerical fluid flow modelling and established that the most likely palaeostress direction for maximum dilation was in fact NNW. Henson et al. (2006) examined the region’s map patterns and inferred a NNW-oriented contractional event to create some of the fault geometries. Mohr circle stress modelling was conducted to examine the relationship between pre-existing and neo-formed fault orientations for a variety of mean stress scenarios (Miller, 2006). A scenario of NNW-oriented contraction correctly predicted the faults which would form under the calculated stress field and those which would reactivate most (be most highly mineralised). These structural insights from careful observation at the mine scale have been extended into the region or camp to predict targets in analogous structural settings (see next section).

Neumayr et al. (2004) noted that regions of chemical gradients (oxidised to reduced) are spatially associated with gold deposits. Mapping of these gradients has proved to be a successful technique for targeting. There is strong evidence for both oxidised and reduced fluids co-existing at the Wallaby and Sunrise Dam deposits. At Sunrise Dam, the elevated As signals the reduced fluids, and the elevated Te signals the oxidised fluids. At Wallaby, the presence of pyrrhotite is the reduced signal, and magnetite/haematite is the oxidised signal. In combination, these contrasting fluid redox/pH states indicate that the deposits formed in domains that are characterised by extreme chemical hydrothermal fluids gradients. Detailed fluid inclusion work and studies of high-grade veins at Sunrise Dam confirm the regional patterns for multiple fluid types (see Cleverley et al., 2006). Stepping this concept of gradients out should provide first pass targets for the Laverton region.

Cleverley et al. (2006) suggested that two fluid types were responsible for mixed mineral assemblages in the high-grade veins of the Sunrise Dam deposit. Micro-scale petrographic evidence suggested that there were redox/pH changes during the evolution from a tourmaline-mica-apatite assemblage (likely related to a deep-sourced carbonatitic fluid) and a carbonate-(quartz)-pyrite assemblage (related to an unknown fluid source). The tourmaline assemblage is located inside quartz veins that record multiple opening events and these assemblages are likely linked to $C0_2$-rich primitive magmas. Melts evolving $C0_2$- and apatite-rich assemblages have also been reported from Wallaby (Drieberg, unpublished report; Miller, 2005). We are still working on the fluids in the system, but it appears from these deposit studies that similar fluids were present at the time of mineralisation. The similarity of fluids between Sunrise Dam and Wallaby and the common architectural framework suggest that region shared a fluid pathway system, or similar source (see also Henson et al., 2006; Miller, 2006).

Concepts to targets at the camp scale

The architecture and the map patterns of the Laverton region are described in Henson et al. (2006) and Chopping (2006). The camp-scale fluid flow and alteration patterns are described in Neumayr et al. (this volume). Miller (2006) has described the structural history of the two principal deposits of the region, the Sunrise Dam and Wallaby deposits. Cleverley et al. (2006) describe fluid mixing at the vein scale, which confirms the concept that more than one fluid was involved (see also Miller, 2005), and that gradients in regional datasets, if mappable, could be used for targeting. The integration of the concepts developed for the structure, fluids and architecture of the Laverton region has led to a series of predictions of targets across the camp. Some of the concepts and hypotheses are being tested through computer simulations by Sheldon et al. (2006).

Neumayr et al. (this volume) used detailed aeromagnetic data to map magnetite-pyrrhotite alteration across the region close to Sunrise Dam and Wallaby deposits. Other examples of the magnetic haloes associated with this type of alteration are also evident in the imagery around Lancefield and Jupiter. The project is attempting to invert this halo using the mineral estimation filter technique of Williams and Dipple (2005) into a 3D predictive volume of rock. Neumayr et al. (2006) also examined the fluid pathways by integrating the PIMA data, HYMAP and geochemical data. These techniques can be used to develop mineral maps that can be interpreted to reflect changes in fluid composition or sources (gradients), similar to those described and successfully applied from St Ives and Kanowna Belle (Neumayr et al., 2004).

Current research aims to produce scale-integrated (mine-scale to district-scale) models of the alteration and architecture of the Laverton region. Preliminary interpretation of the regional-scale data-sets indicates north-south trending pathways characterised by a strong magnetic signature (that does not reflect stratigraphy) over tens of kilometres length scale. These magnetic signatures are interpreted to reflect interaction with oxidised hydrothermal fluids and are aligned along a northwest-trending corridor across the Laverton region broadly spanning the area (the Laverton Tectonic Zone–see Henson et al., 2006) between the Mount Margaret anticline and the Kirgella Dome to the southeast.

The acidic alteration assemblages (e.g., paragonite–ankerite–pyrite±chloritoid-pyrrhotite) are interpreted to represent domains where the deep, reduced fluids in the system have reacted with the ambient fluids (basinal, metamorphic and/or magmatic fluids) that were rock equilibrated. At Wallaby, the Thets and Slaughter Yard thrust faults at the base of the conglomerate packages, and the north-south faults (e.g., Chatterbox, Shocker) have intense acidic alteration developed along them, as mapped with the white mica PIMA 2200 feature. All of the faults away from Wallaby carried acid fluid, and the frequent occurrence of pyrrhotite shows that it is also reduced. The same acidic assemblage occurs also in the Lancefield conglomerate above the Lancefield deposit, and in the Wallaby Basin south of Mount Margaret

The alteration assemblages surrounding the Wallaby deposit are quite different to the alteration signature associated with Thets Fault. In contrast to the paragonite-bearing assemblages along the surrounding faults, all of the white mica proximal to Wallaby is phengitic in composition. This phengitic assemblage is interpreted to reflect a more alkaline (oxidised) fluid composition related to the Wallaby magmatic system. This phengitic region also corresponds to a zone of elevated W-Mo-Bi, in contrast to the As-Sb signature associated with the more acid-reduced fluids along the regional faults. As a consequence, Wallaby is located at a zone of large chemical gradient of mostly acid-reduced alteration and oxidised alkaline alteration. Similar zones of large chemical gradients can be identified along Thets Fault northeast of Wallaby where a domain with below background level As correlates spatially with a higher magnetic response which indicates probably more oxidised fluids adjacent to the general acidic signature, and is a target for the camp scale. The current study will expand the integration of alteration and structural architecture at Sunrise Dam, Wallaby and upscale regionally to identify further prospective targets.

The stress switches (Miller, 2006) are evidenced in the 3D map patterns (Henson et al., 2006) and it is likely that the most prospective faults are those with complex shapes (jogs in 3D) and those that are relatively old and have been reactivated. Furthermore the specific geometry of mineralised faults identified by Miller in the open-pits (e.g., Sunrise Shear Zone) can be extended into the region via the 3D map architecture of Henson et al. (2006).

Henson et al. (2006) describe the Laverton region architecture and note that the primary geometry is a doubly-plunging anticlinorium adjacent to a crustal-penetrating shear zone (the LTZ). A case has been made for the domal architecture being an essential ingredient for these systems (Henson et al., 2005) and these are mapped throughout the Laverton region, and in particular beneath Wallaby and Sunrise Dam. Superimposed on this fundamental camp-scale domal architecture is a complex array of faults that record their history in terms of early extension, later inversion during east-west contraction, and two later contractional events (NNW-SSE and NE-SW oriented). Henson et al. (this volume) showed that early extension initiated the domal architecture, which facilitated felsic magmas into domes (analogous to core complexes). This dome and basin geometry was further amplified by the subsequent contractional events, and resulted in reactivation of the extensional detachments as thrusts in a pop-up structure accommodated by a north-south sinistral strike-slip fault (the Childe Harold Fault).

Detailed examination of the reprocessed 01AGS-NY4 seismic line (Henson et al., 2006) reveals that the low-angle northwest-dipping Sunrise Dam fault system was probably cross-cut by an east-dipping normal fault (Henson et al., 2006). If this concept is correct, then it is predicted that the mineralisation at Sunrise Dam has been dissected and ‘targetable’ extensions of the deposit lie at depth to the southeast of its exposed position. Chopping (2006) has carefully examined the character of the seismic reflections associated with particular structures interpreted to be fluid pathways by Henson et al. (2006). Chopping interpreted the subtle differences in seismic amplitude between faults of similar geometry and attitude as likely fluid pathways and their associated alteration signature. He was also able to demonstrate that the most favourable region for fluid flow was west of the Far Eastern Fault, and that within the spatial extent of the seismic data, he predicted that there were considerable areas to be tested for mineralisation to the west of the Childe Harold Fault. At this stage it is difficult to distinguish between different alteration types (oxidised or reduced) using just seismic data, as most of the alteration mineral assemblages identified by Neumayr et al. (2006) and Cleverley et al. (2006) will produce similar changes to the rock properties. The seismic data however, may image areas of fluid-flow mixing, and areas that might be deeply sourced.

Conclusions

The Y4 project team (with help from the A3 and M9 teams) has tried to answer the 5 questions across the scales (from the lithosphere to ore shoot). The results have been integrated into a series of concepts that have then been applied to the generation of targets at a range of scales. The power of multi-disciplinary cooperation and integration is clearly illustrated here, and our understanding of the orogenic gold mineral systems in the eastern Yilgarn Craton, and particularly the Laverton region, has improved markedly. The concepts have been applied to broad ‘greenfields’ targets (north of Tropicana), under Lake Carey in the Laverton region, and in the near mine environment (brownfields) of the Sunrise Dam deposit. No single magic bullet exists for predictive mineral discovery. It is believed that by following the scientific method of erecting multiple hypotheses (concepts) and applying suitable tests across the scales and disciplines advocated above, however, that we will indeed be successful in predictive mineral discovery.

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Seismic 'mapping' of fluid pathways for Laverton's world-class gold mineral system

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Summary

Seismic data are often used to define geometries of structures at depth in 3D maps. Seismic data can also be used to understand generalised palaeo-fluid flow in the volume of interest of the 3D map. In the Laverton region, regional and mine-scale seismic data have been used to map out potential palaeo-fluid flow systems and provide details on the distribution of mineralisation in the Laverton region.

Introduction

The Laverton region in the Eastern Goldfields of the Yilgarn Craton is an area rich in gold mineralisation with considerable resources, including world-class deposits and other minor deposits (Groves et al., 1998; Jaques et al., 2002). The region is also rich in terms of seismic data with both regional and mine-scale seismic data available. The Laverton region mineral deposits, solid geology and regional seismic are shown in Figure 1.

These seismic traverses have been used to construct a 3D map with the seismic data providing information on the geometry of structures (Henson et al., 2006). More information about the nature of the structures in the map, however, may be obtained by examining the character of seismic reflections around structures to predict those which may represent palaeo fluid-flow pathways. Such mapping of potential fluid flow zones in the Kalgoorlie region was examined by Drummond et al. (2004a).

Based on first principles of seismic reflection (Telford et al., 1990), the seismic character of structures will be influenced by the following factors:

- Processing or acquisition artefacts.
- Change in dip, possibly due to anisotropy of materials in the shear zone. This is depicted in Chopping (2005).
- Change in thickness of the structure.
- 3D topography due to the effect of acquiring 2D seismic over 3D geometries, such as described by Drummond et al. (2004c). This can be somewhat accounted for in the interpretation of anomalous reflectivity by utilising the geometries of the features from the 3D architecture.
- Change in lithology (± alteration) of the structure and/or surrounding crust. An example of this is discussed in Salisbury et al. (2000).

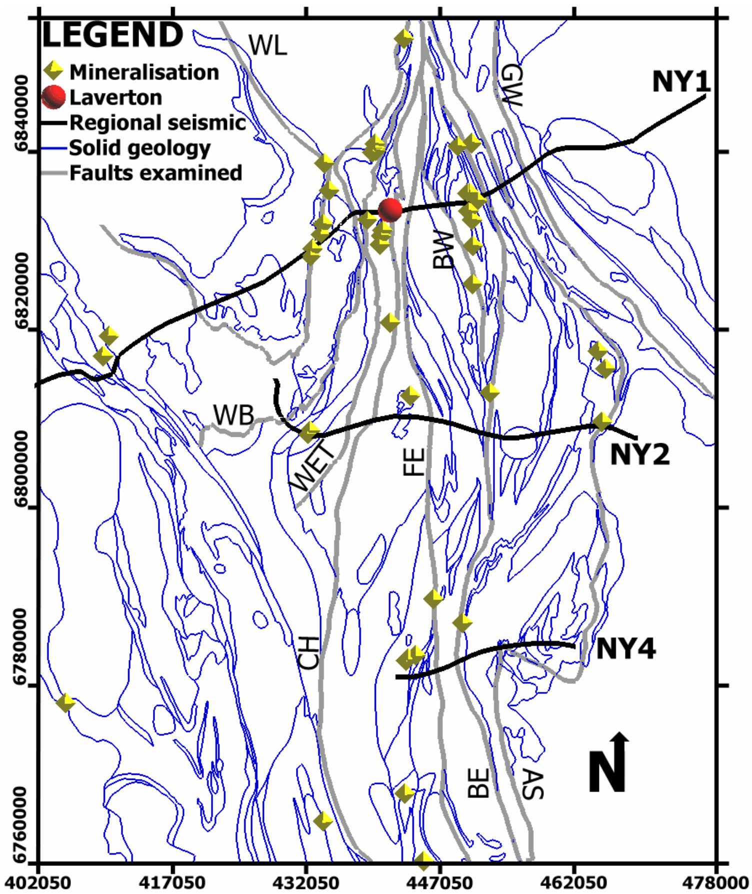

Figure 1: Solid geology, mineralisation and regional seismic traverses in the Laverton region. Solid geology after Henson et al (2006). Mineral deposit locations (points) derived from the MINLOC database (Ewers and Evans, 2001). A full discussion of the seismic data is in Goleby et al. (2003). Seismic lines are 01AGS-NY1 in the north, 01AGS-NY2 through the middle of the region, and 01AGS-NY4 to the south. Laverton township is indicated by the filled circle. Coordinates are GDA94, zone 51. Faults/Surfaces from Henson et al's (2006) 3D model:
WL – Wallaby LASH (Low Angle Shear Zone)
WB – Wallaby Basin
WET – Wallaby East Thrust
CH – Childe Harold Fault
FE – Far East Fault
BW – Barnicoat (West) Fault
BE – Barnicoat (East) Fault
AS – Apollo Shear
GW – Granite Well Fault

Seismic Characteristics

The three regional seismic lines studied in the Laverton region are 01AGS-NY1, 01AGS-NY2 and 01AGS-NY4; these will be referred to as NY1, NY2 and NY4 respectively. These seismic lines, and the processing applied are described in Goleby et al. (2003).

The interpretation of part of seismic line NY1, derived from Henson et al. (2006), is shown in Figure 2. Although the faults and surfaces in Henson et al's model were created partly from the seismic data, these data were used only to constrain the fault geometry. No interpretation was performed regarding the reflection character of the two faults.

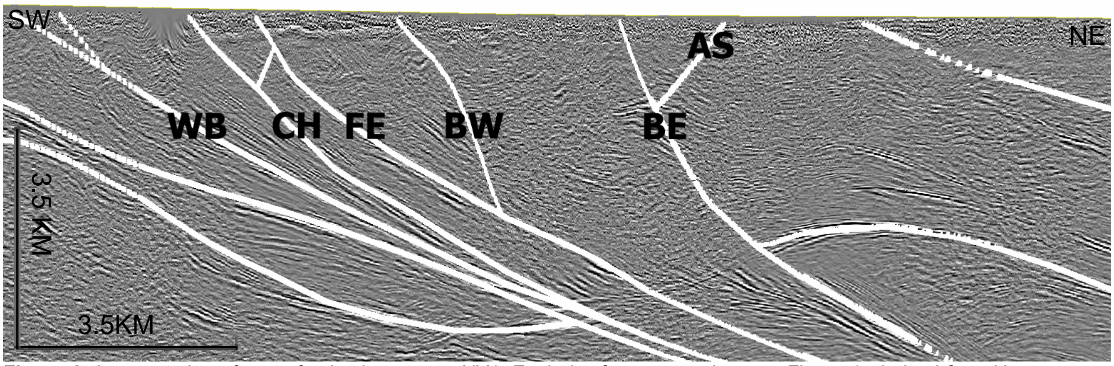

Figure 2: Interpretation of part of seismic traverse NY1. Faults/surfaces named as per Figure 1, derived from Henson et al's (2006) Laverton architecture.

Two faults such as the Childe Harold and Far East Faults (proximity to each other in NY1 visible in Figure 1) appear to differ in seismic response. They differ most significantly in the amount and length of linear reflections around, or at a low angle to, the inferred structures. The largest package of reflections occurs below and to the west of the Childe Harold Fault. Some reflections occur within the block between the Childe Harold and the Far East Faults, although these terminate against the Far East Fault.

There also appears to be some reflectivity sub parallel to the Wallaby Basin which mirrors the amplitudes and other characteristics (such as seismic phase) of reflections seen around the Childe Harold Fault. A simplified summary of all anomalous reflections is shown in Figure 3.

Interpretation

In the context of this research, the term 'fluid pathways' refers to a volume of higher permeability material (e.g. a shear zone) within the crust. This zone acts as a conduit for fluids which may chemically alter the material within the shear zone and the surrounding crust.

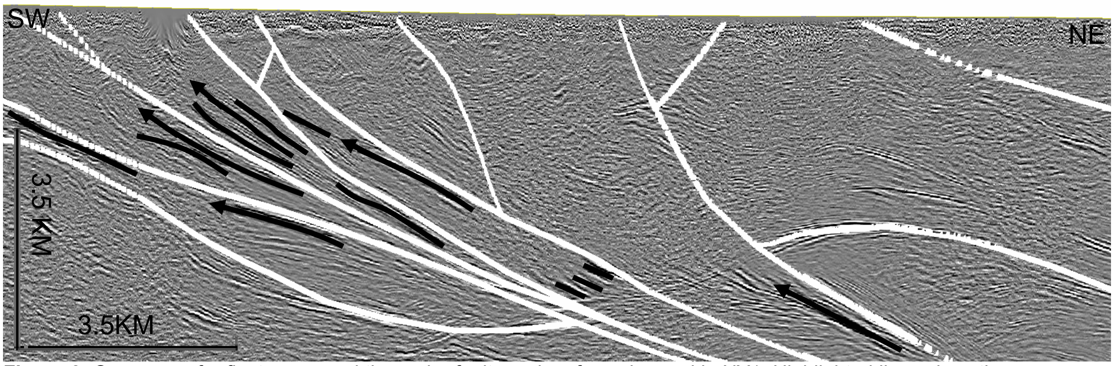

Figure 3: Summary of reflectors around the major faults and surfaces imaged in NY1. Highlighted lines show the areas of anomalous reflectivity around structures in the Laverton Region as imaged by NY1. Flow directions are inferred. Flow interpretation after Drummond et al. (2004).

The anomalous reflectivity appears to be similar to the palaeo-fluid flow hypothesis proposed by Drummond et al. (2004a), with high-amplitude reflections sub parallel and in close proximity to faults which have acted as fluid pathways and thus been altered by the fluids. Anomalous reflectivity could also occur around aquicludes, especially where they are breached.

The Childe Harold and Far East faults have similar dips, similar strikes and occur in a similar area of the seismic traverse. They also have broadly similar 3D geometries around the seismic traverse. Thus the reflection character differences are unlikely to be due to processing or acquisition artefacts or dip or strike changes. 3D topography of the faults is also similar so reflections are unlikely to be different for this reason. Finally the faults are most likely to be of similar thicknesses. Thus by elimination, the reflection difference most likely indicates alteration of the surrounding rocks due to the passage of mineralising fluids (Drummond et al., 2004b).

Assuming the highlighted reflections in Figure 3 represent signatures of altering palaeo-fluid flow, it appears that in the region around NY1 the Childe Harold and structures below are acting as a fluid pathway zone, focussing fluids up and to the west. The spatial distribution of mineralisation, as shown in Figure 1, indicates that there are a large number of areas of reported mineralisation around where the Childe Harold Fault, and faults to the west of it, reaches the surface or near-surface. These faults could represent a broad scale control on the focussing of mineralising fluid. If this is the case, this would be consistent with observed occurrences of mineralisation in the region.

An example of this consistency with observations is that the Far East Fault appears to act as an aquiclude which results in lower fluid-flow through the block between the Far East Fault and the Barnicoat West Fault and there is minimal alteration within this block. The Barnicoat West Fault also does not display the same reflectivity variability as the Childe Harold and Far East faults; the steeper dip on the structure means that the seismic will be unable to resolve the sub parallel features as seen around the Childe Harold and Far East faults. Evidence supporting the Barnicoat West fault focusing some mineralising fluids is that there are several occurrences of mineralisation along the fault (Figure 1).

Conclusion

Application of these principles developed on NY1 to NY2 and NY4 and incorporating knowledge from mine-scale seismic around Granny Smith, Sunrise Dam and Wallaby allows a simplified map of possible fluid-flow zones and directions to be developed (Figure 4).

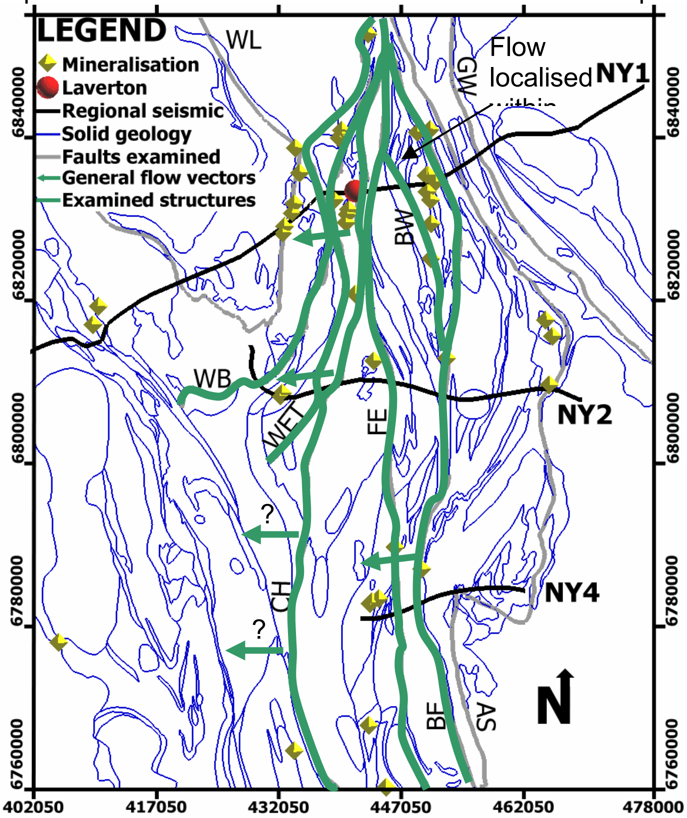

Figure 4: Simplified map view of palaeo-fluid flow in the Laverton region. Arrows indicating fluid flow directions inferred from regional and mine-scale seismic.

Further refinement in the understanding of the mineral systems in the Laverton region may be achieved by integration of these results with synthetic modelling such as the numerical fluid flow modelling of Sheldon et al. (2006). The refinement of this understanding will greatly assist in predicting prospective areas within the Laverton region and other similar systems.

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pmd*RT: Combined fluid, heat and chemical modelling and its application to Yilgarn geology

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Introduction

Mineral systems research within the pmd*CRC has been driven by a multi-scale and multi–discipline approach based around the '5-Questions' proposed during the AGCRC. Large-scale, fully integrated investigations generate a large amount of interlinked data and observations that we need to use to understand physical processes that are generally coupled. In order to understand the coupling and feedback between these observations and their processes we have to turn to computer simulation, in particular reactive transport modelling that attempts to couple the simulation of fluid-flow, heat and chemical transport, and chemical reactions.

The role of numerical modelling in mineral systems analysis in the pmd*CRC has seen much progress and application of chemical, heat and mass transfer, and deformation modelling codes. Nevertheless, there has been limited full coupling between modelling all these processes in a single coherent code (notable exceptions include pmdCRC work with SHEMAT and OS3D). We present here the latest results from *pmd*RT* which couples the modelling of heat, fluid and mass transfer with chemical reaction: currently, the code can not couple deformation. Key advances, however, have been made in modelling the feedback between chemical reaction and porosity-permeability, and the impact of this on the evolving flow field.

As a test case, a simple 2D model of a listric fault cutting basement-basin geometry with an intruded (cooling) granite is used to investigate aspects of the interplay between this static geometry, physical processes and consequent gold mineralization. The results of these models have implications for Yilgarn gold deposition models.

Background to pmd*RT

pmd*RT (working name) is a collection of software codes used for solving physical parameters or setting up and solving partial differential equations. These equations are solved using through an interface with *FastFlo4* (Gross, 2002) via the Python scripting language (Python 2.3). This means that codes written in multiple languages can be used together via a seamless interface to solve multi-process problems. The code is currently at a development stage and this work represents part of the testing and verification of the workflow and ability to generate applied outcomes. Further in-depth benchmarking and verification is planned for the rest of 2006.

The code solves chemistry by transporting the relevant (fluid) bulk composition and passing this composition by node to the *WinGibbs* solver (v.4.0, Shvarov, pers. comm.) which is the Gibbs Energy minimisation solver used in the geochemical modelling code *HCh* (Shvarov and Bastrakov, 1999). At present, mineral solid-solutions are not considered in the RT modelling.

Model geometry is built using the *gmsh* software, which uses a finite element meshing approach enabling the incorporation of smooth geometry (c.f. SHEMAT, which can handle only orthogonal geometry mesh elements). Result visualisation is currently accomplished by two methods: a) live-time plotting and image saving using the *MayAvi* software, or b) by exporting an interpolated x-y-data formatted ASCII file that can be read into 3rd part software. Images in this paper were generated in *Tecplot* (v10r6).

This paper gives some preliminary examples from the listric fault and granite test model that has some implications for Yilgarn-style gold deposition mechanisms. Details of these models and others are available on the pmd*CRC TWiki (project F6).

Listric Fault Model

The listric fault and granite model (*LFG_RT01*) is reproduced in Figure 1. In the model a listric fault cuts and offsets basement-basin units while an intrusive body is situated in the base of the model.

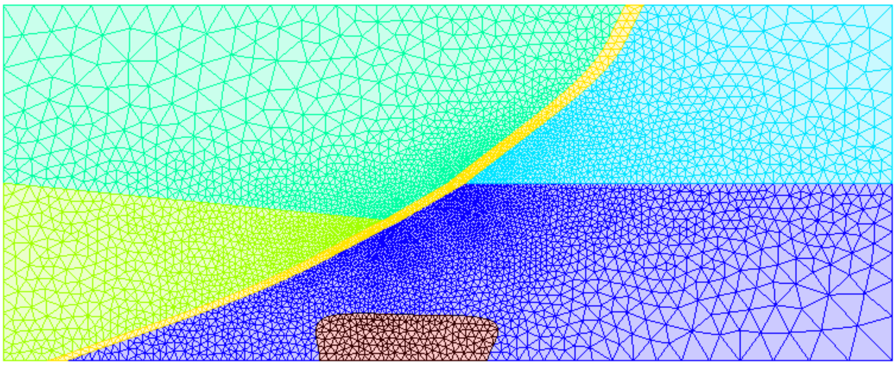

Figure 1: Regions and mesh (high resolution mesh) for the Listric Fault & Granite model using in this work. The model is 10 km deep and 20 km wide. The high resolution model contains 11500 elements and 6 regions while the lower resolution mesh contains 5500 elements.

Physical Structure

The 10 km deep and 20 km wide model is initialised with the top boundary fixed at 100 MPa and 250^{o}C and a hydrostatic pore-pressure gradient with a geothermal gradient of 25^{o}C/km (~500^{o}C at the base of the model). The granite is initialised at 750^{o}C and ambient pressure and is set to cool exponentially to background temperatures following $e^{(-time/event\_length)}$ where *event_length* is 30 Kyr. The flow field and model evolution is driven entirely by the thermal event from the cooling granite with no forced over pressures.

The permeability-porosity structure of the model is initialised manually at values close to those suggested for the continental crust (Manning and Ingebritsen, 1999), with variation from 10^{-17} to 10^{-16} and porosity around 1-5% (see spatial distribution in Figure 2).

Chemistry

pmd*RT allows the user to define the solid and aqueous chemistry by regions. Solid chemistry is defined by volume fraction of minerals while the aqueous chemistry is defined as moles or molality in the fluid phase. The volume of fluid phase is defined as the volume of pore space while there are expansions available to account for non-reactive rock volume (i.e. fracture permeability). While the user specifies the initial chemical distribution, the initialisation of the model adds the fluid and solid and performs an initial equilibration. This means that the actual chemistry at the start of the model is the equilibrium chemistry for the solid-fluid and the exact mineralogy and fluid chemistry will depend on factors such as actual PT distribution and equilibrium fluid/rock ratio. The pre-equilibrium chemical distribution is given in Appendix 1.

Gold was distributed in the equilibrium fluid phase in all the rock units at a concentration below saturation at the coolest temperature of that region (data in Appendix 1). The model hence started with no solid Au present in the rocks, although the hot, S-rich granite-fluid had the greatest capacity to contain Au.

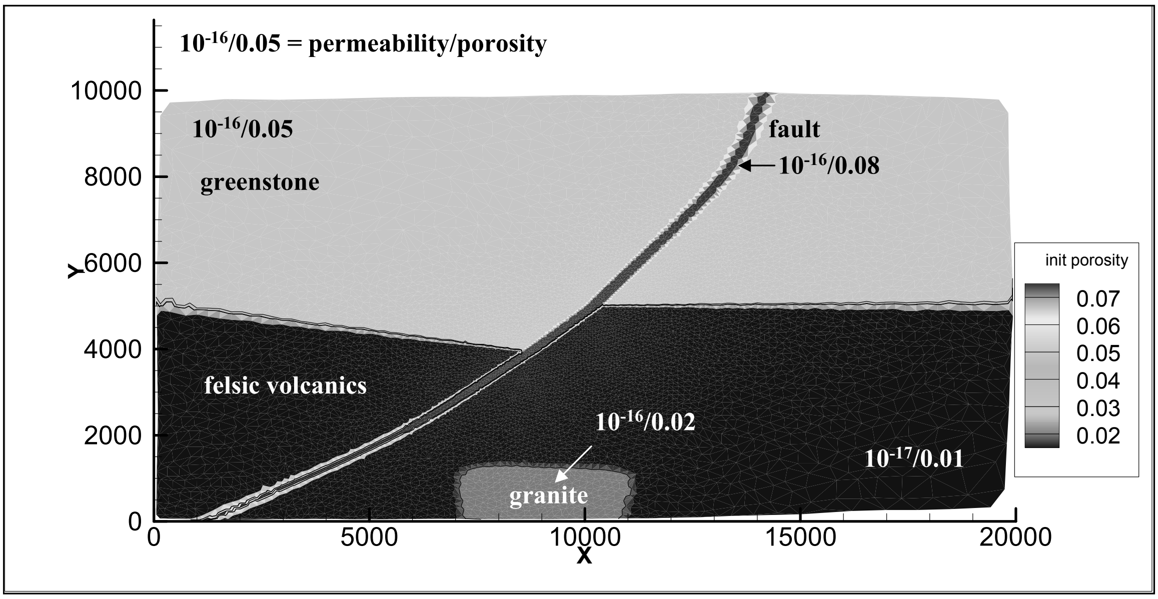

Figure 2: Distribution of lithological units, porosity and permeability at the start of the model.

Porosity & Permeability

pmd*RT models can be run with a fixed porosity-permeability structure or including dynamic feedback between chemical reaction and evolving porosity (and permeability) which in turn feeds back to the evolving flow field. In the dynamic feedback model the porosity (ϕ) is varied as a function of the total liquid volume, $\phi = V_f$ (eq. 1), such that mineral precipitation/ dissolution will decrease or increase the porosity value. The permeability is varied as a function of the porosity using a simple Carmen-Kozeney equation, $\kappa = \kappa_o \left(\frac{\phi}{\phi_0} \right)^n$ (eq, 2), where *k* is permeability, ϕ_0 is the initial porosity at time = 0, and *n* is an exponent that is set to 3 throughout the model in this work (see Clauser, 2003 for variability of n in natural systems). An extension of this procedure allows for an unreactive rock fraction (ω) to be considered, such that the fluid is not reacting with the whole rock volume. This will be the case in systems where fracture porosity dominates over intragranular porosity (Ague, 2003; Steefel and Lasaga, 1994). Using this method the model considers two porosity values, the rock porosity and chemical porosity (ϕ_C) which are dynamically linked but separate values. See poster by Cleverley (this conference) for more details about this methodology and its impact on the model outcomes.

Heat and Mass Transfer Models

Initial heat and mass transfer models (i.e. without chemical reaction) concentrate on the evolution of the thermal and flow fields with a static porosity-permeability. The model evolves in 3 distinct stages: Stage 1) Vigorous convection around the granite with an initial plume of granitic fluid flowing upwards. Down-flow and up-flow in the fault are a direct consequence of with the convection induced by the granite pulse. Stage 2) Thermal pulse moves upwards through the model as the granite cools; forcing convection in the overlying basin. Stage 3) Thermal structure decays to geothermal gradient and convection in basin wanes.

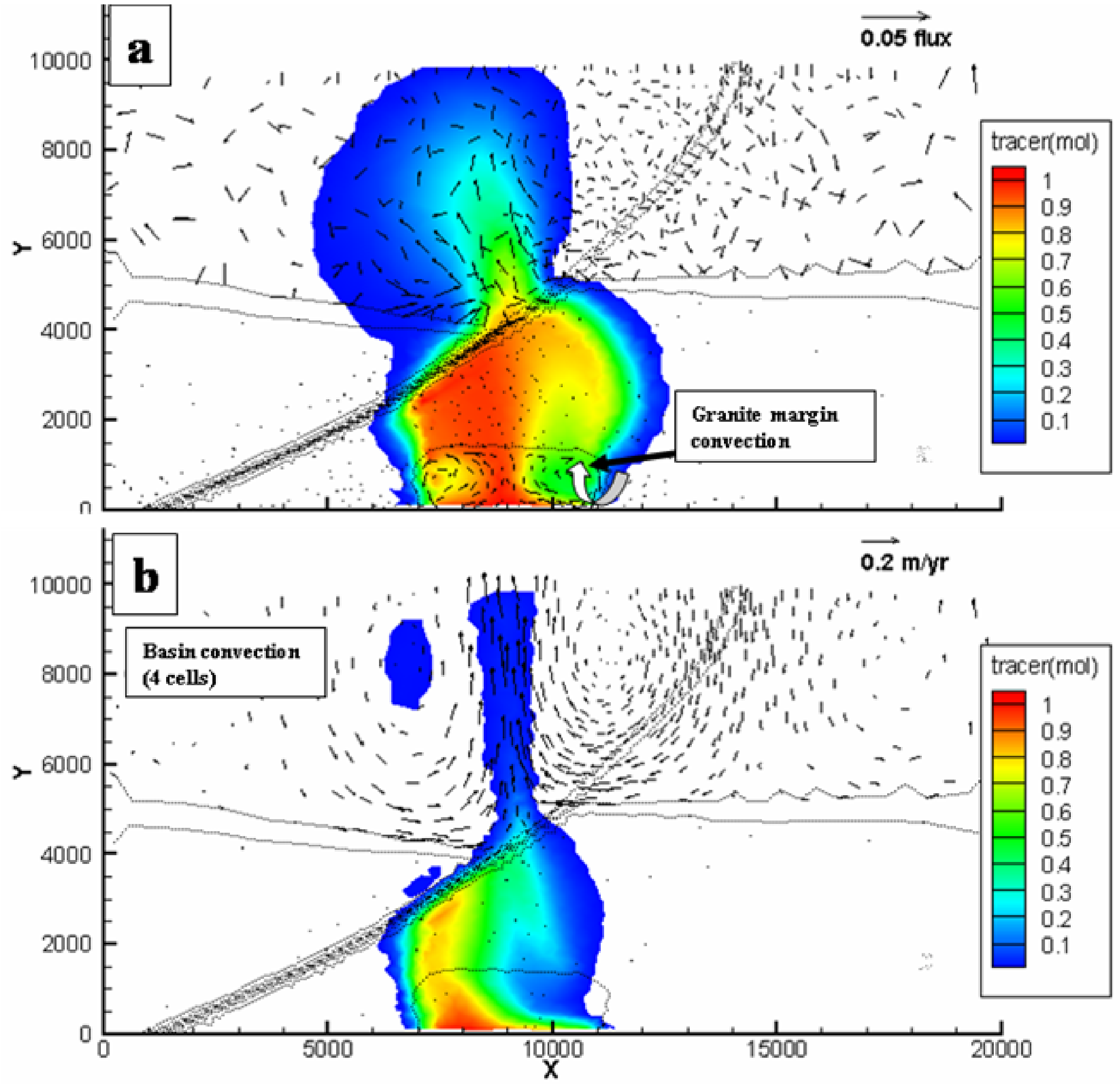

Figure 3: Results from heat- and fluid-flow only model showing inert tracer and darcy-flux vector distribution at a) 65,000 and b) 156,000 years illustrating stage 1 and 2 of the model evolution. Model LFG_HeatFlow_a.

pmd*RT employs an implicit approach to solving the mathematics and these models are solved using a courant overstep factor which causes 'time dilation' in the model. This means that the model time is not exactly equal to the natural system time: the magnitude of the differences is still being investigated with benchmark models.

Reactive Transport Models

The reactive transport models include chemical equilibrium between the fluid and rock as the model evolves. These models also include the dynamic feedback between chemical reaction and porosity-permeability. Figure 4 is the distribution of gold (in ~g/t) and Darcy flux vectors after 157,000 years (compare Figure 3b) in a model with the unreactive solid factor = 0.8 (see earlier section). Although the overall three stage evolution of the model is similar to the non-reactive transport models, the convective response of the basin (upper units) is different. Here the flow is well focused in the up-flow zone above the intrusive while there is now two convecting cells (Figure 4) instead of four (Figure 3b). Gold is precipitated in reasonable grades in the upwelling zone of the greenstone units at a time ~50-100 Kyr after the granite has completely cooled.

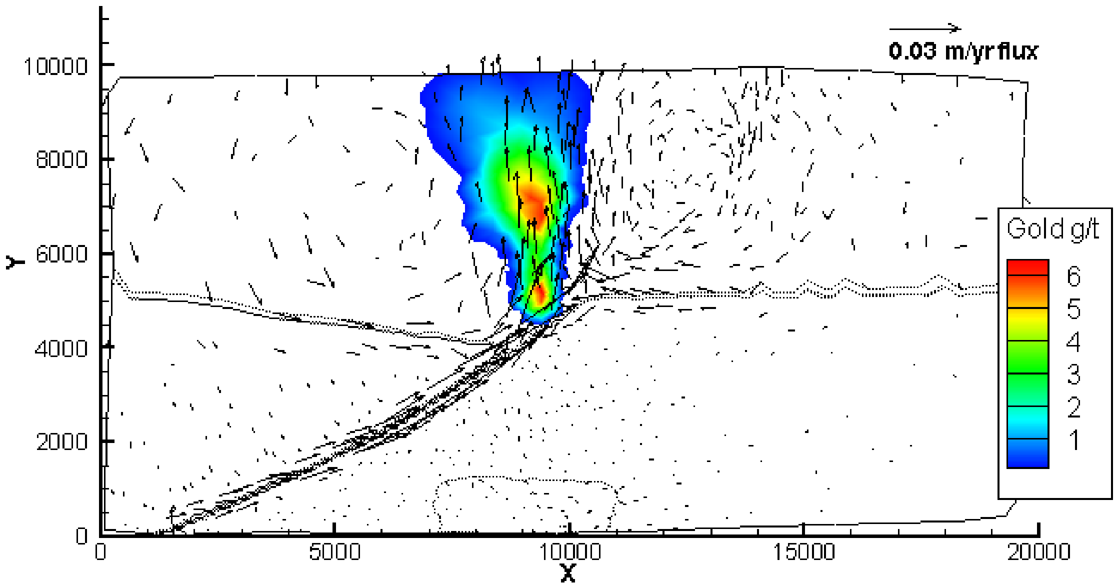

Figure 4: Gold precipitation in a reactive transport model with dynamic permeability-porosity. Fluid and gold are focused in an up-flow zone above the cooled granite because of the 'rock preparation' by the initial magmatic fluid pulse moving through the system that decreases permeability by 0.1-0.3 log units in this zone. Model LFG_RT01_CPor_c at time 157,000 years (compare Figure 3b).

There is active fluid-mixing in the model with convection mixing greenstone fluids with the waning magmatic fluid input from beneath, while the fault focuses down-flow (upper segment) and up-flow (lower segment) driven by the initial magmatic thermal-fluid pulse interaction.

The RT models can also be used to investigate the association of other minerals to help understand the interrelationship between different alteration assemblages and ore deposition. Figure 5 shows the same model and time step as Figure 4 but overlying gold (lines) and calcite (shades) distribution. Calcite forms in the up-flow region of greenstone/magmatic fluids (see Figure 4) and delineates the lower part of the gold distribution.

Summary

The pmd*CRC reactive transport code is starting to be applied to complex geochemical problems in mineral systems. This test model highlights some important aspects of the magmatic-basement-greenstone basin system that have only been possible using pmd*RT:

Although the granite is the primary thermal driver for fluid-flow, the effect of the granite on flow in the basin is not experienced for 50-100 Kyr after the granite has cooled.
Dynamic porosity-permeability feedback from the chemistry has a fundamental effect of the flow evolution. Preferential pathways developed during the initial magmatic fluid release focus flow (by decreasing permeability) and change the geometry and length-scale of the convection cells. This changes the amount of greenstone rock that the fluid can access prior focusing.
Using this model scenario it is possible to precipitate ore-grade gold. The destruction of permeability in the dynamic por-perm model allows the gold to be persevered in the greenstone units above a buried intrusive (4-5 km).

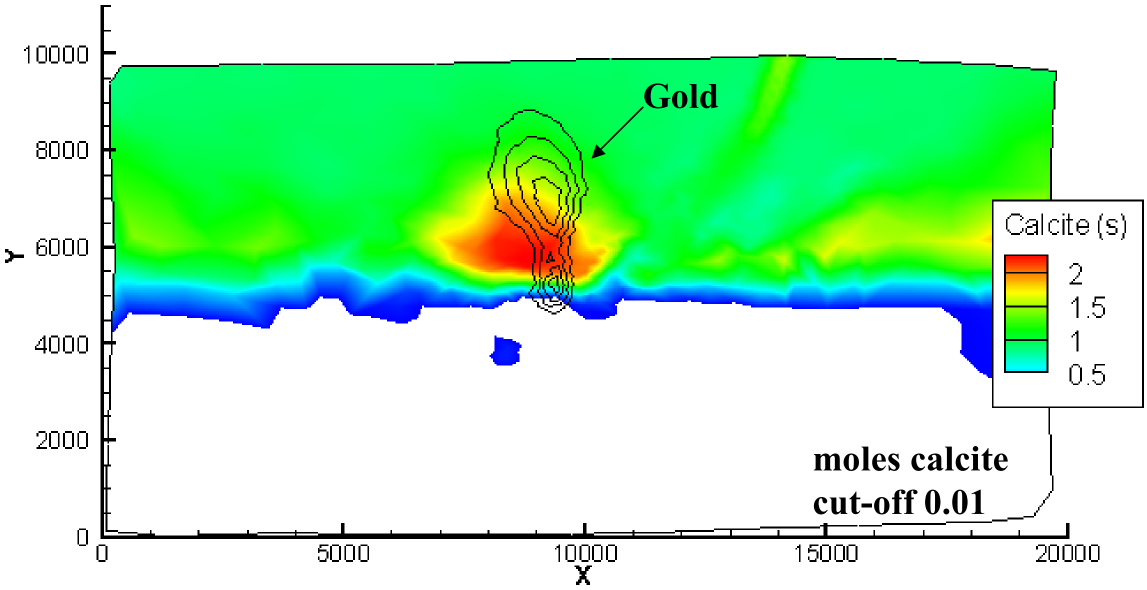

Figure 5: Distribution of calcite (moles) relative to gold (lines) at 157,000 years (see Figure 4). Calcite forms at the up-flow region of greenstone derived fluids mixed with some magmatic/granite derived fluid (provided by the now cooled granite).

Acknowledgements

None of this work would have been possible without the efforts of the team at CSIRO-exploration and mining including Andrzej Welna, Robert Woodcock and others, who have generated a revolutionary reactive transport code. This work has also greatly benefited from discussions with Heather Sheldon and Andy Barnicoat about porosity-permeability.

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Appendix

The following table gives the initial distribution of mineral phases and aqueous components in the reactive transport model. The actual equilibrium distribution will depend on the exact PT and fluid/rock ratio at the specific location in the model.

Rock Unit	Approximate Starting Mineralogy	Starting aqueous composition (molal)	
Greenstone	Qtz, calcite, albite, tremolite, chlorite, pyrrhotite	NaCl	0.78
		KCl	0.16
		$CaCl_2$	0.75
		CO_2	0.05
		H_2S	5.6×10^{-4}
		Au	1×10^{-9}
Felsic Volc	Qtz, pyrite, albite, muscovite, k-feldspar	NaCl	1.32
		KCl	0.40
		$CaCl_2$	0.12
		CO_2	4.7
		H_2S	0.0286
		SO_4	1×10^{-5}
		Au	1×10^{-9}
Fault Zone	Qtz, albite, muscovite, calcite, pyrite, pyrrhotite	NaCl	1.00
		KCl	1.00
Granite	Qtz, muscovite, k-feldspar, plagioclase (ab-an), pyrite, magnetite, biotite	NaCl	0.89
		KCl	0.28
		$CaCl_2$	0.02
		$FeCl_2$	0.40
		H_2S	1×10^{-3}
		Au	1×10^{-6}

Gold in Na-assemblages: Implications for deep fluid sources and pathways in the Eastern Goldfields

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Abstract

Detailed petrographic observations and mineral chemistry coupled with knowledge of meso-scale structural and geochemical trends in ore-systems can help to elucidate not only potential fluid pathways but also the nature and relative timing of fluid accessing the pathways. This study presents early results from observations of material from the Sunrise Dam and Kanowna Belle deposits in the Eastern Yilgarn Craton. Common features of the mineralogy and the association to Au grade can be seen in both study areas hinting at a broad similarity in the types of fluids in spatially distinct gold deposits. A common feature of these assemblages is the dominance of albite with overprinting zones of either paragonite or muscovite-dravite and apatite-rutile-zircon. The apatite in these zones is considered to be CO_2- and Sr-rich (0.3-1.5 wt%). This assemblage and the apatite chemistry might characterise a deep-sourced or carbonatitic fluid. Zoned carbonate-pyrite and gold cyclically overprints the muscovite assemblage at Sunrise Dam, which may record mixing with a second fluid source. A separate but spatially related third assemblage includes pyrite, chalcopyrite, galena and sulfosalts, such as tennantite-tetrahedrite, and Au-Ag-Tellurides, and appears to be related to Cl-rich metasomatism, possibly a more $NaCl/FeCl_2$-rich brine (see fluid types identified in Peterson et al., 2005).

Study Material

Sunrise Dam

Samples from Sunrise Dam (SRD) were collected underground within the Sunrise Shear Zone (SSZ). Most of the focus was on the flat to gently dipping laminated quartz veins (D3 of Miller, 2006), although some other representative samples of folded veins and SSZ alteration sequences were also collected. Most samples were prepared as polished sections with splits being crushed for whole rock and trace element geochemistry and off-cut blocks analysed by PIMA.

The laminated 'D3' veins at SRD contain some of the highest Au grades in the mine. During this work it was found that there is a direct correlation between the concentration of black laminations in the veins and Au contents.

Kanowna Belle (Velvet prospect)

Samples from Kanowna Belle (KB) came from two DD holes, KDU1648 from within the Velvet zone and KDU1879 that intersects the Troy lode. Samples were selected to cover a range of lithologies, alteration types and mineralisation. The holes are characterised by porphyry intrusions cutting and altering late-basin conglomerates. Hole KDU1648 has been thoroughly characterised chemically (see Walshe et al., 2006) with Hylogger data and comprehensive whole rock geochemical samples. To date KDU1879 has been logged and assayed only. All samples were prepared as polished sections and the off-cut blocks analysed using PIMA.

Both drill holes contain Au-rich zones. Samples from the mineralised porphyry and associated breccias in KDU1879 contain between 0.5 and 2 g/t with some intersection up to 10 g/t. Mineralised porphyry in KDU1648 contains intersections grading 2 g/t.

Assemblages

Mica-Tourmaline

The black laminations in 'D3' quartz veins at SRD consist of two distinct mineral assemblages; a) preferentially aligned muscovite-tourmaline-rutile-apatite, often associated with pyrite and, b) open space infilling zoned carbonate-quartz (Figure 1a). The mica assemblage occurs in small to large composite laminations that appear to be stylolitic (Figure 1b). Tourmaline is not always present but in the samples studied here the mica is always close to pure end-member muscovite (K), which is confirmed by PIMA analyses showing close to 2200 nm for the mica Al-OH feature (2190 is paragonite while 2220 is phengitic). The tourmaline is Mg-rich (X_{Mg} = 0.80), Na-rich (0.8-0.7 afu) dravite. The mica-tourmaline laminations are commonly associated with rutile-apatite and hydrothermal zircon.

Wallrocks to the laminated veins contain abundant muscovite-rutile similar to that observed in the laminations... However the tourmaline is only found in the first few 100 microns into the wallrock, and does not form any significant alteration halo around these veins.

Similar assemblages are observed at KB in regular veinlet-fracture fill geometries, and not in laminated quartz veins. There is a wider range of mica chemistry in the KB samples than those at SRD with variability from paragonite to muscovite assemblages associated with the tourmaline-rutile-apatite-zircon.

Gold has been observed in association with and possibly replacing pyrite in the SRD laminations associated with the zoned lamination carbonate event. No gold was observed in thin section in these assemblages at KB.

Carbonate-sulphosalt-sulphide

Structures at a high angle to the flat laminations at SRD contain assemblages dominated by carbonate (zone dolomite), sulphides including tetrahedrite-tennantite, sphalerite, galena, chalcopyrite and occurrences of Au-Ag-Pb-Te minerals. There is no CL evidence to suggest a second generation of quartz with this event. These assemblages were not found in the wallrocks to the laminated quartz veins.

Sulphosalt-bearing assemblages at KB are restricted to dirty cored pyrites that contain inclusions of chalcopyrite, galena, Pb-selenides, tetrahedrite-tennantite. The core-pyrite is always overgrown by a cleaner pyrite with growth zones of As-enrichment (see Figure 2 from Ni-Cr zone).

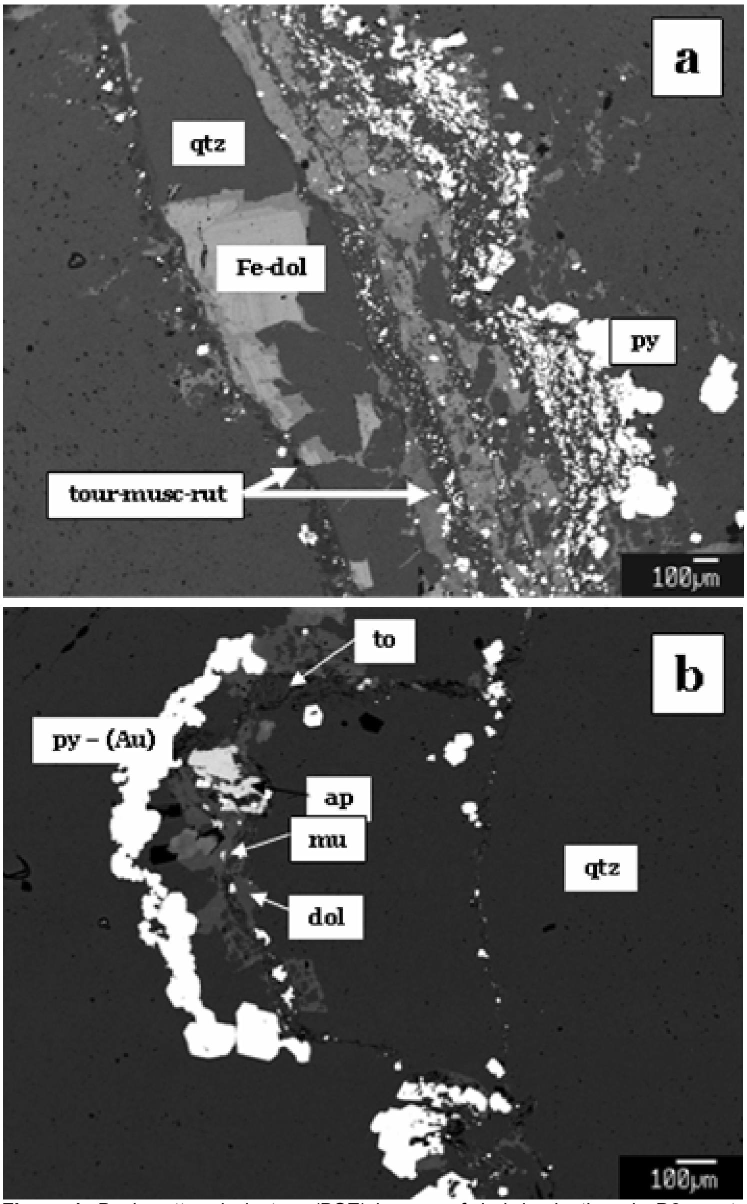

Figure 1: Backscattered electron (BSE) images of dark laminations in D3 quartz veins from Sunrise Dam (Sunrise Shear Zone). a) complex composite lamination cycling between zoned dolomite-quartz and muscovite-tourmaline-rutile laminations, b) Typical stylolitic lamination with tourmaline-muscovite-apatite-rutile, brecciating dolomite and pyrite with Au (not visible in image because of contrast).

Fuchsite-Sulphide

Laminated quartz veins at the SRD GQ lode were also sampled, and the veins are more steeply dipping than those sampled elsewhere. The GQ lode has been mapped as a mafic body in the mine, although initial whole rock geochemistry suggests that these rocks are not mafics, but similar to BIFs elsewhere with the mass addition of Cr and Ni. This will be tested further this year. The veins consist of more complex generations of quartz and laminations than other SRD D3 veins. The mica-laminations are still observed but never include tourmaline and instead the mica is fuchsitic (3-4 wt% Cr_2O_3). Molybdenite is observed in place of rutile in the laminations and carbonate filled open space also includes quartz-tennantite-tetrahedrite.

These types of assemblages with the addition of As-minerals such as gersdorffite (NiAsS) are also observed in KDU1879 in a green coloured hydrothermal breccia on the edge of the main porphyry suite (153m down-hole, Figure 2). This sample contained Au-telluride minerals encapsulated in gersdorffite-dolomite in the matrix of the breccia.

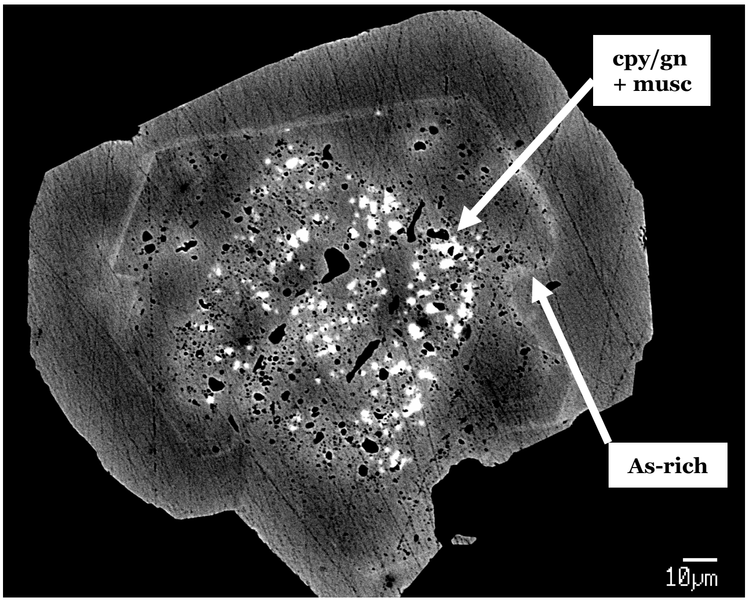

Figure 2: BSE image of dirty-core pyrite from fuchsite-breccia in KDU1879 (153.4). The core contains inclusions of chalcopyrite-galena and muscovite, while the zonation in the pyrite overgrowths is due to changes in As concentration.

Apatite Micro-Chemistry

Apatite chemistry can be used to help track aspects of the fluid chemistry that were present during precipitation because of the halogen (Cl, F) substitution for OH, whereas elements such as S, As, Sr and REE's can all substitute into the structure if the fluid chemistry is favourable.

Apatite forms an integral phase in the tourmaline-mica-rutile laminations at SRD, and is typically zoned with inclusion-rich cores and cleaner rims (Figure 3). The rims are intergrown with dolomite-pyrite, while the cores appear to be associated with the tourmaline-mica assemblage. Inclusions in the apatite core include REE-phosphates and the only observed magnetite in the rocks.

The apatite chemistry is very similar in all samples, close to end-member fluorapatite with no detectable Cl or inferred OH. The F contents are actually more than stoichiometrically possible (2.3-2.5 afu) which may indicate the presence of CO_2 in the PO_4-site via the coupled substitution $CO_3^{2-}F^- \Leftrightarrow PO_4^{3-}$ (Binder and Troll, 1989). The zonation between core and rim observed in backscatter (Figure 3) is caused by Sr, with 1 wt% SrO in the core and 0.3 wt% in the rim. >0.5 wt% SrO in apatite is reported from carbonatite rocks by Le Bas *et. al.* (2004).

Qualitatively, the apatite chemistry looks to be the same at KB although this will be checked later this year. Like SRD, the apatites at KB in these assemblages also include magnetite inclusions.

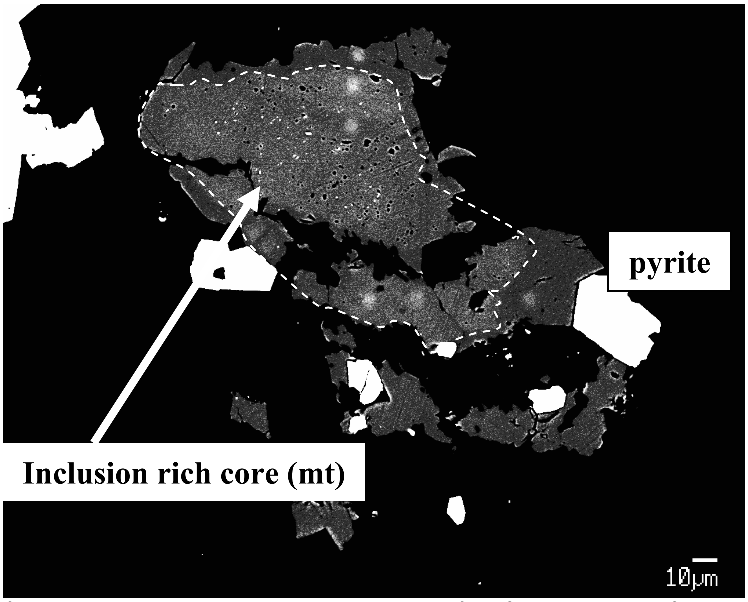

Figure 3: BSE image of zoned apatite in tourmaline-muscovite lamination from SRD. The core is Sr- and inclusion-rich (magnetite and REE phosphate) and is grown with the tourmaline-muscovite. The rim is cleaner with less Sr and is intergrown with pyrite-dolomite-(gold).

Interpretation of the Fluid Sources

Sunrise Dam

The tourmaline-mica laminations contain rutile, zircon and Sr-rich apatite with magnetite inclusions. This assemblage and the location inside quartz veins that appear to have formed during multiple opening events likely link this event to a magmatic volatile fluid source, but one that has evolved from a CO_2-rich, primitive, parental magma. Melts evolving CO_2- and apatite-rich assemblages have been observed at Wallaby (S. Dreiberg, *pers. comm.*) and these were directly associated with gold during D2 (Miller, *2006*). It is not known what the exact nature of these fluids would be, and it is likely that they were undergoing phase immiscibility (boiling); nevertheless they appear to be responsible for transporting hydrothermal Ti/Zr at least short distances. CL images reveal a lack of secondary quartz precipitation around the laminations which might be expected if the fluids were very CO_2-rich (Shmulovich et al., 2001).

The exact relationship between the tourmaline-mica-apatite assemblage and dolomite-pyrite-gold is unclear. There are several examples, however, that illustrate fluctuations between mica-dominant laminations and dolomite-dominant infill and brecciation which may indicate fluid mixing.

The fact that the sulphosalt/sulphide assemblages are never encountered inside the laminations probably indicates that they are later or an unrelated event. Structurally, the assemblage is confined to the quartz veins but occurs in steeply dipping vein-perpendicular structures (D4?). It is difficult to ascertain exactly the nature of the fluid responsible for the carbonate-sulphosalt-sulphide assemblage, but the presence in some samples of telluride phases might suggest the involvement of another magmatic volatile phase. Some small inclusions of the mineral kolarite ($PbTeCl_2$) may also indicate that this fluid was hypersaline.

Kanowna Belle

Similar features are observed in the KB samples to those described for the SRD samples, with the exception that the structural localisation is different (no flat laminated quartz veins) and there is more variation in the mica chemistry (paragonite to phengite). Because the phengitic mica is found proximal and within the altered porphyries, it is also likely that phengite maybe found in porphyry proximal locations at SRD. The association of apatite and gold, as seen in the SRD laminations, is born out in KDU1648 where the gold zone occurs in apatite-rich porphyry rocks (chemistry to be measured later this year). The gold zone porphyries also stand out in the whole rock geochemistry (elevated Th and P related to the apatite) from other porphyries in the holes even though they are logged as the same lithological units. Are these magmas responsible for CO_2-, gold transport from deep fluid sources? Future work should focus on the interrelationship between porphyry chemistry, gold and alteration at Kanowna Belle, Wallaby and Sunrise Dam.

Where are the gradients?

Previous studies at the St Ives mineral district have identified broad-scale gradients in mineral assemblages that can be linked to gradients in pH or redox (Neumayr et al., *2006*). In this initial phase of work at KB and SRD samples of As-rich alteration where not studied, although gradients are still observable within the micro-scale observations. Importantly, the similarity of the apatite and the occurrence of magnetite inclusions in the apatite is the only place where this is observed. There is a micro-scale transition to pyrite-stable assemblages and possibly a subtle shift in redox associated with changes from tourmaline-muscovite to muscovite-only (Frikken et al., 2005) Even at the micro-scale, redox gradients or transitions can be identified in these localities.

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Geodynamic evolution of the Mount Isa Inlier and its influence on the formation, timing and localisation of fluid flow

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Strikingly similar geological histories and metal endowments support the view that Broken Hill and Mt Isa were once contiguous or at least formed part of a single continuous Zn-Pb mineral province during the late Palaeoproterozoic (Giles et al., 2004). Pb model ages for major Zn-Pb deposits like Broken Hill and Cannington (1675 and 1665 Ma respectively) are comparable (Carr et al., 2004) and high grade metasedimentary rocks hosting these deposits are thought to have been deposited about the same time (ca. 1690-1670 Ma) in either an intra-continental rift or back–arc extensional environment (e.g. Walters & Bailey 1998; Betts et al., 2003). High grade deformation and metamorphism at 1600 Ma preclude unequivocal identification of the original ore-forming environment in both cases although clues to the tectonic setting and kinematic framework are still preserved in less intensely metamorphosed rocks of equivalent age in the Mount Isa Western Succession.

Particularly important in this context is the recognition of a major temporal and spatial boundary between successive extensional regimes in the Western Succession and across which there was a switch in the principal extensional direction from ENE-WSW to NE-SW. This switch heralded a major change in basin architecture and the pattern of sedimentation, and superimposed a differently oriented set of extensional structures on a pre-existing structural template. These two regimes correspond to the Calvert and Leichhardt Superbasins of previous researchers (Jackson et al., 2000) and represent a change in the depositional environment from narrow intracontinental rift to passive continental margin. A key objective of research in the pmd*CRC I7 project (Module 4) has been the identification of equivalent sequences and extensional structures in the Eastern Succession and the extent to which they influenced and controlled fluid flow during times of mineralisation. As with the Western Succession, the simplest approach to developing a structural and geodynamic framework for the Eastern Succession is to first identify the syn- and post-rift sequences, bearing in mind that depositional environments in the Eastern Succession are represented by deeper water sedimentary facies compared to the dominantly fluviatile to shallow marine conditions that prevailed farther west.

Leichhardt Superbasin (1800-1750 Ma)

The Leichhardt Superbasin comprises a basal sequence of metabasaltic flows, volcanogenic sediments and minor quartzite up to 6 km thick overlain by a thinner (2-3 km) succession of trough- and cross-bedded, immature quartzofeldspathic sandstones with subordinate amounts of poorly sorted siltstones and redbeds (Derrick, 1982; Jackson et al., 2000). Deposition of these younger sediments took place between 1780 and 1750 Ma into asymmetric NNW-trending basins (half-graben) that deepened towards the eastern margin of the Leichhardt River Fault Trough (LRFT). Fluviatile to lacustrine environments predominated (Erikkson et al., 1993; Jackson et al., 2000) and the sediments were most likely sourced from pre-1800 Ma basement in the adjacent Leichhardt-Kalkadoon Block. Dyke rocks intruded into this basement trend mainly NNW, parallel to the normal faults bounding the LRFT, and provide strong support that extension during this period was mainly ESE-WSW. A major detachment fault inferred to lie at depth beneath the LRFT may once have been continuous with the extensional shear zone reported by Holcombe et al. (1991) in the Wonga Belt farther east. Granitic rocks intruded synkinematically into the lower plate of this shear zone give 1740-1780 Ma ages, indicating that this shear zone was active at the time of basin formation and sedimentation (Myally Supersequence) farther west.

Metabasaltic rocks (Eastern Creek Volcanics) in the LRFT are dominantly of tholeiitic composition and have been widely interpreted as a pile of continental flood basalts (Glikson et al., 1976; Derrick, 1982). Mafic dykes and sills thought to have been feeders to these volcanic rocks are widely developed in the adjacent Leichhardt-Kalkadoon basement (Ellis and Wyborn, 1984) but do not intrude any higher than the base of the Myally Supersequence, indicating that this phase of basaltic magmatism was complete by ca. 1770 Ma (Neumann et al., 2006). Correlatives of the Eastern Creek Volcanics and Myally sediments (Marraba Volcanics and lower Mitakoodi Quartzite respectively) occur as far east as the Mitakoodi anticlinorium in the Eastern Succession where they are underlain by felsic volcanic rocks of the syn-extensional 1760-1780 Ma Argylla Formation (Blake, 1987).

Subsequent to deposition of the Myally Supersequence, the rate of crustal extension in the Western Succession slowed or was completely arrested, leading to burial of the syn-rift sediments beneath a cover of regionally extensive fluviatile-shallow marine sediments dominated by clean, well-sorted quartzite and well-bedded, redeposited carbonate sandstones (Quilalar Supersequence). These post-rift sediments have a sheet-like geometry, and a transgressive lower surface which is both erosive and locally deeply incised into the underlying syn-rift sediments (Jackson et al., 1990). They mark the onset of a marine transgression and correspond to an episode of thermally-induced regional subsidence. Their equivalents in the Eastern Succession are the Ballara Quartzite and platform carbonate sequences of the Corella Formation (Blake, 1987). Detrital zircon ages and intrusion by the 1740 Ma Burstall Granite (Page and Sweet, 1998) constrain the age of this marine transgression to between ca. 1750 and 1740 Ma. The preservation of stromatalites and shallow water sedimentary structures (e.g. hummocky cross-stratification) in both the Quilalar and Corella Formation further attests to a depositional environment where water depths rarely exceeded storm-wave base.

Calvert Superbasin (1740-1670 Ma)

The onset of rifting accompanying formation of the Calvert Superbasin was marked in the Western Succession by deposition of fanglomerates and coarse sandstones in fault-angle depressions and fluviatile environments (Bigie Formation), and a rejuvenation of bimodal magmatism, including extrusion of the 1710 Ma Fiery Creek Volcanics (Scott et al., 2000). Coincidently, the immediately underlying Quilalar Supersequence was intruded and contact metamorphosed by the 1710 Ma Weberra Granite (Neumann et al., 2006). This was followed by deposition of several cycles of upward-fining, mainly siliciclastic sedimentary packages (Prize Supersequence) deposited in a deltaic or shallow marine shelf environment (Southgate et al., 2000). With further deepening of the sedimentary basin(s), increasingly greater amounts of thinly laminated carbonaceous shale or rhythmite were deposited. Stratal thickening of these sequences into east- or NE-trending growth faults points to a syn-rift origin for much of the Calvert Superbasin (Derrick, 1982; O'Dea et al., 1997) as do minor amounts of intercalated felsic magmatic rocks. Magmatic rocks include the 1678 Ma Carters Bore Rhyolite and thin (< 50 cm) syn-sedimentary peperitic intrusions dated at ca. 1690 Ma (Page et al., 2000). These dates provide the best available age constraint on sedimentation in the Calvert Superbasin and are only marginally older than the 1670 Ma age obtained from the Sybella Granite (Neumann et al., 2006) which intrudes Eastern Creek Volcanics near the base of the underlying Leichhardt Superbasin.

By 1685 Ma, basin geometry in the Calvert Superbasin was well established, driven by NE-SW extension and accompanied in the Eastern Succession by intrusion of basaltic magmas through progressively thinner continental crust into deep marine basins filled by turbiditic carbonaceous sediments (Soldiers Cap Group). This group of deep water sediments has no direct lateral or temporal equivalent among the shallower water sedimentary facies preserved farther west in the LRFT. Rather, this sedimentary facies is restricted to the easternmost part of the Mount Isa Inlier where metamorphism has since transformed many of the basaltic dykes and sills into amphibolite (Blake, 1987). Amphibolites have tholeiitic compositions consistent with intrusion into thinned continental crust (Glikson et al., 1976) and yield 1685 Ma magmatic zircon ages (Butera et al., 2005) identical to those obtained from detrital zircon in their host rocks, indicating that sedimentation and magmatic intrusion were contemporaneous in at least part of the Soldiers Cap Group. Turbidite deposition in Soldiers Cap Group is consequently viewed here as a response to the same syn-rift extensional processes that gave rise to the Prize Supersequence farther west, notwithstanding the observation that the turbidites have a slightly younger age. Following later deformation accompanying the Isan orogeny, Soldiers Cap Group was thrust westwards over the previously deposited post-rift sequences of the Leichhardt Superbasin on a structure (Cloncurry Overthrust) that probably originated as a major normal fault.

Farther west in the LRFT, near-shore, shallow water conditions persisted until arrested by a thermal perturbation at ca. 1670 Ma, accompanying intrusion and extensional unroofing of the Sybella Granite and its country rocks from mid-crustal depths (Gibson et al., 2005). Unroofing took place on an ENE-dipping detachment surface that brought about erosion and reworking of rocks belonging to the Leichhardt Superbasin and older parts of the Calvert Superbasin, and their subsequent redeposition in half-graben elsewhere in the basin. Shear fabrics in the Sybella Granite and rotated tilt blocks in Calvert age rocks above the detachment on which unroofing took place further indicate that extension during this stage of basin evolution involved displacement of the upper plate towards the NE and thus on a detachment that dipped oceanward in the same direction as deeper water, increasingly marine conditions developed (Soldiers Cap Group and younger rocks).

Fluid sources and pathways in relation to crustal architecture

By virtue of their structural position and depositional age in an evolving continental rift, the Western and Eastern Successions are characterised by different sedimentary facies and show a lateral and vertical trend towards progressively deeper water environments with fluviatile-shallow marine conditions increasingly superseded by more open marine conditions. Sediments deposited in oxidising, occasionally evaporitic shallow-water environments are increasingly buried below deeper water sedimentary sequences deposited under more anoxic (reduced) conditions. Shallow water environments are likely to have been an important source of brines, particularly if coupled to evaporitic conditions in either a lacustrine or shallow marine shelf setting. Subsequent burial of these brine-bearing reservoirs would have created conditions suited to the leaching of metals, although at this stage it cannot be determined whether the metals were sourced locally or from deeper in the sedimentary-volcanic pile. Irrespective of such questions, the boundary between oxidized and anoxic (carbonaceous) packages is likely to be of prime importance as an exploration target because it is represents both a seal and a steep geochemical gradient (redox boundary) along which, or across which, there may have been periodic fluid flow and/or mixing. In the Broken Hill region, a regional redox boundary serves as the locus for several major mineral deposits. The equivalent boundary in the Mount Isa region is the surface at the base of the Soldiers Cap Group, now represented by the post-depositional Cloncurry Overthrust.

In addition to an evolving sedimentary environment induced by changes in crustal architecture, several other elements are likely to have contributed to conditions conducive to formation of an ore-body: a heat source in the form of synkinematic magmatic intrusion; a plumbing system that links normal faults at upper crustal levels to extensional shear zones at mid-crustal depths, source rocks for metals and fluid generation in the volcanic and sedimentary sequences laid down during crustal extension; and appropriate seals in the form of syn- and post-rift carbonaceous rocks that prevented early escape of potential mineralizing fluids. It is equally evident that many of these key elements are present at all scales from individual half graben up to the superbasins themselves. Critically, most of the key elements must have been in place during or immediately following the cessation of crustal extension because presently available Pb model ages for Broken Hill-style and Mount Isa-style Pb-Zn mineralization preclude ore formation consequent to deep burial beneath younger post-rift sediments of the Isa Superbasin.

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Big system-big picture: integrating geology, geophysics, seismology, geochemistry and geochronology to determine why the Yilgarn is there. Setting the scene for the Laverton region.

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Introduction

The main economic driver for most mineral explorers is finding the next big ore body. This quest is proving to be elusive despite the vast array of tools and techniques that have been employed in this search. As with other ore-deposit types, small orogenic gold deposits have the same deposit-scale geological and geochemical features as the big/giant deposits (Goldfarb et al., 2004). More detailed studies at the deposit end of the system are necessarily not going to find the next big one; rather, studies at a different scale are required to define signatures that will help identify favourable ground for the discovery of new giants (Goldfarb et al., 2004). At the broadest scale, the mineral exploration process generally starts with some form of terrane selection. It is, therefore, very important to have a good understanding of the 4D evolution of a province and its constituent terranes in order to make a first order evaluation and ranking of one terrane over another.

Hronsky (2004) presented a conceptual pyramid model for the hierarchy of the scale of processes of a generic mineral system. In this model, mineral deposits sit atop a pyramid reflecting the focus of large mass and energy transport systems. At the base of the pyramid lie the processes operating at the global scale (e.g., secular change, plate reorganisation, climate etc.), and in the intermediate position lie the processes operating at the province (e.g., delamination, regional tectonic drivers etc.), sub-province (e.g., major fluid pathways), district to camp scales (e.g., subsidiary structures, specific alteration gradients), and finally to the deposit. Fortunately, the larger and more energetic systems generally equate to bigger ore deposits, and these systems have large footprints that are more easily imaged or detected. Despite being able to recognise parts of the system (e.g., breaks in Moho tomography), the precise genetic links with mineralisation (apex of the pyramid) remain unclear.

This paper considers the largest parts of the system and considers geodynamic processes and architectural consequences at the scale of Yilgarn Craton and its mantle lithosphere. The process involved in developing such an understanding must rely on the integration of results from many disciplines within the Earth Sciences. Several of the questions that need to be asked during this process are:
Do we understand the deep crustal architecture including the lithosphere?
Do we understand structural controls on various stages of the geodynamic history, including the late stage evolution, processes and deformation history?
Do we understand deformation processes and timing within regions of known mineralisation so we can test exploration strategies based on structural targets at all scales?

One critical element in each of these is being able to understand the depth dimension, and to do this the best way is to use all available seismic data, from shallow reflection data through to lithospheric scale tomography data. Within the Eastern Yilgarn Craton, researchers are fortunate to have a good seismic coverage to provide a whole of lithosphere framework in which to work. In addition there is a good craton-wide geological coverage including detailed geochemical and isotopic data sets.

Recent work by the *pmd**CRC is progressing the integration of the geology, geophysics, seismology, geochemistry and geochronology of the Yilgarn Craton into a craton scale three-dimension model and allowing the hypothesising of why the Yilgarn Craton is so well endowed. This work (Blewett et al., 2004; Blewett, 2005, Henson et al., 2005; Goleby et al., 2006) has suggested that lithospheric scale processes are responsible for the present data Yilgarn Craton architecture and that these processes have played an important role in mineral focusing within unique regions. They postulated that craton-wide delamination of the basal part of the lower crust occurred and that this process explains the temporal link between the late-stage Low-Ca granites and the late-stage gold event that occurred almost simultaneously across the entire Yilgarn Craton (Cassidy et al., 2002; Blewett, 2005). Such a lithospheric-scale process is consistent with many of the seismic and geological observations, including the presence of a thin crust, an easterly dipping Moho, a fast easterly dipping S-wave velocity layer body at 100-120 km depth and an apparent simple layering within the crust and upper mantle (Goleby et al., 2006). Heat introduced into the base of the crust during this process resulted in widespread melting and the emplacement of Low-Ca granites during late-orogenic extensional collapse (Blewett, 2005).

We further investigate the 'big system-big picture' within the Yilgarn Craton and set the scene for the Laverton region.

Big-picture data sets

Seismic data available within the Yilgarn Craton includes lithospheric-scale 3D teleseismic S-wave velocity volumes from distant earthquakes, crustal-scale 1D receiver functions, 2D wide-angle velocity profiles and 2D regional deep seismic to mine-scale seismic reflection transects. At the lithospheric scale, S-wave velocity measurements reveal clearly identifiable large-scale velocity variations (Fishwick et al., 2005; Goleby et al., 2006), including a fast, east dipping S-wave velocity anomaly (>4.8 $km.s^{-1}$) within the upper mantle. This fast S-wave velocity anomaly has a series of step-down offsets (edges) that coincide approximately with the known highly endowed areas within the craton. Receiver Function velocity profiles show a first-order correlation between the province's characteristic velocity function and the larger-scale geological subdivision of the craton (Goleby et al., 2006; Reading et al., 2006). The receiver function data agree with the deep seismic reflection data on the depth to the Moho, with both indicating the Moho deepens to the east. Crustal scale seismic refraction results (Drummond, 1988, Dentith et al., 2000) indicate the middle and lower crust is predominately felsic in composition. An extensive deep seismic reflection coverage provides crustal-scale geometrical constraints on the architecture, in particular the geometry of the region's fault systems as well as variations in the thickness of the granite-greenstone succession. The seismic reflection data suggest that the world-class mineral systems involved deeply sourced fluid flowing up crustal-penetrating shear zones and being focussed into sites located above fault-breached domal regions in the upper crust (Blewett, 2005; Henson et al., 2005; Goleby et al., 2006; Henson et al., 2006).

In addition to the seismic data sets described above, the Yilgarn Craton has a well-populated stratigraphic, geochemical, and geochronological database which, when integrated, provide powerful inferences for the geodynamic evolution. The preserved Yilgarn Craton consists of meta-volcanic and metasedimentary rocks and granites that formed principally between ca. 3.05 and 2.6 Ga, with a minor older component (to >3.7 Ga). Previous subdivisions of the Yilgarn Craton have been on the basis of greenstone morphology (Gee et al., 1981) or fault-bounded tectonostratigraphy (Myers, 1995). These subdivisions, however, have not taken into consideration the felsic magmatic rocks that form over 70% of the craton. Over the past ten years, systematic studies of the granites and gneisses provide key constraints on the evolution of the Yilgarn from the earliest recorded events at >3.7 Ga to major plutonism between ~2.76 and

2.63 Ga, and provide an indication of the nature of large-scale processes. Felsic rocks from across the Yilgarn have been used as crustal probes to constrain the age and extent of basement terranes (Cassidy et al., 2005). A collage of crustal fragments is revealed that implicates both autochthonous and allochthonous components for the crustal development. The studies indicate a complex history of crustal recycling throughout the Mesoarchaean and Neoarchaean. Autochthonous development for much of the granite-greenstone terranes in a continental environment is implicated. Voluminous granite intrusion, between 2.76 and 2.63 Ga, was coincident with Neoarchaean orogeny that resulted in the amalgamation and assembly of several cratonic elements to form the present Yilgarn Craton.

The Sm-Nd isotopic system is a proxy for the separation from the mantle (T_{DM}) and is an indicator of the primitiveness of a particular volume of crust (Cassidy et al., 2005). Although these T_{DM} data are broad, there are systematic differences between the terranes. In virtually all cases the Nd model age is significantly older than crystallisation age of the host granite and/or felsic volcanic rock, generally 200-300 Myr and sometimes over 500 Myr older. There are a number of obvious divisions, with the central-western Yilgarn consisting of relatively consistent block (?protocraton) of 3.3-3.1 Ga old crust, except for a belt of younger 3.0-2.95 Ga model ages in the north-west part of the terrane. A distinct ‘break’ that approximates to the Ida Fault marks the possible eastern margin of the Youanmi terrane, and virtually all granites east of the Ida Fault have Nd model ages <3.1, and generally <2.95 Ga. The Eastern Yilgarn is an isotopically complex region that can be divided into several zones, and the isotope distribution in the granites mirrors the distribution of the komatiites. The youngest T_{DM} ages are located in an elongate north-south zone through the central Kurnalpi Terrane, and these correspond to poor gold endowment, and few if any komatiites. Conversely, this zone has increased occurrences of VHMS deposits (e.g., Teutonic Bore). Gold and komatiite occur in regions where the crust has a T_{DM} age of 2.9 Ga to 3.0 Ga. The reasons for this are unknown at this stage but, interestingly, the Abitibi Subprovince in Canada is equally well-endowed in gold and VHMS deposits, and these are hosted in the most juvenile crust.

The deformation history for the Yilgarn Craton is complex and long lived and a succession of deformation events has produced structurally bounded architecture of north-south oriented regional-scale terranes (Swager, 1997). These province and terrane boundaries are mapped as regional scale shear zones, many are considered to reflect a sequence of extensional and contractional deformational events. The deep seismic reflection, in most cases, has successfully imaged these shear zones and provided both geometry information and structural relationships.

The resulting crustal evolution of the Yilgarn places significant constraints on the development of various metallogenic associations that may provide some important implications for terrane selection.

Big-picture constraints from Seismic Data

The crust is approximately 33 km thick beneath the Southern Cross Province, thickening to 40 km in the Leonora region, 42 km in the Laverton region and 46 km at the eastern end of the seismic traverse, near the Albany-Fraser Province. This deepening of the Moho is achieved by a series of ramps and flats, with the Moho generally sub-horizontal for long sections, then ramping downwards over short distances. Within the crust, there are three distinct sub-horizontal layers, which have superimposed, a prominent fabric that dips 30° easterly. Within this east-dipping fabric, there are four prominent east-dipping shear zones. All three deep penetrating shear zones have a complex geometry, suggesting that these zones developed during several episodes of deformation.

Refraction seismic data recorded predominately low velocities within the crust (Drummond et al., 1993; Fomin et al., 2003) which implies that the Yilgarn Craton consists of essentially felsic material with only a small percentage of mafic (dense) material within the lower crust. This predominately felsic composition raises the issue of where is the dense garnet-rich lower crust residue from the High-Ca granite magmatism (as postulated by Champion and Sheraton, 1997;

Smithies and Champion, 1999). One solution is that this layer delaminated and is mapped as the high-velocity S-wave layer within the upper mantle.

Receiver function velocity profiles show geologically correlatable and internally consistent velocity differences across the Yilgarn Craton. These profiles can be attributed to fundamental changes in the composition of the crust within each province (Reading et al., 2006; Goleby et al., 2006). The receiver function results also confirm that the Moho deepens eastward across the craton. Reading et al. (2006) proposed extensive reworking of crustal rocks, resulting in the lower crust becoming more felsic and that the crustal architecture and resultant velocity profile imaged was 'frozen in' for each province prior to the assembly of the craton.

Craton scale tomographic S-wave data show that the lithosphere is around 220 km thick beneath the Yilgarn Craton. The craton consists of low velocity crust underlain by mantle material, with S-wave velocities faster than the world average (Kennett, 2003; Fishwick et al., 2005), indicating the Yilgarn Craton lithosphere is fast, depleted, refractory, cold, less dense, dry, strong and buoyant. The S-wave velocity data map the location of a region of higher-velocity S-wave material beneath the Yilgarn Craton. This higher-velocity body has an overall southeast dip and is located at a depth of 70 km beneath the Murchison Province, increasing to approximately 100 km beneath the Ida Fault, then approximately 120 km beneath the Laverton region. There is an indication that this body is not just a single southeast dipping slab but rather it steps down across a series of structures. The location of the edges and steps of this higher-velocity lithospheric body appear to approximate with regions of significantly enhanced mineralisation. When the locations of recorded mantle nodules, kimberlites, lamprophyres and carbonatites were displayed in relation to these edges defining the higher-velocity body a similar 'fit' was observed. However an improved 'fit' between mantle-derived magmas and mineralisation and the edges was achieved when a 100 km northwest-directed relative shift of the crust is applied at the Moho. Although it is a somewhat circular argument in improving the fit, consideration of the possibility of relative movements between the crust, the mantle and within the mantle should be made, especially if area or terrane selection is made on this basis.

Big system-big picture implications for predictive mineral discovery

We suggest that the gold deposits within the Yilgarn Craton are the result of processes at a range of scales, including the lithospheric scale. We now believe we can predict which domain will be mineralised. Exactly where within that domain still relies on additional geoscientific analysis. The prospective domains are located through the chance arrangement of fluid fluxes that originate from the upper mantle, some existing pathways into the upper crust via the deep penetrating shear zones, suitable focusing and ponding locations, and a favourable upper crustal geology-geochemistry. Within the upper crust, Henson et al. (2005) has shown a strong relationship between location of dome structures and world-class ore deposits. The geometry and relationship of these faults to other shears is a key control in gold distribution. The spatial association between mantle tapping magmas and large gold deposits may reflect a common pathway, a source for fluids and metal, or both. At the crustal scale, the seismic reflection method is mapping possible pathways. At the lithospheric scale, seismic tomography methods are potentially imaging the source area.

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Towards a unified architecture of the Laverton Region, WA

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Introduction

The Laverton region ranks a close second to the Kalgoorlie region for Au endowment and contains the world class Sunrise Dam (>9 million ounces gold; Newton et al., 1998) and Wallaby (7.1 million ounces gold; Nielsen & Currie, 1999) mines. As part of research into this region, the *pmd**CRC has adopted the use of three dimensional software packages to build 3D geological maps, to provide new insights into the region's **architecture** and fluid pathways, and to gain a better understanding of the characteristic detectable properties/ features of Au deposits.

The software package GOCAD^R has been used to visualise a variety of mine and regional scale data to constrain the three dimensional architecture of faults and lithological packages. Significant industry involvement has enabled the compilation of a world class dataset to be integrated into the latest surface and subsurface interpretations of the Laverton region. This has enabled new insights to be made into the architectural elements of Au systems and a greater understanding of the formation of giant deposits.

Definition of regional architecture is highly dependent on detailed surface solid geology. Reinterpreted solid geology for the Laverton region was constructed using a combination of detailed industry geological data sets, historical regional geological interpretations, and industry potential field data merged with regional geophysical datasets to produce an improved regional coverage. The area also contains three regional seismic reflection lines and nine short industry lines. These data combined to provide significant constraints in the interpretation of the three dimensional architecture in the Laverton region.

The structural history of the Laverton region is complex. Examination of map patterns in three dimensions, integrated with pre-existing (Blewett et al., 2004) and contemporary structural studies (Miller, 2006), have defined four regional deformation events that appear to have played dominant roles in developing a suitable architecture for mineralisation (Table 1).

D_1	~E-W extension	The development of large extensional faults and detachments facilitating granite intrusion and probable large scale dome formation
D_2	~E-W contraction	The development of ~N-S trending folds
D_3	~NW-SE contraction	Sinistral movement of pre-existing faults and intrusion of mantle-derived magmas
D_4	~NE-SW contraction	Dextral reactivation of early structures

Table 1: A simplified structural history for the Laverton region (Miller, 2006).

Deep tapping faults (fluid pathways lower crust)

Previous researchers have noted that deep crustal-penetrating faults are spatially associated with giant mineral deposits (Goleby et al., 2003). This implies that the source of mineralising fluids (and, possibly the gold) was deep, and they migrated via pathways associated with these faults into upper crustal areas where the gold was deposited in suitable structural and lithological sites. One such east-dipping fault zone is well imaged in the seismic reflection data within the Laverton region. The regionally acquired 01AGS-NY1 seismic reflection line clearly displays a significant shear zone described as the Laverton Tectonic Zone (LTZ) extending down to the Moho. Further evidence of the LTZ can be imaged on both the 01AGS-NY2 (over Wallaby Mine) and 01AGS-NY4 (over Sunrise Dam Mine) seismic reflection lines (see also Chopping, 2006). The LTZ delineates the bulk of mineralisation in the Laverton region, with Sunrise Dam, Wallaby and Granny Smith deposits occurring within the zone. A series of faults delineating the LTZ at surface display a complex array of interconnected often sigmoidal geometries in plan view. The three dimensional geometry of these faults indicate that they have a variable dip (sigmoidal) and they sole at depth into one large crustal detachment that penetrates to the Moho (the LTZ). It is this deep structural architecture that provides fluid pathways from the lower crust that can be further focused into suitable sites within the upper crust.

Dome formation (fluid focussing mid-upper crust)

A recurring feature of the architecture defined by 3D maps is domes and anticlines, spatially associated with some of the region's larger gold deposits. The architecture of the Laverton region is defined by domes and associated deep crustal penetrating faults (LTZ) which are closely linked to its endowment. At the semi-regional scale, domes are defined at several levels within the upper 10-15 km of the present crust. The gross geometry of the Laverton region identified in this study is that of a doubly plunging dome that links the Mt Margaret Dome in the northwest with the Kirgella Dome in the southeast. These granite-cored domes consist of multi-age and multi-phase felsic intrusions that underlie the Laverton greenstone belt.

The base of the Laverton greenstone belt has been mapped from 0 to 7 km thick, with a dome-and-basin geometry (mirroring the granite shapes further below), and clearly delineated in 2D map patterns. Beneath the greenstone base, the felsic (granitic) upper crust is dominated by sets of high-amplitude seismic reflections that are interpreted as fossil shear zones altered by fluid flow during orogenesis and mineralisation (see Chopping, 2006). These high-amplitude reflections are openly folded into a series of stacked domes of ever decreasing wavelength upwards towards the greenstone base. These stacked domes are interpreted to provide an efficient pathway for focusing orogenic fluids into the apex of the domes at higher structural levels (cf. Sheldon et al., 2006, for numerical modelling of fluid flow and domes). 'Breaching' faults occur near the apex of many domes, forming pathways for the dome-focused fluid to migrate to progressively higher structural levels for subsequent trapping and potential mineral deposit formation.

The timing between the folding/doming and granite emplacement is unclear. Granites that crop out in the north and south in the dome core have a range of ages from >2700 Ma to ~ 2640 Ma (Cassidy et al., 2002). If the granites are late syn-folding then magmatic fluids may have contributed to the fluid flux and mineralisation. If they are pre-folding, rheological contrasts may have influenced local stress fields and also explain the local endowment. Both these factors may be important.

Au deposition (Sunrise Dam and Wallaby deposits)

The main stage of Au deposition was around 2650 ±6 Ma (Salier et al., 2004), and this period was coincident with emplacement of mantle-derived felsic intrusions (Cassidy et al., 2002; Miller, 2006). These mantle-derived rocks are commonly spatially related with Au deposits (e.g., syenites at Wallaby, Mafic-type granites at Granny Smith). In some cases, igneous bodies can be imaged beneath Au deposits using seismic reflection data, although the precise genetic links at Laverton are equivocal within our current datasets. The contribution of granitoids to the mineralising process is problematic and currently can only be qualitatively linked. The structural trap, however, is clearly delineated at the mine scale as a series of dilational structures and this study demonstrates that regional scale processes can be linked back to these geometries.

Structural analysis across the region (Blewett et al., 2004), and at the Wallaby and Sunrise Dam deposits indicate that equivalent stress fields operated during the mineralisation phases within both deposits (Miller, 2006). These mine scale similarities raise interesting questions regarding the overarching regional architecture needed to produce a genetic link between both mines. Lithologically, Wallaby and Sunrise Dam are quite different. Wallaby is hosted within a conglomeratic unit, while Sunrise Dam is hosted within intermediate volcanic rocks. Structurally though, both deposits display striking similarities and more interestingly, the gross structures within the Wallaby Mine are the 'mirror image' of those within Sunrise Dam. Although structurally complex, the dominant through going structures are shallow 15-40° thrusts which can be identified in 3D map patterns (Figure 1), dipping to the NW at Sunrise Dam and to the SE at Wallaby Mine. Within both deposits numerous steep structures occur that are variably offset by the thrusts (for details refer to, Miller, 2006).

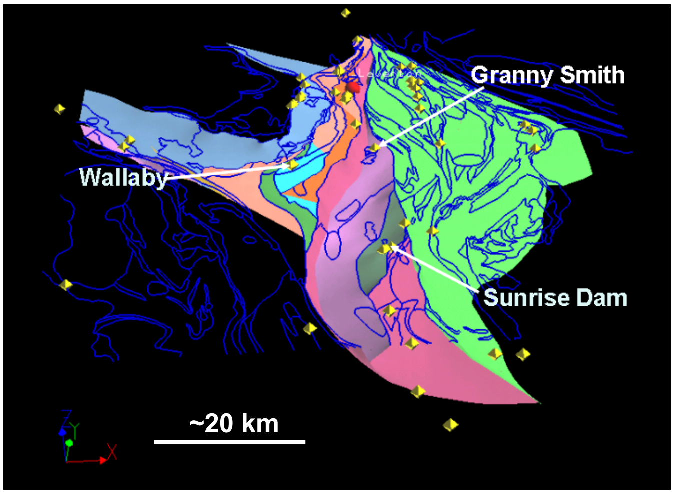

Figure 1: Gocad image of the Laverton region looking north, displaying 3D fault surfaces. Opposing low-angle faults (thrusts) at Wallaby and Sunrise Dam sole into a central, steeper strike-slip structural corridor. Blue lines represent fault traces and solid geology outlines.

Both mines are separated by a large structural corridor which records both sinistral and dextral movement during its history (Table 1). In order to produce co-genetic deposits within an overarching structural framework, critical architectural elements must combine within a specific stress field. In an attempt to categorise a regional structure capable of linking both deposits, the current interpreted 3D geometries were compared with some analogue modelling of strike-slip scenarios, superimposed on early discontinuous 'extensional' faults. The structural model that best fits the current architecture is a restraining stepover within a sinistral strike-slip system (McClay and Massimo, 2001) (Figure 2).

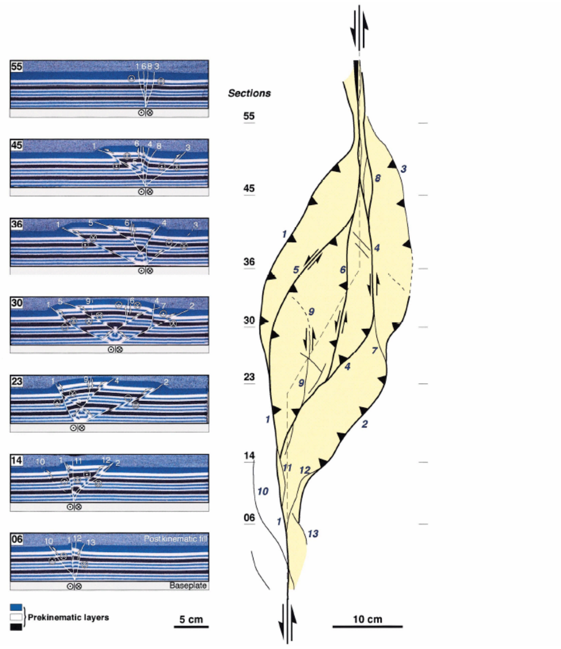

Figure 2: Diagram from McClay and Massimo (2001), displaying an analogue model of a restraining stepover within a sinistral strike-slip system. Both plan and section views are displayed. The similarity in geometry between this analogue model and the regional architecture at Laverton are striking.

In a comparison with this analogue model (Figure 2), two early extensional basement faults are reactivated during northwest-southeast contraction (D_3) producing low-angle thrusts in a pop-up zone. This architecture exists in the region between Wallaby and Sunrise Dam, where both deposits are located on the low-angle thrusts on opposing sides of a sigmoidal structure, produced by sinistral strike-slip movement. This process would provide significant dilation and also drive fluids, through overpressuring to sites of deposition (see Miller, 2006). It is not expected that significant movement occurred on the basement faults during this event. Late dextral movement of the basement faults during NE-SW contraction (D_4) reactivated the low-angle thrusts at both Wallaby and Sunrise Dam producing normal movement and further dilation within the overall restraining stepover. Identification of a mega structure (large restraining stepover) controlling the co-genetic nature of both Wallaby and Sunrise Dam deposits provides an explanation for Au deposition at the two known sites (Miller, 2006), but also provides numerous potential sites of Au deposition in the region between them (Blewett et al., 2006 and Chopping, 2006).

Conclusions

The geometries constructed within the Laverton 3D map provide insights into the formation of world class gold deposits. The early extensional architecture provides a critical framework onto which all subsequent deformations develop. A large crustal penetrating shear zone probably developed early in the structural history of the Laverton region and provided a suitable conduit for tapping mineralising fluids at depth. This structural zone and its subsidiary extensional structures facilitated the early intrusion of significant felsic igneous bodies into the upper crust. The extensional process unloaded the crust developing core complexes and doming of the units surrounding the syn-intrusive granites (McIntyre & Martyn, 2005). This domal architecture provided a focussing mechanism for rising mineralising fluids concentrating their flow in the mid-upper crust. Late-stage mantle-derived intrusive bodies are spatially related to many Au deposits and, although no direct link can be drawn, seismic reflection data delineate bodies with a seismic reflection character similar to that of granites below some major deposits. A genetic link can be drawn between Wallaby and Sunrise Dam deposits placing them within a large scale restraining stepover, developed during sinistral strike-slip movement of pre-existing basement faults, that was reactivated during late dextral strike-slip movement. This is evident in the architecture, geochronology and structural histories of both deposits.

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Noble gases and halogens in crustal fluids: New data through space and time

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Introduction

Combined noble gas and halogen data are now available from fluid inclusions in ore deposits formed in diverse geographic location, depth in the crust and at different times in Earth History. Two years ago the combined dataset included Mississippi Valley-Type (MVT) districts from the central US and the UK, Porphyry Copper Deposits (PCD) from the US, granophile mineralisation from the UK, and sandstone-hosted Pb-Zn deposits in Sweden, all of which have a Phanerozoic age and were formed in the upper 1-2 km of the Earth's crust (Kelley et al., 1986; Turner and Bannon, 1992; Böhlke and Irwin 1992a 1992b; Kendrick et al., 2001a, 2001b; 2002a,2002b; 2005).
Over the last two years, new data have been acquired from several ore deposits in the Mt Isa Inlier of northeast Queensland. The Australian deposits include the Mt Isa Copper deposit and 'IOCG' (Iron Oxide Copper Gold) deposits such as Ernest Henry, Eloise, Osborne and Starra (Fisher et al., 2005; Kendrick et al., 2006a, 2006b). All of the deposits studied formed during the Proterozoic at ~1.5-1.6 Ga and at depths in the crust of between 6 and 10 km.
The total dataset of all the ore deposits now studied includes examples formed from surface fluids (modified meteoric water), crustal fluids (bittern brines or sedimentary formation waters), and deeply derived magmatic fluids evolved during the crystallisation of igneous rocks or metamorphic fluids evolved by dehydration of the basement.
It has long been known that the mantle is characterised by $^{40}Ar/^{36}Ar$ values more than two orders of magnitude greater than the atmosphere ($^{40}Ar/^{36}Ar$ of meteoric water = 296; MORB = 44,000; see Ozima and Podosek, 2002). Upper-crustal fluids, however, typically have $^{40}Ar/^{36}Ar$ between 296 and only ~3,000 (e.g. Kendrick et al., 2001a). In the last two years, since noble gas and halogen studies have been extended to include fluids from the mid-crust, the true extent of the variation in $^{40}Ar/^{36}Ar$ values and noble gas concentrations have been revealed.
The new data provide an enhanced understanding of noble gas geochemistry in mineralising fluids. We will demonstrate that it is now possible to confidently distinguish 'evolved' bittern brines from metamorphic fluids and to quantify the role of magmatic fluids in ore genesis. As expected, our data confirm the presence of magmatic fluids in the Ernest Henry IOCG deposit. We can demonstrate, however, that magmatic fluids were not present in the majority of deposits traditionally classified as 'IOCG' (see poster). A second surprise is that the Mt Isa Copper deposit is most likely to have formed from metamorphic dehydration fluids, and a surface-derived evolved bittern-brine origin is precluded unless previously unrecognised fluid boiling has occurred.

Crustal Fluids from the top down

Low salinity surface fluids have Air Saturated Water (ASW) ^{36}Ar concentrations of 1.3-2.7 ppb, dependent on temperature plus salinity, and a $^{40}Ar/^{36}Ar$ value of 296 (Ozima and Podosek, 2002). In arid climates, shallow marine lagoons or inland lakes acquire elevated salinity as a consequence of evaporation. Because rainwater acquires trace Br, Cl and I from the ocean, inland lakes quickly acquire seawater-like compositions. Evaporation to higher salinities, in either a lake or a lagoon, results in a reduced concentration of ^{36}Ar, such that high salinity surface brines have <1.3 ppb ^{36}Ar (Smith and Kennedy, 1983). Bittern brines are generated when evaporation proceeds beyond the point of halite saturation (~30 wt %). Halite is then precipitated and Cl is preferentially removed from solution, resulting in an elevated Br/Cl value in the residual bittern brine (Seawater Evaporation Trajectory; Figure 1).

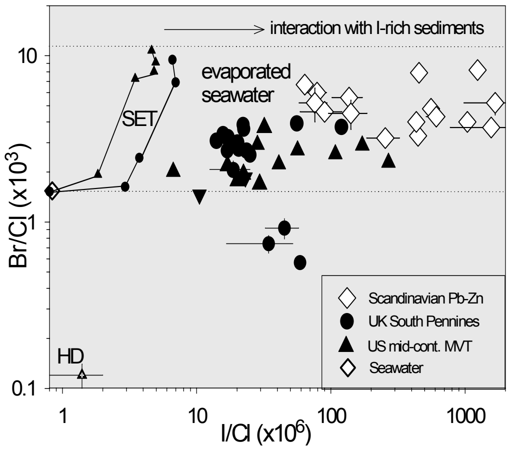

Figure 1: Br/Cl vs I/Cl values for MVT and Scandinavian sandstone hosted Pb-Zn deposits. SET = seawater evaporation trajectory.

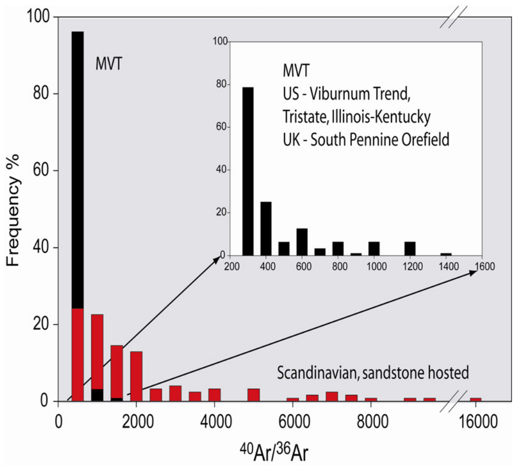

Figure 2: ^{40}Ar/^{36}Ar values for MVT (black) and Scandinavian sandstone hosted Pb-Zn deposits (grey).

Bittern Brines in MVT

Bittern brines that become involved in epigenetic MVT mineralisation have infiltrated the sub-surface and acquired Pb and Zn from fertile source rocks (Ozark MVT have regional extent of 240,000 km^2; >140 Mt 5% Pb + Zn mined from Viburnum Trend). Bromine and Cl behave conservatively in most crustal environments meaning the origin of the bittern brine can be deduced from the Br/Cl value. The I/Cl value, however, is increased through interaction with I-rich sedimentary rocks, the ^{40}Ar/^{36}Ar value is increased to values of <1,500 (Fig 2.), and the ^{36}Ar concentration is increased to ~3-27 ppb (Turner and Bannon, 1992; Kendrick et al., 2002a, 2002b). It is fairly rare for MVT to have acquired their salinity by the dissolution of halite, but the Hansonburg MVT of New Mexico is one example (HD in Figure 1; Bölhke and Irwin, 1992a).

Evolved Bittern Brines in Laisvall Pb-Zn

The sandstone-hosted epigenetic Pb-Zn deposits of Laisvall, Sweden (120 Mt at 4% Pb and Zn) have long been compared to MVT because of their superficially similar mineralogy and crustal setting. ^{40}Ar/^{36}Ar values, however, determined for the Laisvall deposit, however, range up to 16,000, which is an order of magnitude higher than the highest measured in 'typical' MVT deposits (Figure 2).
The data are compatible with 'thin skinned' migration of MVT bittern brines through sedimentary aquifers in the upper 1-2 km of the crust from a foreland basin that has a greater elevation than the site of mineralisation (e.g. Leach and Rowan, 1986). In contrast, fluids involved in the Laisvall ore deposit probably originated in the continental-rise-prism on the Baltoscandian margin of Scandia. The continental margin was lower than the eventual site of mineralisation and fluid migration may have been triggered by overthrusting of the sediment prism with Scandian nappes during the continent-continent collision that followed closure of Iapetus (Kendrick et al., 2005). This idea is supported by petrographic observations and Ar-Ar dating of K-feldspar overgrowths (Sherlock et al., 2005). During this process the mineralising fluids were 'tectonically' buried to an unknown depth and interacted with the Precambrian basement acquiring high ^{40}Ar/^{36}Ar values

that are distinct to all other MVT studied to date (Figure 2). The evolved bittern brines at Laisvall also have elevated ^{36}Ar concentrations of ~20-40 ppb that are higher than most MVT (Kendrick et al., 2005).

Metamorphic Fluids in Mt Isa Cu

Our data (Kendrick et al., submitted) show that silica-dolomite alteration associated with the 255 Mt (at 3.3 % Cu) Mt Isa Cu deposit is characterized by maximum $^{40}Ar/^{36}Ar$ values of 28,000 in the Buck Quartz vein in the Cu-orebody's footwall, and similar values of 8,000-21,000 in the silica. These $^{40}Ar/^{36}Ar$ values are higher than has been measured in any Phanerozoic ore deposit formed in the upper crust. The dolomite alteration has lower values of 1,600-8,000, which are similar to MVT and Laisvall fluids with bittern brine origins.

Previous fluid inclusion, stable isotope and Br/Cl studies of Mt Isa have indicated a fluid origin as either an evolved bittern brine or as a metamorphic fluid (Heinrich et al., 1989, 1993, 1995). Because Mt Isa has high Br/Cl values similar to MVT, all recent research has assumed a surface bittern-brine origin and the ECV that underlie the site of mineralization have been proposed as a Cu-source (e.g. Heinrich et al., 1995).

The new data favour a metamorphic fluid origin for silica fluid inclusions that are most closely associated with Cu. Evolved bittern brines are expected to have ^{36}Ar concentrations of >20 ppb and the ^{36}Ar concentration should be positively correlated with $^{40}Ar/^{36}Ar$. Metamorphic fluids have ASW or lower ^{36}Ar concentrations similar to those measured in silica fluid inclusions (Figure 3; Kendrick et al., submitted). A metamorphic origin is compatible with the previously reported high Br/Cl values, because fluids in metamorphic environments are characterized by high (bittern brine-like) Br/Cl values (Svenson et al., 2001).

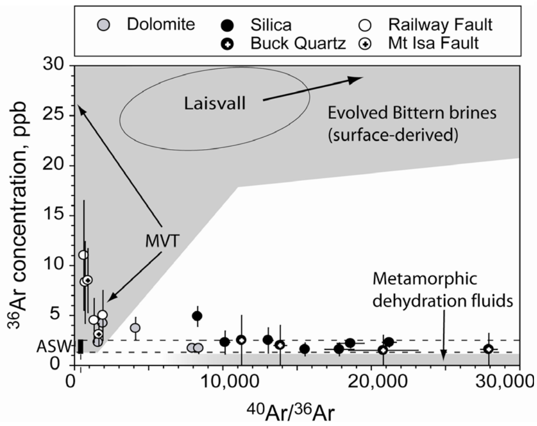

Figure 3: $^{40}Ar/^{36}Ar$ v. ^{36}Ar concentration for Mt Isa samples. Evolved bittern brines are expected to exhibit a positive correlation and have ^{36}Ar concentration of greater than ~20 ppb. The data from Mt Isa has a weak negative correlation and is explained by mixing a metamorphic fluid (in silica) with $^{40}Ar/^{36}Ar$ ~47,000 and ^{36}Ar concentration < 1ppb and a bittern brine (in dolomite) with $^{40}Ar/^{36}Ar$ ~1000 and ^{36}Ar concentration ~10 ppb (Kendrick et al., submitted).

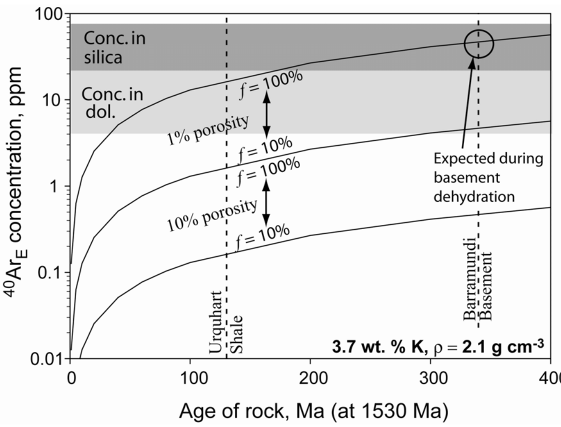

Figure 4: The concentration of excess $^{40}Ar_E$ in a fluid (non-atmospheric external source) can be predicted from the following relationship:

$$[^{40}Ar_E] = \frac{[\mathrm{K}] \cdot f \cdot \rho \cdot (^{40}K/K) \cdot (\lambda_e/\lambda) \cdot (e^{\lambda t} - e^{\lambda t_o})}{P} \cdot \times$$

P = porosity, f = ^{40}Ar extraction efficiency, ρ = density. The graph shows that the $^{40}Ar_E$ concentration in the dolomite fluid (4-24 ppm) could 'just' be acquired by degassing of the Urquhart Shale. The high concentration in the silica fluids <74 ppm can only be acquired by 100% degassing of the low porosity Barramundi Basement – supporting a metamorphic fluid origin.

Further evidence for a metamorphic fluid origin is provided by the silica fluid excess ^{40}Ar ($^{40}Ar_E$) concentration. The fluid $^{40}Ar_E$ concentration is limited by the concentration of $^{40}Ar_E$ in the rock aquifer (or source) and the degassing efficiency of $^{40}Ar_E$. The concentration of $^{40}Ar_E$ in the rock is determined by the concentration of K, the density, the age and the K-Ar decay equation (Figure 4). The concentration of $^{40}Ar_E$ in silica fluid inclusions is within error of that expected for 100% degassing of the low porosity Barramundi Basement (Figure 4; Kendrick et al., submitted).

A metamorphic fluid origin (for silica-hosted fluid inclusions) is compatible with the syn-D_3 timing preferred for epigenetic copper mineralisation at Mt Isa. Amongst other criteria, chalcopyrite is constrained as syn-D_3 by quartz overgrowths with D_3 orientation (Swager, 1985). Mineralization at Mt Isa may therefore have been synchronous with post-D_2 metamorphism of the Sybella Batholith at ~1530 Ma (Connors and Page, 1995; Perkins et al., 1999). Mineralisation may have occurred when the metamorphic fluids preserved in silica mixed with bittern brines better preserved in the dolomite fluid inclusions. The data support D_3 strain zones as the most promising exploration targets and suggest that geochemical models should evaluate basement rocks as a source of copper.

Compositional variation through time?

The data obtained from the Mt Isa Inlier have demonstrated that noble gas and halogen geochemistry can successfully unravel fluid origins in Proterozoic and older ore deposits (Kendrick et al., 2006b). Radiogenic ingrowth of ^{40}Ar is not a problem and can be corrected for on the basis of the simultaneous K measurement (extended Ar-Ar methodology). The data indicate that similar processes governed the concentration and composition of noble gases in the Proterozoic as they did in the Phanerozoic.

If Br/Cl values are to be used to choose between bittern brine and halite dissolution fluid origins, it is desirable to constrain the Br/Cl composition of Proterozoic seawater. To date, the Br-Cl-I composition of crustal fluids in the Mt Isa inlier are compatible with a steady state model. Mantle-derived magmatic fluids in the Ernest Henry IOCG have a similar Br/Cl composition to magmatic fluids in Phanerozoic PCD suggesting that the mantle has had a similar Br/Cl value since the Proterozoic. As the mantle Br/Cl value buffers the composition of seawater (Schilling et al., 1978), it is likely that seawater has also had a fairly constant Br/Cl value since the Proterozoic. The origin of IOCG deposits and the involvement of magmatic fluids are evaluated fully elsewhere (see poster).

Acknowledgements

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Numerical Models of fluid pathways in extension-related mineral systems

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Abstract

The migration of basinal brines into basement has been proposed as a means of scouring or leaching metals for subsequent ore deposition. Here we numerically examine competing processes, namely deformation, fluid flow and thermal gradients to highlight potential fluid pathways resulting in enrichment of metals and ore deposition in basin related mineralization. Stable convective cells may be established across the cover-basement interfaces if permeability contrasts are minimized, although, at the onset of extensional deformation these convective patterns quickly collapse. On cessation of the deformation, convection cells again develop, which are oscillatory with time. Input to the thermal budget from a radiogenic heat source suggests that basinal fluids can be drawn down around the margins of granite intrusions and fluid mixing processes may take place due to small and localised convective patterns. Fluid migration from basin into basement and back is highly likely given the right conditions. Nevertheless, the rate and extent of fluid flow is determined by thermal and deformation processes.

Introduction

Several factors are responsible for the behaviour of fluid flow during basin development, including compaction, topography, deformation, temperature, chemical complexities and combinations of the above (e.g. Domenico and Schwartz, 1998). The most accepted models for ore deposition in basinal settings include fluid mixing at the surface or subsurface, rapid pressure or thermal gradient changes and fluid-rock interactions. There is generally a lack of agreement, however, in the processes involved in fluid flow driving mechanisms. Numerical studies have proved useful in testing fluid flow driving mechanisms and the varying effects of deformation and temperature (e.g. McLellan *et al*., 2004; Simms and Garven, 2004), although, the complexity of coupling numerical processes has historically been a major problem. Here we aim to numerically investigate basin processes with the full coupling of deformation, thermal advection and fluid flow using FLAC 2D. In addition, we also investigate the role of intrusion-related heat sources and their effect on convection and fluid flow.

Conceptual Models

The conceptual models are based loosely on a rift-and-sag phase scenario (similar to the processes involved in the Mt Isa Inlier) Australia, where we include low permeability basement material, permeable sedimentary cover sequences, more permeable faults, and a large intrusion (e.g. Sybella Granite) providing a localised heat source (Figure 1). This geometry is consistent with the onset of Pb-Zn deposition of the Mt Isa Block (O'Dea et al., 1997; Betts et al., 2003), and in more general terms can be representative of SEDEX or near surface base metal mineralisation. This scenario also provides a good template for understanding the potential mixing of near-surface and deeper derived fluids in many other deposit types e.g. unconformity-related uranium deposits (Derome et al., 2003), Olympic Dam-style iron-oxide Cu-Au deposits (Hitzman et al., 1992) and core complex Au deposits (Lister et al., 1986) amongst others. Extensional deformation and thermal gradients are applied to the models at different stages, allowing comparisons to be made regarding the relative efficiencies of structurally and thermally-driven fluid flow. Preliminary models to investigate the role of a high heat producing granite are also presented. Fluid thermal properties were also considered and fluid has temperature dependent viscosity and density terms incorporated (see Oliver et al., 2006).

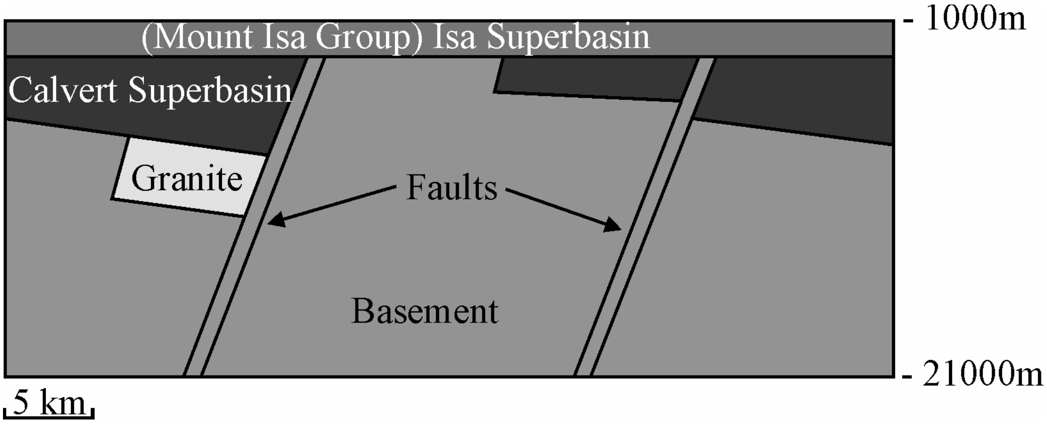

Figure 1: Starting block geometry showing the blanket of shales (Isa Superbasin) over a flooded unconformity consisting of rift-fill sediments of the Calvert Superbasin, and basement mafic volcanics, gneisses and granite, based on (Betts et al., 2003; Southgate et al., 2000). The model is approximately 50 km wide by 20 km deep, with the top surface being set at -1 km (representing the top model boundary as a flooding surface). The top model boundary is allowed to deform, has a fixed pore pressure and fluid is allowed to move across this interface.

Results

Three scenarios are presented here:
a) convection followed by deformation, which examines the potential of extensional fault reactivation as a cause for orebody localisation above long lived convection systems,
b) deformation followed by convection which examines the transition from active rifting, uplift and erosion, to blanketing by sag-phase shales and related SEDEX mineralisation, and
c) the influence of a radiogenic heat source from an intrusion.

Convection followed by extension

Coupling heat transport and fluid flow produces stable convections cells in the models, which are established across the cover-basement interfaces (Figure 2a), with maximum flow rates of 0.015 m/yr. The downward penetrating fluids allow cooler fluids to reach basement rocks through more permeable fault structures: this is also reflected in the thermal decay within the fault structures (Figure 2c). Following the onset of extensional deformation, with strain rates of 3 x $10^{-14}s^{-1}$, convection cells quickly collapse and do not re-establish during continued deformation, and dilation within the middle of the model and faults allows mixing of cooler surficial and warmer basement derived fluids (Figure 2b). This might provide suitable conditions for unconformity-related uranium deposits, or deposits that prescribe fluid mixing as an important genetic process, but not SEDEX style deposits. This is also evident in the thermal response in subsequent model steps (Figure 2d).

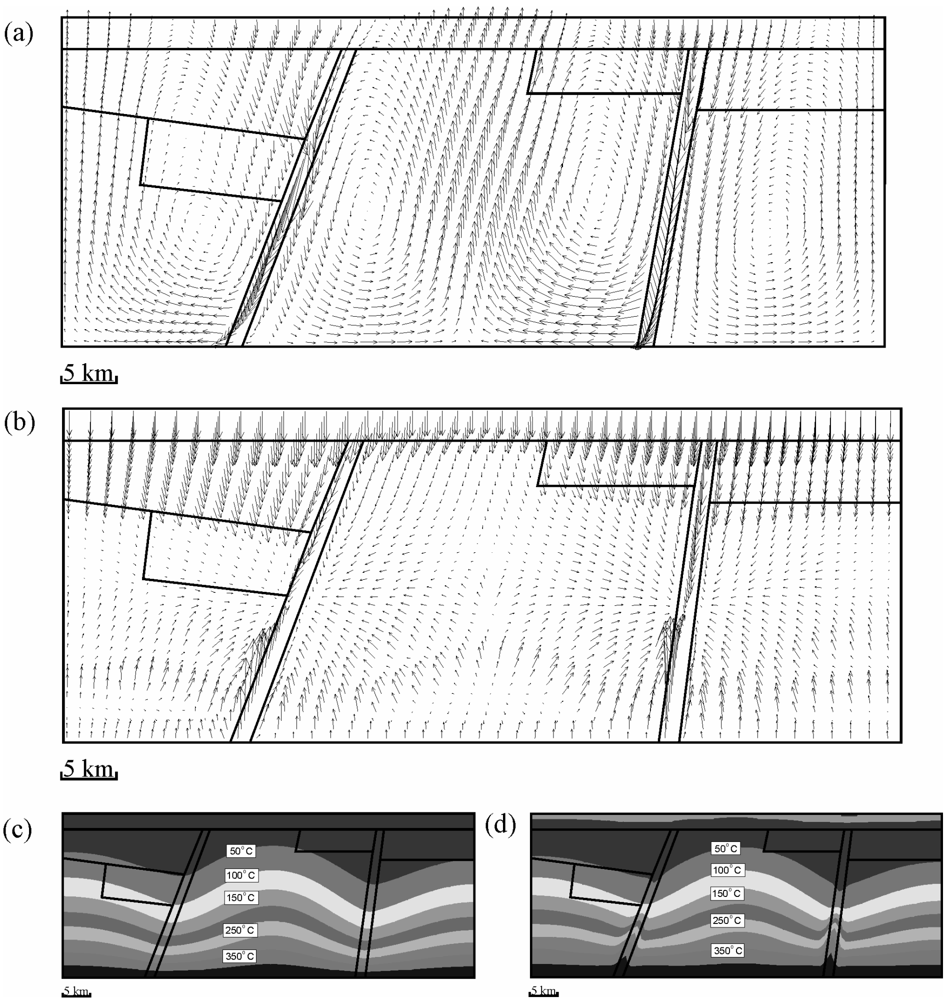

Figure 2: FLAC results for coupled deformation, heat- and fluid flow a) with no deformation, broad convection cells develop. b) When deformation is turned on at the modest strain rate of 3 x $10^{-14}s^{-1}$, convection cells collapse and fluid is drawn rapidly both down from above and up from beneath towards dilatant areas developed in the fault zones. c) Temperature distribution corresponding to the convection shown in a), showing broad cooling of the cover sequences. d) Temperature distribution after the fluid mixing shown in c), showing perturbation of isotherms due to the strong flow up and down the faults.

Extension followed by convection and the effects of overpressure

In light of the broader tectono-thermal evolution of the Mt Isa Inlier, extensional strain rates decayed with time from c. 1730 Ma (active rifting, volcanism and siliciclastics) to the onset of thermal subsidence, flooding of the rift, and deposition of the quiet-water Mt Isa Group shales at around 1650 Ma (Betts *et al*., 2003). The numerical models show that an initial extensional strain rate of 3 x $10^{-14}s^{-1}$ results in the deformation dominating the flow patterns, with downward migrating fluids and focussed flow within permeable faults. On cessation of deformation we see the development of convection cells as a result of temperature gradients with down-flow in the fault structures again evident in the thermal response. If overpressure is also applied to the base of the model, this stimulates initial upward migration of fluids (Figure 3a) and when deformation is ceased convection cells begin in the cover sequences (Figure 3b), drawing fluid into faults and upward to potential exhalation sites providing ideal conditions for SEDEX style deposits.

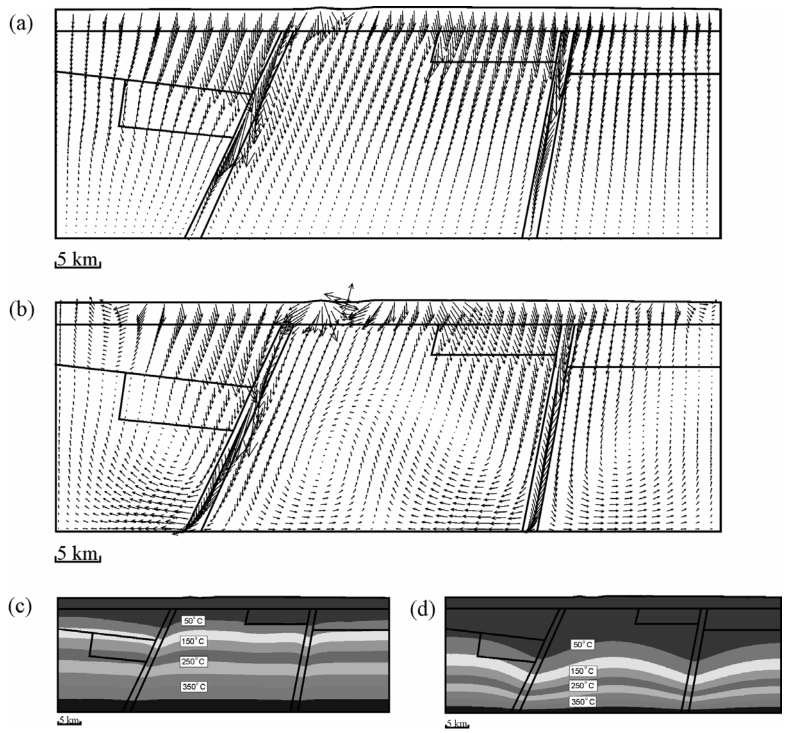

Figure 3: FLAC results for coupled deformation, heat- and fluid flow with an initial overpressure at the start. a) the overpressure stimulates upflow along faults and elsewhere. b) Once the deformation is turned off, convection starts in the cover sequences, drawing fluid into the fault zones and upwards towards potential exhalation sites.

Radiogenic heat source post deformation

The Sybella granite (1670 Ma) in the Mt Isa Inlier has provided a relatively long lasting heat source in the Western Succession, and as a result of radioactive decay an inferred 7 to 8 μWm^{-3} can be justified as a heat source from the present day values of around 5.1 μWm^{-3} (Wyborn, et al., 1988). The applied radiogenic heat source allows initial small scale convection cells to form around the granite body, resulting in an upwelling of hot fluids from the granite carapace and a downwelling of cooler fluids around the margins (Figure 4). These initial results suggest that basinal fluids can be drawn down around the margins of granite intrusions and fluid mixing processes may take place before returning to overlying sediments.

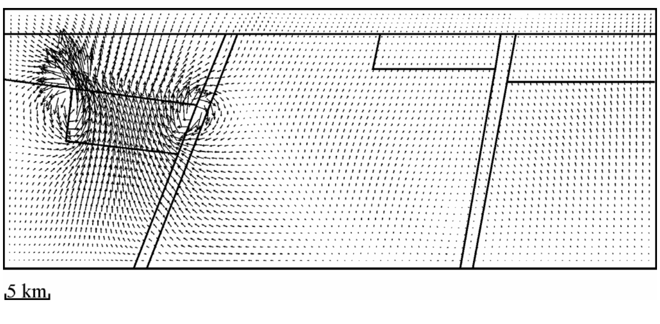

Figure 4: FLAC results for coupled heat and fluid flow displaying small focused convective cells around the granite margins, which aid in upflow of hot deep derived fluids and downflow of cooler basinal brines.

Discussion and conclusions

Extensional deformation in elastic-plastic materials can have a strong influence on dilation and fluid flow, and here extensional deformation at reasonable strain rates provides a structural mechanism for downward migration of basinal brines into less permeable basement materials due to under-pressure. This process is strain dependent, although, at reasonable to slow geological strain rates ($10^{-13}s^{-1}$ to $10^{-16}s^{-1}$) similar results are achieved. The more obvious result, however, is the perturbation of the thermal structure by the deformation, in particular the destruction of convection cells. The timing of convection versus deformation, and the sequence of these processes has a strong influence on the direction of fluid flow and hence determines the focussing of fluids in particular areas within the model. This may have a major impact on the types of mineralization styles and the availability of metals to produce economic deposits. The presence of a radiogenic heat source, such as an intrusive body, provides mechanisms for small scale convection and fluid mixing in a localised manner, which may contribute to enriching basinal brines with intrusion related metals.

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Linking structure and mineralisation in Laverton, with specific reference to Sunrise Dam and Wallaby

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Introduction

The 7.1 Moz Wallaby and >9.5 Moz Sunrise Dam gold deposits are located within 30 km of each other in the Laverton area of the Eastern Goldfields (Figure 1). As part of the Y4 project detailed structural analysis was undertaken at both of these deposits, combined with Leapfrog™ modelling of grade, alteration and rock types, to produce coherent deformation and alteration histories. This paper presents an attempt at a new correlation diagram (Table 1) for Wallaby, Granny Smith and Sunrise Dam deposits (> 16 Moz gold), with integration of an existing regional and granite event deformation history (Blewett et al., 2004a, 2004b).

A revised model for the evolution of the goldfield is proposed. This model has been developed in the Y4 project and integrated with the regional 3-D model being constructed at Geoscience Australia. Both datasets and will provide improved inputs for the numerical modelling programs undertaken at CSIRO. The combination of these will provide more predictive models for targeting within the Laverton area.

Evolution of the Wallaby, Granny Smith and Sunrise Dam deposits

Wallaby

The Wallaby gold deposit occurs in an actinolite-magnetite-epidote-calcite alteration pipe associated with a pipe-like syenite body (U-Pb age 2664±3 Ma Salier et al., 2004) that intruded a massive conglomerate unit. Syenite dykes and associated calcite veins (with pyrite, biotite and some Au) have a distribution that implies radial extension (Miller, 2005). The gold lodes have two main phases, generally dip shallowly to the north or northeast, and overprint the alteration pipe associated with the syenite body. The syenite intrudes through the southeast-dipping eastern limb of the regional Margaret anticline – this fold has been linked to the regional D_2 (e.g., Swager, 1997) and thus the gold lodes post-date the regional D_2 event. The first phase of gold lodes are hematite-associated (with pyrite, calcite, quartz and Fe-rich dolomite) and are linked to north-directed ductile shearing and NNW-SSE contractions with development of conjugate brittle faults. These lodes are overprinted by sinistral-slip gold lodes that do not have a hematite association (with pyrite, sericite, quartz, calcite), but are still associated with a similarly oriented σ_1 (but not the same σ_2 or σ_3). One of the sinistral-slip lodes has been dated at 2650±6 Ma (Salier et al., 2004) and these lodes are interpreted to be linked to a deeper-level fluid not directly associated with the syenite intrusion.

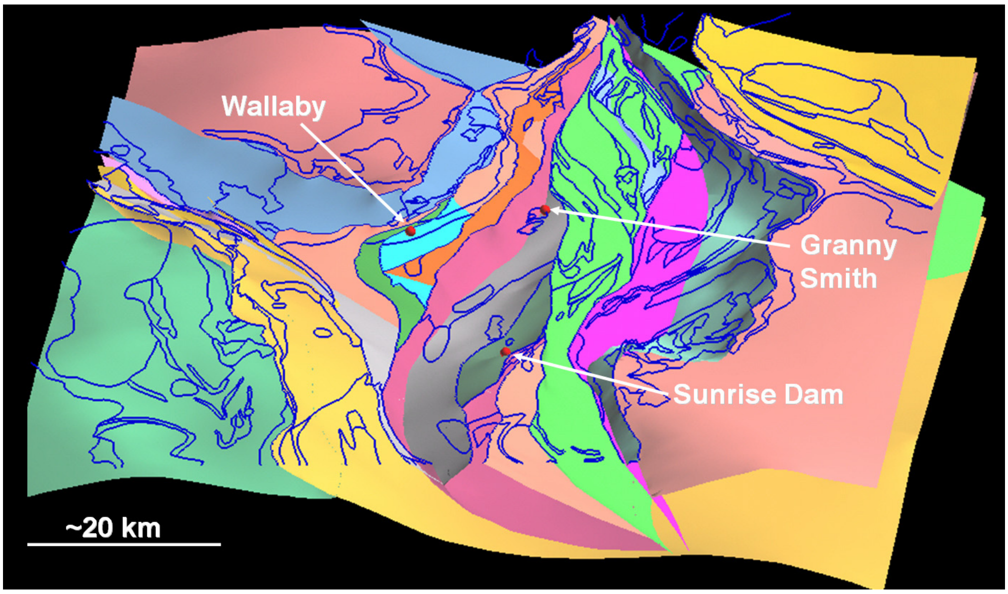


Figure 1: Screen capture from the 3D Laverton model (constructed in gOcad at Geoscience Australia by Paul Henson) with Wallaby, Granny Smith and Sunrise Dam shown. Width of image approximately 150 km, viewed looking north.

Sunrise Dam

This deposit is hosted by variable lithologies (volcanic rocks, BIF's and porphyries) and has initial low gold grades associated with early ductile shearing linked to a north-south trending mineral lineation and the development of low angle dipping ductile shear zones (D_1; Newton et al., 1998) and steeper dipping extensional shear veins. These D_1 structures are over printed by east-west to ENE-WSW shortening with associated BIF-style gold mineralisation (previously linked to the regional D_2 event e.g., Newton et al., 1998). All of these structures are then overprinted by sinistral-slip deformation (σ_1 oriented NNW-SSE; local D_3 of Nugus et al., 2005) with the associated introduction of arsenic and tellurides. High-grade, steeper dipping D_3 structures developed between the D_1 low angle shear zones. These structures are located at strike-changes on the ductile shear zones and are inferred to be accommodation structures that developed in areas of the faults that were poorly oriented for slip within a given stress field. Microstructural data indicates the steep structures are early D_1 extensional shear veins that were reactivated and reopened during the D_3 event, but they appear to have been "clamped" within the D2 stress field with no reactivation during this event. The steeper dipping structures are also reactivated as late-stage dextral faults with additional gold mineralisation (local D_4 of Nugus et al., 2005).

Correlation

One of the most striking observations is that stress switches (marked by changes in fault kinematics and fault/extension vein geometries) at both Sunrise Dam and Wallaby are linked to changes in alteration assemblage. This is highlighted by the change in shading in Table 1 and marks a change from compression to strike-slip deformation. The majority of brittle failure linked to the formation of gold lodes appears to be relatively low strain. Existing work (Ojala et al., 1993) has constrained an east-west compressive stress field for the Granny Smith gold deposits (termed regional D_2 by Swager, 1997; but note this event is complex in detail, Blewett et al., 2004a) – these lodes overprint the mafic Granny Smith granodiorite. This D_2 shortening event can be identified at all of the deposits in the correlation diagram. Henson et al. (2006) also make the correlation between Sunrise Dam and Wallaby based on an equivalent, but opposite verging architecture, linked across the strike-slip Childe Harold Fault.

The world-class deposits have gold lodes linked to more than one stress field, however some of the major periods of gold introduction at Wallaby and Sunrise Dam are not identical (no D_2 gold or dextral shearing at Wallaby and no observed hematite-associated lodes linked to NNW-SSE shortening at Sunrise Dam). The observed deformation histories at Wallaby and Sunrise Dam, however, link well with the granite deformation history produced by Blewett et al. (2004b) (Table 1). Furthermore, Blewett et al. (2004b) link late-stage dextral strike-slip to the emplacement of low Ca granitoids (Blewett et al., 2004b). Available age constraints indicate the east-west shortening (D_2) to eventual late-stage dextral strike-slip occurred over a time range that may have been as short as 11 Ma (but possibly up to 25 Ma).

Revised model

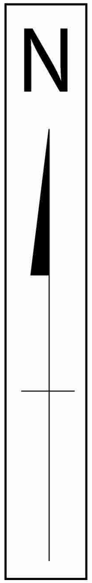
Multiple gold events?

The gold systems have developed in association with a series of changes in structural kinematics. These could be interpreted as multiple gold events, although this inference depends on what is defined as an event (in this case, stress switches versus a major change in geotherm). The time scale over which a thermal event is manifest throughout the lithosphere is at least an order of magnitude slower than a change in stress field (e.g., Hobbs lecture series).

The time period over which the “gold events” occur marks a change from High Ca to Low Ca granites at the end stage or post the regional D_2 event (Table 1). This change in magmatism has previously been linked to a major increase in geothermal gradient triggering melting of crustal rocks (e.g., Champion and Cassidy, 2002). This thermal event is linked to the generation/infiltration of fluids from metamorphism at depth (“orogenic/metamorphic fluid”) and possibly the mantle. The proposed model is that a series of transient stress switches occurred that changed the fluid pathways through time during this major thermal event. This resulted in fluids that may have been sourced from same reservoir at depth travelling up different pathways (and possibly through different rock types) and also interacting more or less with wall rock depending on the continuity of permeability occurring within each stress field (different for compression versus strike-slip). Some gold also appears to be related to oxidised fluids linked to intrusions (e.g., magmatic calcite veins at Wallaby, Drieberg et al., 2004; Miller, 2005), with high grade gold in many areas associated with reduced mineralogy (inferred deeply sourced reduced fluids). The relative importance and abundance of each fluid type may have changed through time (and there may have been more than one source of reduced fluids). The complex structural history indicates there were multiple ways to focus gold deposition to make a world-class deposit, and this makes each major deposit unique.

The observed complexity within the deposits has not been observed in many regional mapping studies (e.g., Swager, 1997), which indicates the deformation may be driven by fluid overpressure linked to gold mineralisation (or the emplacement of the plutons – Blewett et al., 2004b) with inconclusive evidence preserved in the rock record any major distance from the deposits (or plutons). Many of the observed deformation events are low strain and the cause of the stress switches may not have been an external event that changed the dynamics of the system, (such as a collision from the north), but could have been internally driven (e.g., linked to magmatism, or reflect the response/re-equilibration of Archaean lithosphere post the regional D_2 event). Some of the observed stress switches from compression to extension could also reflect a local field associated with emplacement of an intrusion overwhelming a weak far field regional stress field. To resolve the question as to whether the observed stress switches are linked to external or internal processes requires lithospheric scale numerical modelling.

Table 1 (opposite). Correlation diagram for key deposits in the Laverton region. Size of arrows represents inferred magnitude of strain associated with each event. Note change from compressional to strike-slip kinematics is linked to a major change in alteration types at the Wallaby and Sunrise Dam gold deposits. Left side of diagram highlights regional deformation events of Swager (1997) with that of Blewett et al. (2004b) also shown.



Swager (1997)	Laverton granite deformation events (from Blewett et al. 2004b - D numbers from this report)	Jupiter (Duuring et al. 2000)	Wallaby (Miller, 2005)	Granny Smith (Ojala et al. 1993)	Sunrise Dam[8] (Newton et al., 1998, Mair et al. 2000; Tornatora 2002; Nugus et al. 2005)
Extension					2677 ± 6 Ma[1] (felsic dyke)
D_1					Au Extension and/or compression (early ductile structures)
Extension D_2	D_5 (D_{2e})[2] 2667 ± 4 Ma[3] Pindinnis granite (High Ca) D_6 (D_{2b})[2] 2662 ± 5 Ma[3]			2665 ± 4 Ma[4] Granny Smith granodiorite (mafic)	
	D_7		Folding pre-Syenite	Au σ_2 horizontal	Au BIF-hosted ore σ_2 horizontal
Extension			2664 ± 3 Ma[5] Wallaby syenite Minor Au		
Some sinistral-slip kinematics described, but no reference to NW-SE shortening	D_8 2664 ± 5 Ma[3]		Minor Au σ_2 horizontal Oxidised assemblages[6]	?	? Note: early ductile structures at Sunrise Dam have similar slip directions to the Wallaby post syenite events making identification of these events problematic at Sunrise Dam
	D_9	Au?	Au σ_2 horizontal Oxidised Au lodes[6]	? Note: Ojala et al. 1993 linked different slip directions to stress refraction around the mafic intrusive body and not to different stress fields	?
			Minor Au? Oxidised assemblages[6]		
	D_9	Au?	Au σ_2 inclined Reduced[6,7] Au lodes 2650 ± 6 Ma[5] (monazite/xenotime)	?	Au σ_2 inclined Formation of very distinct high arsenic Au lodes
D_3 Extension D_4	D_{10} 2647 ± 3 Ma[3] Deformation associated with emplacement of Low Ca granites[3]	Au?			σ_2 inclined to vertical If Au associated then linked to formation of very distinct high arsenic Au lodes Au

Mainly ductile

Mainly brittle

[1]Age data of Ojala et al., 1997; [2]Deformation numbers in brackets are events in history of Blewett et al. 2004a (Pre-Cambrian Research paper). Note that the red arrows indicate D_{2e} extension direction observed in greenstones by this group - this was not documented in the granites; [3]Field constraints and age data compiled in Blewett et al. 2004b (GA record 2004/10); [4]Age data of Hill et al. 1992 (in Champion & Cassidy 2002); [5]Age data of Salier et al. 2004; [6]Field constraints reported in Miller 2005; [7]Sulphur isotopes reported in Neumayr et al. 2005: [8]Deformation history follows that of Nugus et al. (2005).

Comment on fluid mixing models

Different fluids may not be moving up faults at the same time. Field mapping at the Wallaby deposit (Miller, 2005) suggests that if mixing occurs it happens via a stress switch. One model could be that the intrusions were emplaced into a weak far-field stress regime with a local tensional stress regime developing around the intrusion. At the waning stage of magmatism the weak far-field stress regime was reimposed on system. This sealed vertical fluid pathways, suddenly trapping fluids, leading rapidly to supra-lithostatic fluid overpressure. Subsequently, fault and ductile shear development allowed mixing of fluids and gold mineralisation.

Acknowledgements

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Structural controls on Cu distribution at Mt Isa - implications for exploration targeting

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Introduction

As part of the I7 project, a detailed underground mapping project was commenced at Mount Isa copper with a specific focus on the Enterprise Orebody. The mapping areas were targeted by using a 3D model compiled in FracSis^{TM} with mine data (development, grade shells) and Leapfrog^{TM} modelling of Cu, Co, rock and alteration types. The key aims of the project were to define: 1) the basement geometries, the controls on how basement topography developed and basement links to ore body development, 2) The kinematics behind the formation of the copper breccias and ore shoot controls, 3) Post ore faulting. These new results will be integrated with structural work on the Gunpowder Cu deposit to the west (Damien Keys PhD work) and with regional studies done within the *pmd*CRC*. The kinematics will also provide input into regional numerical modelling projects. The combination of these will provide more predictive models for targeting Cu deposits within the Mount Isa terrane.

Basement controls

The copper lodes have developed within silicified shale above a basement composed of volcanics and quartzite (Perkins, 1984). This basement-shale contact has been folded with development of a strong cleavage (inferred regional D_3). The observed basement relationships are identical to those reported by Perkins (1984) and Bell et al. (1988), with the basement contact being either a folded D_1 or D_2 fault. The Leapfrog^{TM} modelling suggests an inverse correlation between the volcanics and copper mineralisation, with the presence of quartzite units being a key factor. These quartzite units may be linked to silicification of the overlying shale producing a unit rheologically favourable for breccia development. North and northwest-trending basement lineaments are linked to the overlying Cu breccia bodies. The majority of these are associated with regional D_3 deformation. Extensive graphite is associated with D_3 cleavages within the shale at the contact with the underlying basement, which implies reducing conditions syn-D_3. These graphitic zones are sites of strong fault development and reactivation post the formation of the copper breccias.

Kinematic analysis of the copper breccias

Bedding parallel slip along planes dipping (on average 60° to the west) is the key control on the development of the copper breccias. The presence of the S_3 cleavages provide additional permeability with the $L_{03intersection}$ lineation (= F_3 fold plunge) being a key control on ore shoot plunge. There are major plunge variations of this lineation between different areas producing variable ore shoot plunges. The copper breccias also have no major mesoscopic quartz, with chalcopyrite being the dominant infill (with some pyrite), and the brecciation appears to post date the S_3 cleavages (also noted by Perkins, 1984). There is no mesoscopic evidence for multiple phases of brecciation - the copper breccias appear to reflect a single discrete event.

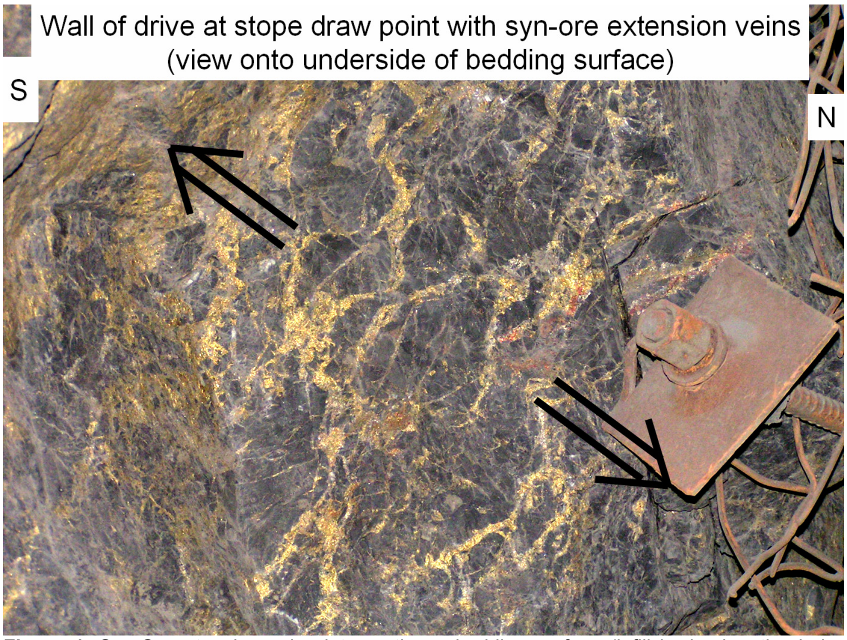

Figure 1: Syn-Cu extension veins intersecting a bedding surface (infill is dominantly chalcopyrite). Arrows highlight extension direction.

Systematic mapping of extension veins (Figure 1) within the copper ore bodies, along key Cu and basement trends in both plan and vertical directions, constrained the extension direction along the bedding planes (= slip vector orientation). This was remarkably consistent irrespective of fold plunge or location with respect to basement. The majority of vein and fault data indicates top-to-southeast hangingwall transport (i.e., sinistral-reverse movement; Figure 2a). The dominant angle between the extension veins and bedding indicates it is not dextral-normal (and cannot be dextral-reverse). Apart from vein-bedding relations there is also evidence (dilational jogs etc.) for a component of reverse movement. At a larger scale, the Cu lodes developed along jogs dilatant in a sinistral slip regime, some of these dilatant zones are S_3 cleavages or northwest-trending basement lineaments that have dilated during sinistral slip (Figure 3). To produce the observed slip vector orientation, the stress field associated with the copper breccias would have had σ_1 lying somewhere within the northwest (or southeast) quadrant of a stereonet; σ_1 was not oriented east-west.

Main post Cu breccia faults

First set of post Cu breccia faults

A major set of west-dipping and northwest-dipping faults overprint the copper breccias. These have an east-directed hangingwall transport with reverse or dextral-reverse movement when they strike more to the northeast. The faults are associated with quartz, pyrite, talc and chalcopyrite (= some enrichment – could have lodes associated with these in some areas) with remobilised galena near Pb lodes. These faults commonly slip along bedding with lower angle diverging splays, although, they have a completely different extension direction parallel to bedding compared to the Cu breccias (Figure 2b).

Second set of post Cu breccia faults

A major set of northeast- and east-northeast-dipping faults over print the copper breccias and the west-dipping faults. These are associated with extensive quartz veining in some areas. The faults have complex geometries (inverted flower structures) with big dip changes ranging from 80° to 40° (unlike the west-dipping set, this is not caused by slip along bedding). These faults are sinistral-reverse and displace some of the copper breccias with potential for offset high grade footwall wedges down-dip.

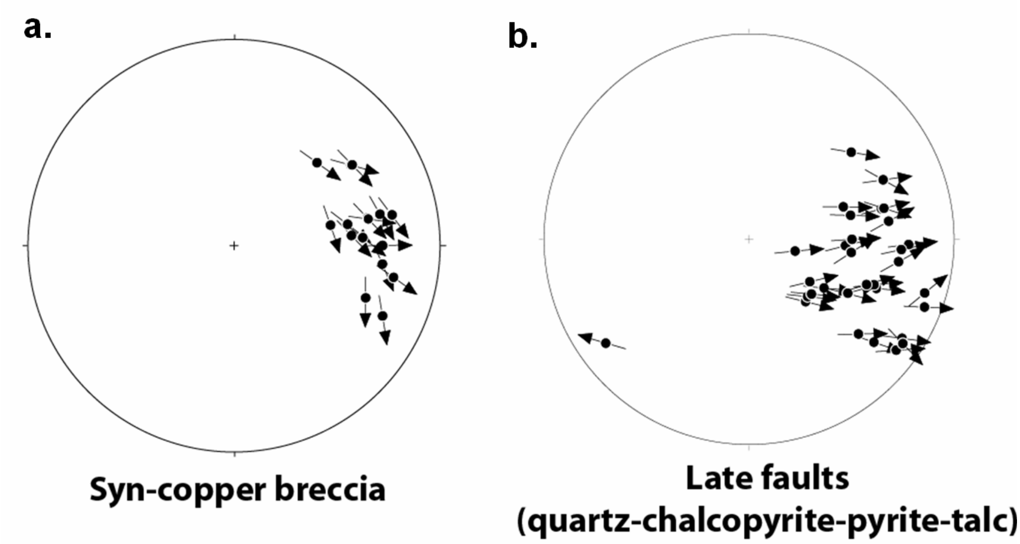

Figure 2: Hangingwall transport directions (see method in Miller and Wilson, 2004) plotted at the pole to the slip surface (commonly bedding). (a) Copper breccia (hangingwall top-to-southeast). (b) Later west and northwest-dipping faults (hangingwall top-to-east). Note different transport directions.

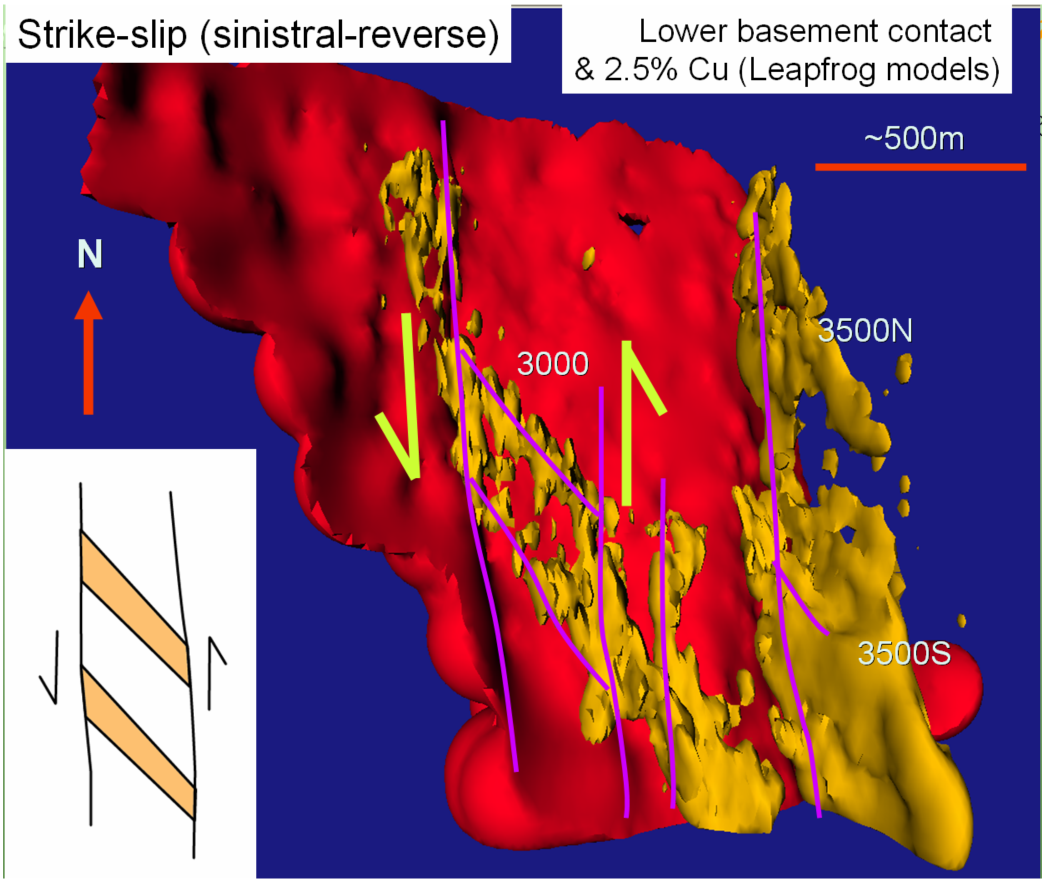

Figure 3. Leapfrog model of lower basement contact and Cu for the Enterprise Mine area (3000, 3500S and 3500N ore bodies). Kinematic interpretation utilizes slip data in Figure 2a, bedding strikes north-south and dips on average at 60° to the west.

Key points and implications for regional targeting

The main Cu breccias are linked to sinistral-reverse movement and postdate regional D_3 deformation – NO REGIONAL EVENT OF THIS NATURE HAS BEEN RECORDED (e.g. Betts et al., 2006)

Cu may not be a major regional “orogenic” event (i.e. not main folding or faulting observed) – fluid overpressure could cause breccia development and one may not see associated deformation any distance from the Cu ore body

Strike changes (dilatant in sinistral regime) and pre-existing cleavages are important

The first set of post Cu breccia structures are west- and northwest-dipping reverse and dextral reverse faults (have quartz and chalcopyrite) with consistent top-to-the-east hangingwall transport. NOTE: different slip-vector/extension direction to Cu breccias

The second set of post Cu breccia structures are northeast- and ENE-dipping sinistral-reverse faults

The most obvious features are post Cu breccia faults – this will need to be integrated into the interpretation of regional faults

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Integration of Potential Field derived architectural maps and mineral deposit datasets in the Tasmanides

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Introduction

There is high potential for increasing the mineral wealth of the Tasmanides of southeast Australia, especially in shallow under-cover areas of New South Wales and Victoria (Figure 1). A metal endowment or prospectivity-related analysis is being undertaken to determine what impact the interpreted structural architecture has on extant metal distributions. How is metal distributed in relation to this architecture, and can this help to trace out areas of high exploration potential in the region? Work is in progress, addressing these questions.

Taking a high level classification of deposits by commodity group, and a semi-quantitative ranking of deposit size, the sensitivity of metal distributions to a range of parameters is being investigated through a spatial buffering GIS-based technique. This provides a measure of metal content (e.g. gold distribution per km^2) with distance from the architectural elements. A similar methodology has been applied with some encouraging results for area-selection scale exploration activities in the Yilgarn region of WA (Bierlein et al., in press) and in Tasmania (Murphy et al., 2004).

Mineral Deposit Data

The data derive from two main sources: GSV (MinSite/VicMin) and GSNSW (Metmin). GA's MinOcc database contains components of both data sets. While there is a range of possible schemes for grouping deposits, an appropriate classification is by Principal Commodity or Commodity Group, with subdivisions of this into Primary (e.g. hard rock) and Secondary (e.g. alluvial) deposits. These reflect existing fields in the databases, with nine main groups being identified thus far in the analysis (Table 1):

Commodity Group
Au-only
Au Sb
Au Ag
Cu Ag Au
Cu Au
Cu Pb Zn Ag
Pb Zn
Cu-only
Fe

Table 1: Primary Commodity Groups.

Subdivision of these groupings can be made, where appropriate, according to four fields with associated variables (Table 2):

Host Rock	Intrusive	Mafic/Felsic
	Volcanic	Mafic/Felsic
	Sedimentary	Shale/Sst/Carbonate
Class	“Orogenic”	
	SHMS	
	VHMS	
	Epithermal	
	Intrusion-related	
Style	Vein/Fault	
	Disseminated/Stockwork	
	Skarn	
	Massive Sulphide	
Age	Host rock	Relative &/or Absolute
	Mineralisation	Relative &/or Absolute

Table 2: Subsets of Primary Commodity Groups.

A semi-quantitative ranking of “global” deposit size is being used, rather than recorded production-resource-reserve figures. It is important that all deposits are ranked, small and large alike. A ranking scheme for gold-related groupings is shown in Table 3:

Ranking	Size	“ID”
6	>10,000,000 oz	Supergiants
5	>1,000,000 to <10,000,000 oz	Giants
4	>100,000 to < 1,000,000 oz	Large Mine
3	>10,000 to <100,000 oz	Small Mine
2	>1,000 to 10,000 oz	Prospect
1	<1,000 oz	Occurrence

Table 3: Deposit size ranking for gold-related groups.

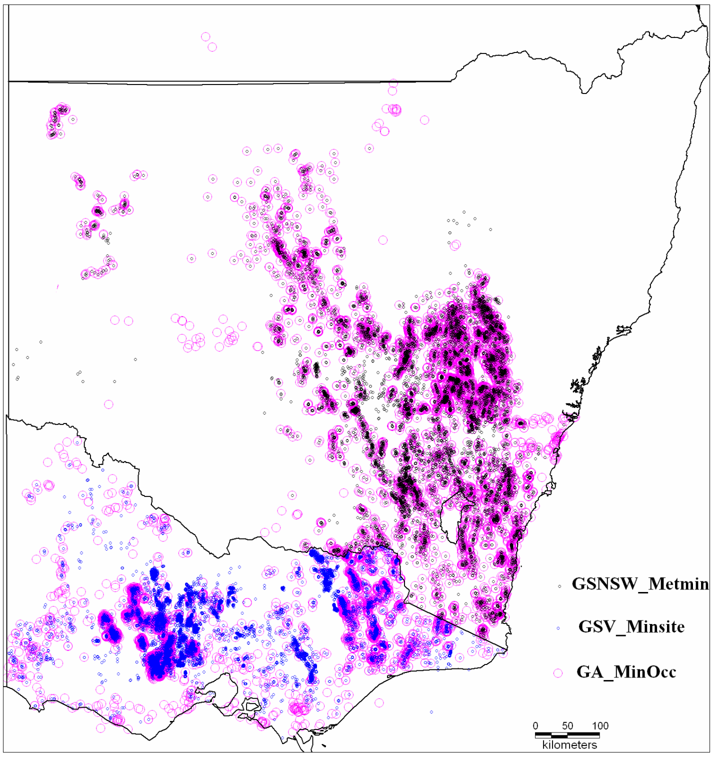
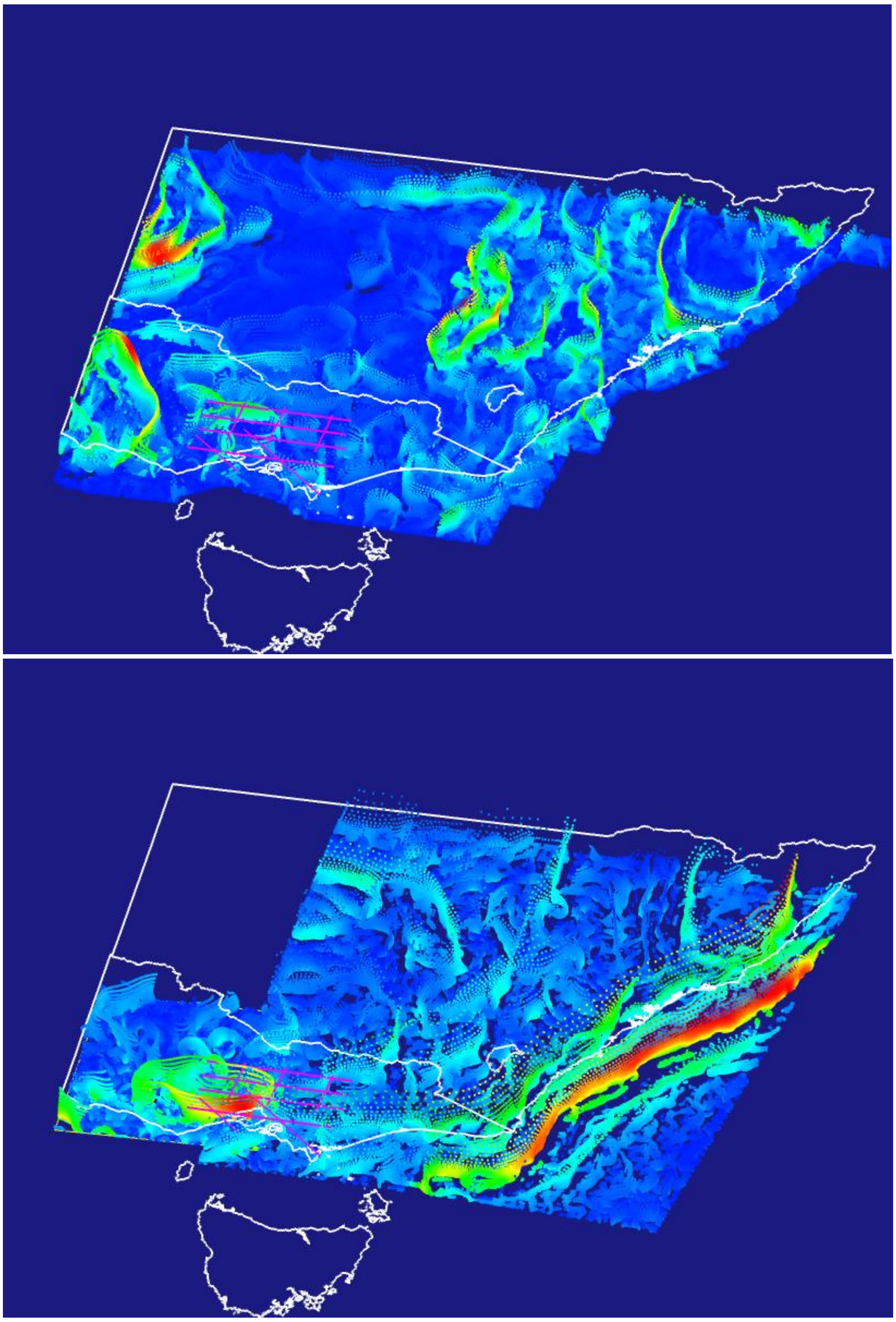


Figure 1: Deposit locations of the 3 data sets (unfiltered) for the T5 Tasmanides project area.

Potential Field Data

Despite some cross-border differences in geophysical data coverage and geological interpretations, the regional scale of the data provides a platform for interpreting a structural architecture from maps and potential field data. The gravity and aeromagnetic data were processed to derive multiscale wavelet edges, or worms, as a way to automatically map gradients in 3D space (Figure 2). These gradients are interpreted to yield a 2.5D representation of faults, intrusives and stratigraphic boundaries. The edges are parameterised according to trend, straightness, length, apparent penetration depth and intersections.



a)

b)

Figure 2: Perspective views of multiscale wavelet edges for a) aeromagnetics and b) gravity.

Analysis

A combined mineral occurrence data set will be used in the analysis, while preserving fidelity of the data sources. Some new fields will be introduced, based on the above tables. Analysis will proceed firstly with dealing with “noise” in the data (unresolved groupings, attributes, duplicates, non-metallic occurrences, redundant fields), then sorting according to Commodity Groupings, sub-setting and attributing according to other variables. Comparable size ranking tables need to be devised for other major commodity groups. Further work is underway to complete the interpreted architecture, prior to integration with the deposit data using the buffering technique.

Buffer regions (i.e. sub-set areas) are created surrounding the vector lines, with one buffer made for all lines (*not* individual buffers per line). Successive buffer windows were created incrementally so as to capture the entire region of the data coverage. The cumulative rank of deposits within each buffer area is calculated to provide an ‘endowment’ value of metal content per unit area. To test the sensitivity of different parameters to metal distribution, two approaches are taken (Figure 3): firstly, where the buffer size is independent of fault parameters and is at a fixed distance (e.g., 1 km, 2 km, etc.) from the vector line and, secondly, where the buffer size is a function of fault parameters (e.g., length, depth), resulting in a variable distance buffer from the vector distance. In the first method, all vectors have a similar areal influence, whereas in the second, longer (or deeper/higher) features are weighted compared to short vectors. This has the effect that large dimension features will have a greater spatial influence. This has a reasonable geological basis in relation to fault growth models that show, in general, an increasing damage zone width with increased displacement (e.g., Childs et al., 1996).

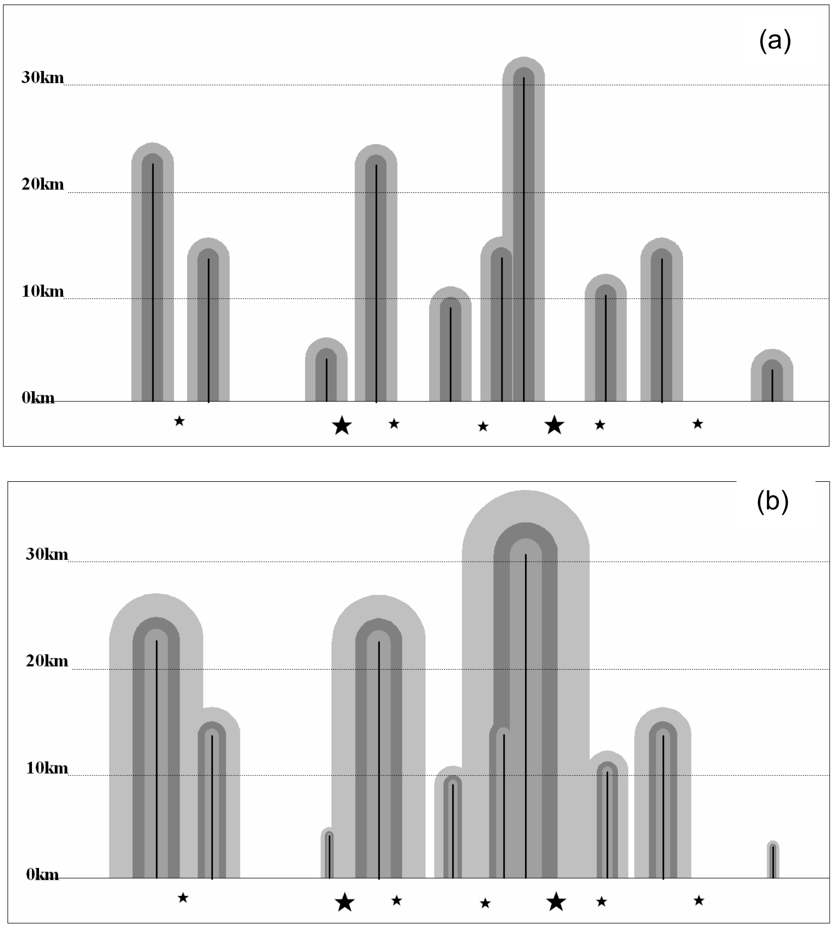


Figure 3: Hypothetical scan line plot of faults (vertical black lines) with varying length (plotted on the y-axis), identical in both plots. Faults lines are enclosed by buffers (shaded regions) where: a) width of each buffer is fixed or constant (e.g. 1 km, 2 km), and b) width of each buffer increment is variable, being a function of fault length, so that longer faults have greater spatial influence. Star symbols (identical in a) and b) beneath the x-axis represent positions of fictional deposits (of different sizes).

Note that individual deposits (star symbols with identical positions in Figure 3a and b) can fall within different fault buffer envelopes depending on whether buffers are fixed or variable. Results from other regions where this has been applied (see pmd*CRC T3 and A1 project outcomes) suggest that there is a greater metal endowment (depending on commodity) in relation to large dimension fault corridors. Whilst this is not entirely surprising, for example, in terms of large faults accessing different fluid sources, this has a significant impact on reducing the search area *by an order of magnitude* while increasing the chance of discovery (Bierlein et al. 2006). A first pass interpretation of the "Edge Architecture" for the Tasmanide region, combining fault-related worm length and mapped fault length is shown in Figure 4 in relation to the distribution of major deposits. Some empirical correlations are evident, giving confidence in extrapolating mineralised corridors into un-chartered regions of shallow cover.

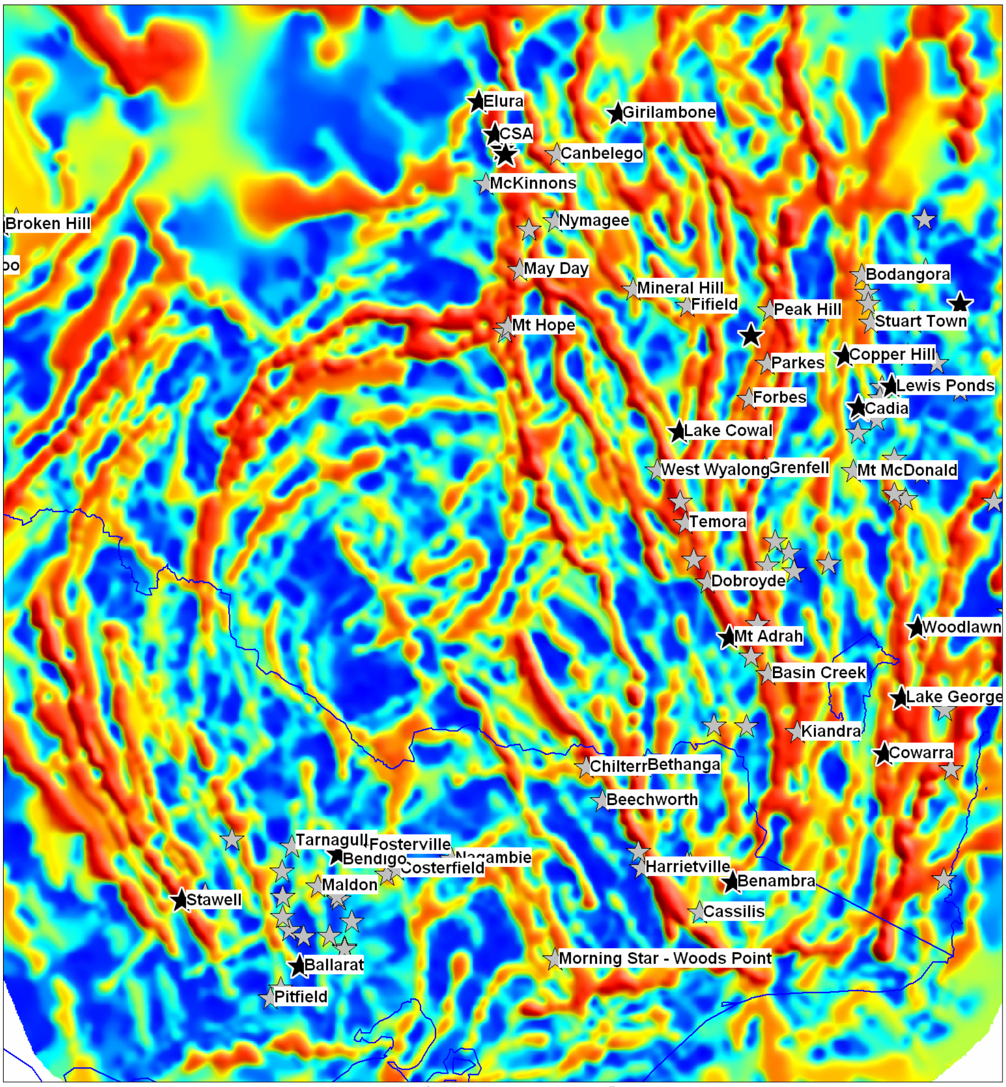


Figure 4: Preliminary regional scale image of "Edge Architecture" coloured by strike length, with locations of major mineral deposits (stars). The length data is derived from combining gravity and aeromagnetic fault-related gradients (from worm interpretation) and mapped faultS.

Acknowledgements

Thanks to personnel from New South Wales and Victorian geological surveys for their input.

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Multi-scale analysis of Isan Mineral Systems

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Introduction

"Bring it back to exploration" is the catch cry for the I7 project, which is seeking knowledge- and technology-based outcomes that may result in reducing the time and cost to discovery. Two critical success factors for exploration are to be confident that the right area has been selected, geologically, within the "economic skin depth" for the commodity of interest, and to use the appropriate tools in exploring such areas. This operates across scales and a range of techniques. Mineral system research mirrors the exploration process, underpinned by a multidisciplinary approach, and the "5 Questions" provide a framework for research activities under the I7 banner (Table 1).

<table>
<tr><th>Exploration Process</th><th>Theme</th><th>Research Stream</th><th>Commodity</th></tr>
<tr><td>Terrane Selection</td><td>Geodynamics</td><td>Tectonostratigraphic Evolution
Isotopes/Geochronology
Thermal Structure and Magmas</td><td rowspan="5">Cu
Pb-Zn
Cu-Au
U</td></tr>
<tr><td>Area Selection</td><td>Architecture</td><td>E-W Correlation
3D Maps</td></tr>
<tr><td>Area Selection</td><td>Fluids and Reservoirs</td><td>Permeability Structure
Magmas
Noble gases and Halogens
Carbonaceous rocks</td></tr>
<tr><td>Area Selection</td><td>Drivers</td><td>Numerical modelling -Topography
Deformation/Heating (FLAC)</td></tr>
<tr><td>Target Selection</td><td>Deposition</td><td>Faulting and Mineralisation
Geochemical RT modelling
Numerical modelling (FLAC/UDEC)
Alteration and Remote Sensing</td></tr>
</table>

Table 1. Structure of the I7 project.

Scope of Studies

The project commenced in April 2005 and primary research continues to June 2007, followed by consolidation/integration and delivery of outcomes by June 2008. Some results to date and questions arising are outlined elsewhere (Allieres, 2006, Miller, 2006, Wilde, 2006, McLellan, 2006, Neumann, 2006, Southgate 2006, Gibson 2006) in previous talks. The objective here is to draw together some key outcomes and key uncertainties, seeking a holistic view of the mineral systems, and to put a personal spin on where this might lead us in the drive for discovery.

Why is the region so well endowed in metals?

The scale of the question involves terrane selection and draws on three geodynamically-related research streams (Table 1). Comparative analysis with other terranes helps inform us of the answers. The Proterozoic age is a first criterion and reflects whole of earth processes, simply based on global metal distributions over time. Characteristics of the region include strong metamorphic gradients, multiple magmatic and metasomatic events, deep rooted fault architecture, repeated extension and protracted inversion events. There are also multiple fluid flow events. While these characters are not in themselves unique to the terrane, it may be that the development of core complexes during Sybella and Wonga Events(?) results in high thermal gradients in a weakened crust and, together with large volumes of mafic material emplaced over long periods, were factors in the overall metal budget.

Several (if not most) of the world class mineral deposits of the region are contained in the Isa Superbasin (ISB) and lateral equivalents in the Mc Arthur River region (Figure 1). This developed at a relatively late stage of the terrane, following two major rift-sag events, the Leichhardt (LSB) and Calvert Superbasins (CSB) respectively. It is relatively certain that the pre-Barramundi basement was a coherent substrate to these rift basins and has similar composition across some of the major fault structures (e.g. Mt Isa Fault). There is uncertainty as to the tectonic setting of the Isa Superbasin. Was extension the main control? Was a foreland basin initiated during ISB sedimentation, or does emergence at the end of the Superbasin cycle mark foreland propagation? What is the relationship of D1 deformation (~north-south shortening) to the Superbasin? These questions impact on determining drivers for the mineral systems. Early sedimentation involved growth faulting, reactivating earlier structures, in a marine carbonate platform with multiple transgressive and regressive events. Later, a thick silt-sand-shaly facies, suggesting deeper marine conditions, was widespread – preserved on the Lawn Hill Platform – but with less evidence for growth fault control higher in the pile. There is an increased volcanic component in the detrital record upwards through the Lawn Hill Formation, together with organic-rich shales, and the first influx of feldspathic sands into the system signals a change in provenance towards the top of the formation. Unconformably overlying this is the South Nicholson Basin which is largely regarded as post-orogenic, although it is deformed along similar trends as its ISB substrate.

How does the 3D architecture impact on metal distributions?

This question mainly relates to area selection (Table 1). The objective is to provide an interface between the explorationist's view of the world (as it is today) versus the modeller's view of the world (at the time of mineralisation). Recognising that a 3D model/map is a non-unique, simplified and scale-dependant interpretation, our modelling is based on published maps and cross sections, regional potential field and limited seismic data. These data will be upgraded and/or superseded by Queensland's Smart Exploration program over the coming years. The project area covers the entire Isa Inlier and extends to the McArthur River region (Figure 1). Incorporating most aspects of existing models (e.g. from pmd*CRC projects I1, I2, I4 and G14), new models are under construction for remaining areas. Within a confidence volume, upwards of eight primary surfaces are modelled above the pre-Barramundi basement, utilising sequence stratigraphic concepts in combination with lithostratigraphic units and broad-based interpretations of potential aquifers and seals. Major faults and intrusive bodies are also represented.

The three Superbasins are interpreted as autochthonous or para- autochthonous with respect to the local basement. In a regional context, basement is interpreted at relatively shallow depths beneath the rifts. Current outcrop margins of the basement approximate to depositional margins or rift shoulders for the overlying Proterozoic Superbasins *and* exert control on the outcrop pattern of the Palaeozoic Georgina Basin. The proximity of major deposits to long lived margins in the pre-Barramundi basement may help define areas of perceived higher prospectivity.

Results from the east-west correlation program have led to a paradigm shift in our understanding of a coherent relationship of the twice rifted platform to an adjoining basinal setting in the Eastern Succession. The latter, represented by the Soldiers Cap Formation, largely lies to the east of an inferred east-dipping margin, and is currently equated with the "Cloncurry Worm" (Blenkinsop *et al.* 2005). The western margin of the Leichhardt Superbasin appears to thin across an inferred east-dipping detachment, termed the Russell Creek Fault (Gibson and Hitchman, 2005) and 29 Mile Fault system. This "break-away" structure may relate to the "Barramundi Worm" (Hobbs *et al.* 2000), a persistent gradient in the North Australian gravity field. The likelihood is that such features represent trans-crustal breaks, with continuity of pre-Barramundi basement across them. The Mt Isa Fault has propagated along parts of this detachment as a *steep west* dipping structure.

What fluid sources and reservoirs were involved in the metallogenic history?

First pass area selection decisions may be made on the basis of *relative proximity* of major Zn-Pb, Cu, Cu-Au and Au deposits to regional scale, deep seated fault structures and related potential field gradients, such as the Barramundi, Pilgrim and Cloncurry Worms (Blenkinsop *et al.* 2004). This suggests a process control on metal distributions by penetrative faults that perturb the thermal structure, and can access buried and/or near-surface reservoirs. The permeability structure and geometry at times of mineralisation are key factors (Table 1). There remains considerable uncertainty, however, regarding the age and timing of deposits within the Isa Superbasin, particularly the Zn-Pb and Cu systems. Fluid inclusion data provides constraints on the compositions of fluids at regional and at deposit scales. Work to date has characterised a variety magmatic, metamorphic, basinal and bittern brines at varying times and places, and the involvement of mantle fluids may be implicated. Fluid mixing is evident for different deposit types, e.g. IOCG and Zn-Pb systems.

Were the sediment-hosted Zn-Pb deposits formed during early extension, later shortening, or somewhere in between?

Numerical modelling of a range of scenarios is being undertaken using FLAC and relates to the area selection scale (Table 1). A control on Zn-Pb mineralisation may involve competing processes (e.g. Murphy *et al*., in review) of inversion driving fluids from basinal reservoirs and mixing across fault breached seals with convecting fluids from burial and extension. The position of a topographic front (providing a direction of fluid flow) is not well constrained. Alternatively, extensional models could drive the mineralising system (Oliver *et al.* in revision). Deeper (mantle/magmatic) sourced fluids may be implicated, utilising penetrative fault structures. Conversely, the contribution from upper level fluids in post to late-Isa Superbasin sources is being investigated through targeted sampling in and around some Zn-Pb deposits.

Was the late Cu system an Isa-wide event?

Initial Isan deformation (D1) involved north-south contraction, utilising the Calvert Superbasin fault boundaries in particular. Substantial deformation of the Isa Superbasin was mainly due to east-west convergence, a geometry inherited from the Leichhardt Superbasin, and developed in the ductile and brittle regime. Reactivation is commonplace along the major fault trends.

Work at the target selection to deposit-scale (Table 1) has recognised a component of north-south sinistral strike slip of uncertain (syn/late/post-D3) age that appears to control Cu distributions at Mt Isa. Similar controls are seen elsewhere in the Western and Eastern Successions. The possibility that there may be an Isa-wide Cu mineral system is being investigated, using UDEC modelling of fault architectures. The primary control was mechanical rather than a unique host rock composition. Constraints on the age of Cu mineralisation, fluid and metal sources and alteration signatures are a focus of on-going research.

Acknowledgements

Thanks to those in the I7 team who contributed ideas, even if at times unbeknownst to themselves.

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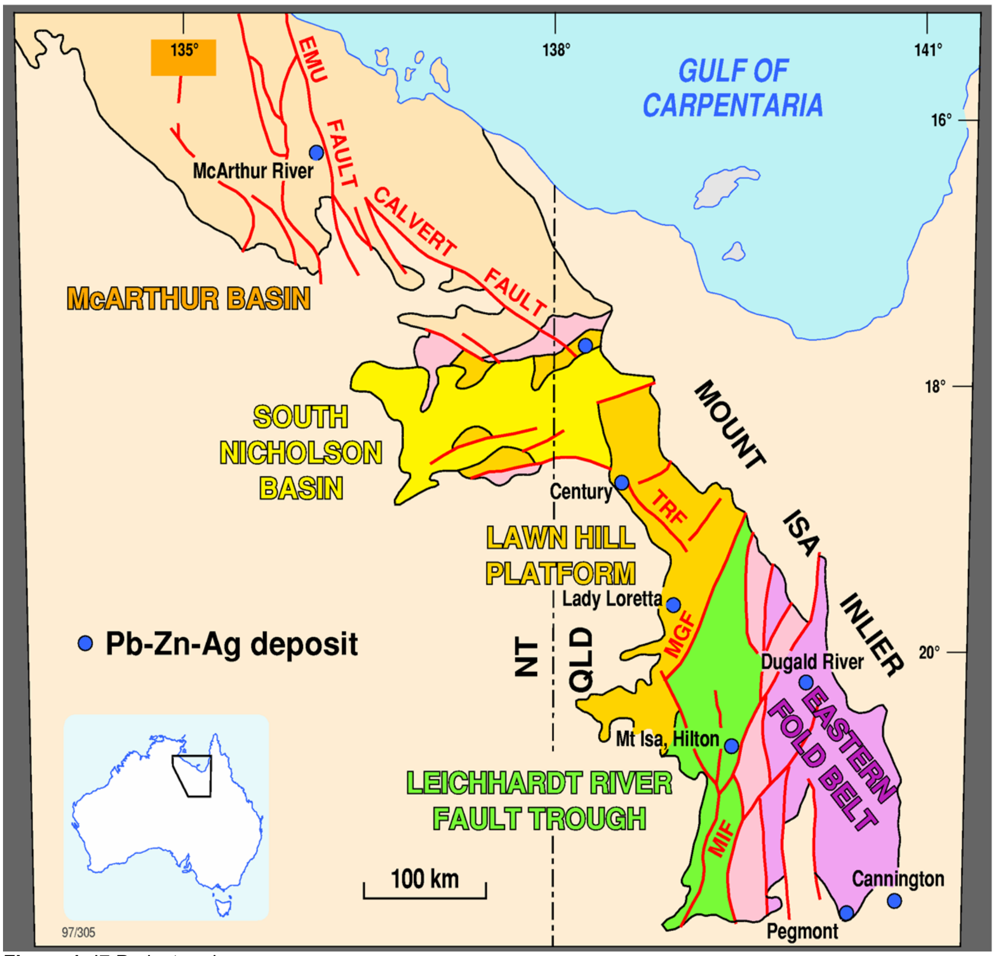

Figure 1: I7 Project region.

Regional scale correlations – Sequencing the SHRIMP detrital record

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The Mount Isa Inlier records an extensive record of sedimentation between ~1880 and 1575 Ma. This basin record is well documented in the Western Succession, where extensive outcrop and low metamorphic grade has allowed detailed description of the development of the Leichhardt, Calvert and Isan Superbasins (e.g. Jackson *et al*., 2000; Southgate *et al*., 2000). Further, the timing of sedimentation within the Calvert and Isan Superbasins has been well constrained due to the abundance of volcanic and shallow-level intrusives available for geochronological dating (Page *et al*., 2000). In contrast, the timing, extent and nature of basin evolution in the Eastern Succession, and its relationship to the Western Succession, has been restricted due to more limited outcrop, the small number of volcanics available for dating, and the higher metamorphic grade recorded in this area (e.g. Page and Sun, 1998). Understanding the depositional age and extent of these basin systems and their relationship to Western Succession stratigraphy, however, is important because they are the host for significant Pb-Zn and IOCG mineralisation, and because their geometries may have a significant control on the fluid migration.

The pmd*CRC I7 Module 4 project aims to establish correlations between the Western and Eastern Successions, and place the stratigraphy within a geodynamic framework.

Approach to correlating the Western and Eastern Successions of the Mount Isa Inlier

Stratigraphic correlations have relied strongly on using the 1800 to 1575 Ma framework established in the Western Succession (Figure 1). In particular, we have focused on the ~1750 Ma surface at the base of the Quilalar Formation (Western Succession), Ballara Quartzite (Mary Kathleen Zone) and Mitakoodi Quartzite (Mitakoodi Block) as a time-line datum to link the Western and Eastern successions, and have used this datum to better understand lateral and vertical variations in basin stratigraphies. We have then extended these correlations along a transect that crosses the principal structural blocks of the Eastern Succession (Mary Kathleen Zone, Mitakoodi Block, Marimo Belt and Snake Creek).

Within each block, the project has focused on detailed sedimentary and structural descriptions along a stratigraphic section through all the mapped units. Geochronology sampling for igneous and detrital zircon SHRIMP analysis along these sections permits the identification of chronostratigraphic surfaces and allows a temporal framework to be applied within and across these regions.

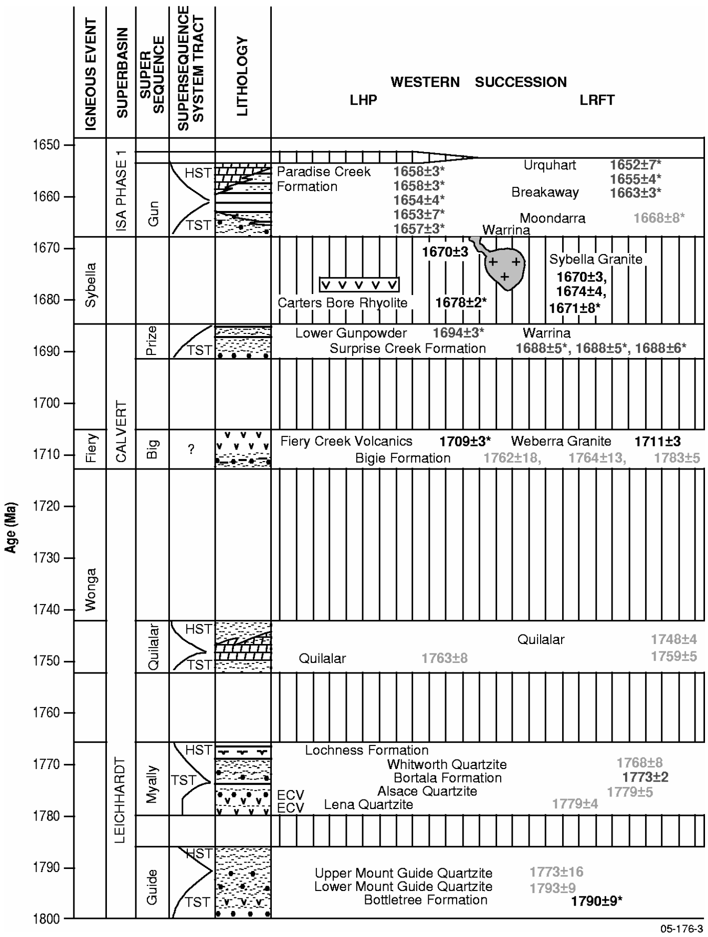

Figure 1: Event chart for the Leichhardt and Calvert Superbasins of the Western Succession, Mount Isa Inlier. Ages in Ma. Colour code for ages: black = magmatic crystallisation age, dark grey = sedimentary depositional age and light grey = sedimentary maximum depositional age. Ages with * from Page *et al.* (2000) and Jackson *et al.* (2005), all other ages from Neumann *et al.*, *in press*. LHP = Lawn Hill Platform, LRFT = Leichhardt River Fault Trough.

Results from the Mary Kathleen Block

Stratigraphic section

A composite section for the Mary Kathleen Block is presented in Figure 2. The basal package overlying the Leichhardt Metamorphics includes the Magna Lynn Metabasalt and the regionally extensive felsic Argylla Formation. These units are overlain by the Ballara Quartzite and Corella Formation, which consists of basal sandstones grading to fine-grained sandstones and carbonates. The overlying Deighton Quartzite has been subdivided into five units (Figure 2). The basal unit includes sandstones interbedded with basalts, which is overlain by a thick conglomeratic sandstone. The upper part of unit 1 comprises thick-bedded sandstones. Units 2, 3 and 4 represent a deepening-upwards package of medium- to fine-grained sandstones deposited in a fluvial to shallow marine environment. The base of unit 5 consists of a sharp-based, thick polymict conglomerate unit, grading up into sandstones. The stratigraphic sequence is intruded by the Wonga and Burstall Granites (Figure 2). SHRIMP geochronology focused on sedimentary samples through the complete section, and key igneous units, integrated with sedimentary and structural analysis, and previous geochronological constraints.

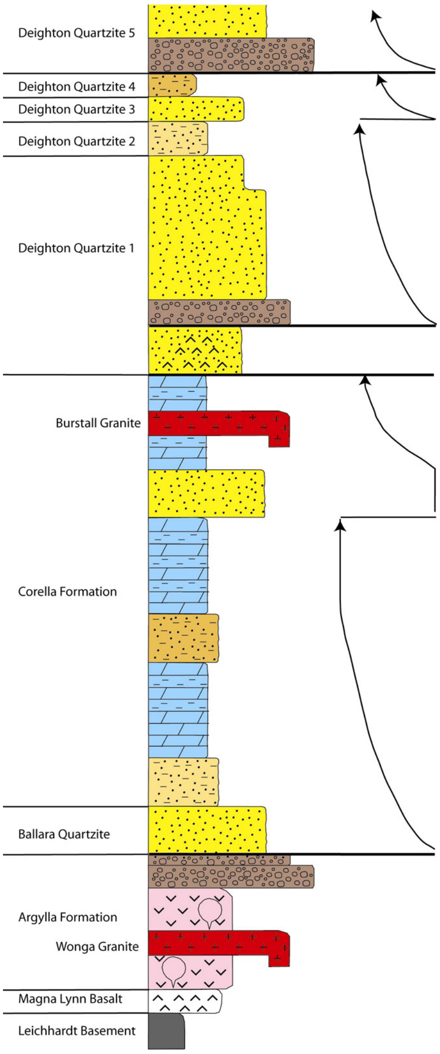

Figure 2: Composite stratigraphic section for the Mary Kathleen Block.

New SHRIMP data

Preliminary new SHRIMP results for volcanic and shallow-intrusive rocks from the Argylla Formation range between ~1780-1777 Ma in Mary Kathleen region. Tuffaceous mudstones from within a 15-20m thick interval of small clast, polymict conglomerate and poorly sorted sandstones overlying the Argylla Formation volcanics also record a ~1780 Ma age, confirming a temporal and genetic link between these poorly sorted siliciclastics and the underlying Argylla Formation, rather than the overlying Ballara Quartzite. New maximum depositional ages of ~1765 Ma derived from detrital zircons in the Ballara Quartzite and Corella Formation are slightly older than the depositional age of ~1755 Ma determined by Page (1998). The overlying Deighton Quartzite is dominated by Ballara Quartzite and Corella Formation-type ages in the base, and younger populations of ~1725 Ma near top of this formation.

New interpretations

We interpret the Magna Lynn Metabasalt and Argylla Formation to represent a major magmatic event in the Mary Kathleen Block between 1780 and 1775 Ma. This magmatic event is correlated with the Myally Supersequence in the Western Succession, and may be a major source of detrital zircons for this basin sequence. We have not identified a sedimentary package equivalent in age to the Myally Supersequence in the Mary Kathleen Block.

The Ballara Quartzite and Corella Formation are equivalent to the Quilalar Supersequence of the Western Succession, as suggested by Jackson *et al.* (1990). The Deighton Quartzite is correlated with three different Western Succession supersequences: the Basal Deighton Quartzite and interbedded basalts are equated with to the ~1710 Ma Big Supersequence and coeval Fiery magmatic event. The

Deighton Quartzite 1 conglomerate, together with the remaining Units 1,2,3 and 4 equate to the ~1690 Ma Prize Supersequence, and the conglomerate and sandstones of Deighton Quartzite 5 is correlated with the base of the ~1670 Ma Gun Supersequence. This suggests that fluvial systems developed as far east as the Mary Kathleen Zone, and at this locality, may record the fill of an incised valley at the base of the Gun Supersequence.

Results from the Mitakoodi Block

The stratigraphy of the Mitakoodi Block includes the Argylla Formation, the Marraba Volcanics (Cone Creek Basalt, Mount Start Member, Timberoo Member), the Mitakoodi Quartzite and the Overhang Jasperlite. Samples have been collected from all units to determine their maximum depositional ages and provenance spectra, and their relationship to the Western Succession supersequence stratigraphy.

Current age constraints for Argylla Formation (R.W. Page, *pers comm.*) indicate that this unit is ~20 my younger than in Mary Kathleen section, even though it has similar lithological characteristics. Further, current age interpretations for the Mitakoodi Quartzite (R.W. Page, *pers comm.*) indicate that it has a depositional age of ~1755 Ma. Field observations suggest that the Marraba Volcanics may represent an extra cycle between Argylla Formation and the Mitakoodi Quartzite, which is not recognised in the Western Succession.

Results from the Snake Creek region

Stratigraphic section

The Snake Creek Anticline was chosen as an introduction to the Soldiers Cap Group, as the units in this area record the lowest metamorphic grade of the region, therefore making it easier to identify primary sedimentary facies. This area also appeared to have most continuous stratigraphy for constructing a composite section. The units studied in detail were the Llewellyn Creek Formation, the Mount Norna Quartzite and the Toole Creek Volcanics. The Llewellyn Creek Formation is dominated by siltstones and shales with minor thin sandstones, whereas the Mount Norna Quartzite contains thick amalgamated sandstones and siltstones, with subordinate shales. These packages are interpreted to represent a thick, turbiditic system developed in a deep-water basinal setting.

New SHRIMP data

Three sedimentary samples were analysed from the Snake Creek Anticline. The Llewellyn Creek Formation was sampled near its interpreted stratigraphic base and provided a maximum depositional age of ~1685 Ma, with a major population at ~1730 Ma and a minor ~1850 Ma and Late Archaean component. The basal sample from the overlying Mount Norna Quartzite also records a maximum depositional age of ~1685 Ma, with a major component at ~1755 Ma and small number of ~2500 Ma ages. The upper Mount Norna Quartzite was taken near the top of this unit, and also recorded a maximum depositional age of ~1685 Ma, with a small proportion of ~1730 Ma and Late Archaean ages.

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Big system–big footprint: integrating Laverton's geology, geochemistry and geophysics for predictive mineral discovery

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Introduction

Reducing the risk in greenfields and brownfields exploration requires a new generation of targeting models that integrate the chemistry and architecture of mineral systems from terrane to deposit scales. Developing such models for the Eastern Yilgarn requires understanding of the deep architecture and its interaction with the upper crustal architecture, consideration of multiple fluids with contrasting chemistry, and detection of the big footprints generated by the interaction these fluids in space and time.

Traditionally, hydrothermal alteration studies have focused on the ore shoot- to deposit-scale and were of limited value for regional- to camp-scale exploration targeting because mineralogical alteration haloes (e.g., biotite, chlorite) around lodes are typically too small (e.g., <50 m). A number of studies specifically targeted deposit- to camp-scale dispersion haloes and determined pathfinder elements which may be useful as vectors to mineralization (e.g., Eilu and Mikucki, 1996). Whilst the determined dispersion haloes appeared to be a useful guide to ore in the studied deposit, they tended to fail as a guide in some other deposits, or even failed to identify other lodes within the same deposit, indicating that there are either different types of deposits, or a more complex fluid flow patterns and chemical interactions. These early studies assumed single mineralization and fluid models and consequently tried to identify concentric alteration and geochemical dispersions around gold-bearing structures.

In a series of research projects in the last decade (AMIRA P511, Y3 project of the *pmd**CRC and the MERIWA M358 and M377 projects), it has been recognized that single fluid and mineralization models for Archaean gold deposits do not adequately describe observed hydrothermal alteration and geochemical dispersion patterns at a camp- to district-scale. It is now recognized that asymmetric, kilometre-scale alteration footprints can be identified in selected world class Archaean gold deposits in the Yilgarn Craton of Western Australia. Gold mineralization occurs preferentially within or subjacent to boundary zones between contrasting alteration domains (e.g., Neumayr et al., 2003; Neumayr et al., 2004a; Neumayr et al., 2004b; Neumayr et al., 2005; Walshe et al., 2003).

These large scale observations were made possible by examining extensive drill data sets provided by Placer Dome Asia Pacific (Kanowna Belle, Wallaby) and St Ives Gold Mining Company Pty Ltd (St Ives gold camp). Petrological observations were standardized by analysing bottom-of-the-hole samples in regional drilling campaigns for multi-element pathfinders and spectral PIMA and ASD analysis. Detailed interpretations of gravity, and magnetic data and geophysical inversion techniques being developed in the *pmd**CRC, allow first pass interpretations of hydrothermal alteration systems in covered terrains.

Multiple fluids in the system

Traditionally, models of formation of Archaean lode Au deposits have assumed one dominant aqueous-carbonic fluid (H_2O - CO_2 - NaCl ± H_2S ± CH_4 ± N_2) in the system with the CO_2 concentration in the fluid taken as >5 mole percent (Groves et al., 2003; Hagemann and Cassidy, 2000 and references therein). In these single-fluid models Au is considered to have been transported by a reduced sulphur complex in a near neutral fluid with Au deposition occurring through fluid-rock reaction or fluid phase separation.

Here it is argued that at least three significant fluid types or end-members of fluids are typically involved in the formation of the gold deposits.
An ambient fluid, representing fluids of diverse origins (basinal brines, metamorphic fluids or magmatic fluids that were rock-equilibrated). This fluid is equivalent to the aqueous-carbonic fluid described in the literature on Archaean lode Au deposits. The CO_2 in this fluid was derived from the greenstones and ultimately derived from Archaean seawater.
An oxidized, volatile-rich magmatic fluid dominantly composed of CO_2 but transporting SO_2 and elements such as Te, V, Mo, Bi and W.
Deep Earth fluids introduced into the mid- and upper-crust via the trans-crustal architecture. These fluids are considered hydridic or hydrogen rich (in the sense of Larin, 1993), rather than hydrous or water rich and were composed dominantly of H_2 - CH_4 - H_2S - N_2 with components of Na, Cl. These fluids were potentially the most important Au-transporting fluid (Walshe et al., 2004a; Walshe et al., 2004b; Walshe et al., 2005).

These end-member fluids are considered necessary to account for the geochemical characteristics of the deposits and environs in the Eastern Yilgarn Au systems, the inferred physicochemical conditions within the system, the spatial associations of Au deposits and camps with significant architectural elements of the system (trans-crustal structures, intrusive complexes, district-scale structural culminations) and temporal correlations with the geodynamic and magmatic history of the terrane. Potentially, a fourth, near-surface derived fluid (meteoric fluids of Hagemann et al., 1994) may have been important in some parts of the Au systems.

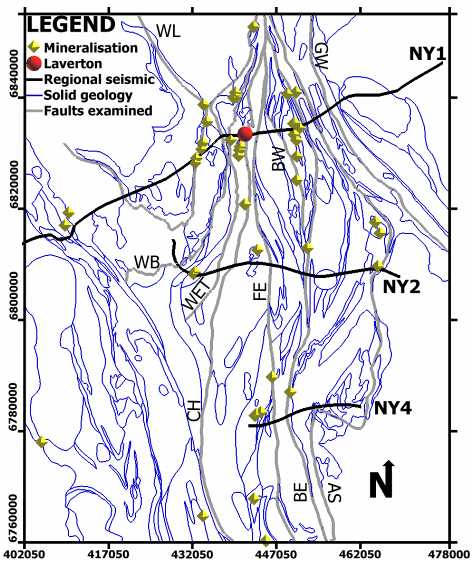

Figure 1: Solid geology, mineralisation and regional seismic traverses in the Laverton region. Solid geology after Henson et al (2006). Mineral deposit locations (points) derived from the MINLOC database. Laverton township is indicated by the filled circle. Coordinates are GDA94, zone 51.
Faults:
WL – Wallaby Low angle shearzone
WB – Wallaby Basin
WET – Wallaby East Thrust
CH – Childe Harold Fault
FE – Far East Fault
BW – Barnicoat (West) Fault
BE – Barnicoat (East) Fault
AS – Apollo Shear
GW – Granite Well Fault

Hydrothermal alteration footprints

Large-scale alteration systems, with significance for targeting Au deposits, have been identified in the Kanowna Belle deposit, the St Ives gold camp and the Wallaby deposit in the Laverton district (Figure 1). Initial data from other Au deposits world-wide also indicate similar systems.

Most, if not all, of the major Au camps in the Eastern Yilgarn Craton contain proximal mineral assemblages formed under reduced (pyrite, pyrrhotite stable) as well as oxidized (hematite, magnetite, pyrite stable) conditions. Reduced and oxidized assemblages may occur in both distal and proximal environments. The S and C isotope constraints support the argument that the different mineral assemblages primarily reflect differences in redox, acidity and S activity of the fluids, and are not simply a function of changes in temperature, pressure and the composition of host rocks in the system. Albite and phengite are the common silicates in the proximal settings with biotite-actinolite occurring with the more reduced assemblages. Albite ± phengite may also occur distally, such as in the footwall of the Kanowna Belle deposit and in the Lancefield deposit near Laverton. The most acidic conditions are typically confined to distal settings, as indicated by andalusite or equivalent minerals: chloritoid, observed distally to the Golden Mile, Wallaby and Lancefield deposits and pyrophyllite observed in the Kanowna Belle district (Tom Cudahy, pers. comm., 2005). Fluids in these distal environments apparently contained lower S contents compared with fluids in proximal environments. Minerals such as epidote, muscovite, paragonite and tourmaline formed in neutral to acidic conditions, commonly in transitional proximal to distal settings.

Location of gold deposits with respect to hydrothermal footprints

Regional hydrothermal alteration patterns in all three deposits/camps typically have:
1) large-scale acidic domains,
2) reduced domains, and
3) oxidized domains.
The acidic domains are interpreted as zones where possibly deeply sourced reduced fluids were degraded and contain only small Au deposits (if any). Reduced domains occur either focussed along structures (e.g., the Fitzroy Fault) or they form wide and dispersed haloes around gold deposits such as in the St Ives gold camp. Oxidized domains are typically well focussed. High-grade Au mineralization typically occurs at the domain boundary between reduced and oxidized domains, interpreted as representing the highest chemical gradient, most likely caused by the mixing of the oxidized and reduced hydrothermal fluids. As such, this relationship and spatial pattern is extremely useful in both regional-scale and deposit scale targeting.

Mapping hydrothermal alteration

The major challenge for utilizing these concepts in Au exploration is to detect the hydrothermal minerals at a large scale. Where drilling is available, bottom-of-the-hole samples can be analysed for selected pathfinder elements, PIMA spectra or simple petrographical observations. Where drilling data are not available, however, geophysical data can map the presence of hydrothermal pyrrhotite and magnetite, which are indicative of reduced and oxidized domains, respectively.

Pyrrhotite alteration haloes can be mapped in regional and detailed magnetic data. Discrimination between a magnetic anomaly due to pyrrhotite and one generated by a body containing magnetite, however, is not possible using the magnetic response alone, since both minerals are magnetic. Pyrrhotite is less magnetic than magnetite, but a large amount of pyrrhotite could have a similar magnetic response to a small amount of magnetite. To differentiate between the two, the use of another physical property is required. Pyrrhotite is one of the most electrically conductive minerals (Milsom, 1989), whereas magnetite is mildly conductive to strongly resistive. Likewise, pyrrhotite commonly has a lower density than magnetite. One potential way of delineating the occurrence of pyrrhotite could be to compare magnetic and EM datasets, where a corresponding subtle magnetic response would be coincident with a pronounced conductivity response. A more subtle method would be to identify coincident magnetic and gravity highs, although, since lithological changes could also cause such responses, a detailed understanding of the 3D geology and its inherent rock properties is essential. These methods could be applied to regional datasets to infer outflow zones generated by a mineralising fluid.

Mass density and magnetic susceptibility data can be used to identify anomalous sulphide accumulations based on a set of end-member components expected in a sample. With selection of appropriate end-members and their physical properties, a mineral estimation calculation can be applied to physical property estimates derived from 3D inversion results. When applied to district- or regional-scale inversion models it can be used to prioritize exploration targets, or to identify portions of the mineral system footprint such as fluid outflow zones surrounding Au deposits.

The calculation has been tested on measured density and susceptibility values from drill core for which mineralization had been independently assessed at the Perseverance Ni-sulphide deposit in Western Australia and the Olympic Fe-oxide Cu-Au province in South Australia. We intend to apply these methods to regional magnetic and gravity data in the Laverton area to assess the detectability of pyrrhotite haloes in fluid outflow zones surrounding several large Au deposits. These subtle features should have slightly different physical properties to adjacent magnetite-bearing rocks, but robust methods incorporating the geophysics, expected geology, and uncertainty estimates are required to differentiate them from the less prospective magnetite rocks. The physical properties of the rocks will be estimated using geologically-constrained 3D inversions of regional magnetic and gravity data. Mineral estimates will then be calculated from the physical property models relative to the expected geology in the Laverton 3D geology models. It is hoped that the integration of these multiple datasets will aid in improving our understanding of the distribution and definition of alteration haloes, and ultimately provide a method for identifying prospective alteration surrounding Au deposits at a regional/scale.

Chemical gradients and targeting in the Laverton camp

Current research aims to produce scale-integrated (mine-scale to district-scale) models of the alteration and architecture of the Laverton district (e.g., Blewett et al., 2006). Regional magnetic images show that the Wallaby and Sunrise Dam deposits are located at the edges of magnetic features to non magnetic zones. Both deposits show evidence for oxidized and reduced fluid flow (Sunrise Dam: elevated As signals - reduced fluids; elevated Te signals - oxidized fluids, Wallaby: pyrrhotite - reduced signal - and magnetite/hematite - oxidized signal). In combination, the deposit- and district-scale constraints indicate that the Wallaby and Sunrise Dam deposits formed in domains characterized by gradients in the redox state of the hydrothermal fluids.

At Wallaby, all the distal sections of the faults (e.g., Thets and Slaughteryard thrust faults) at the base of the conglomerate packages and the north-south faults like Chatterbox and Shocker have intense acidic and reduced paragonite–ankerite–pyrite±chloritoid-pyrrhotite alteration developed along them, as mapped with the white mica PIMA 2200 feature. The acidic alteration assemblages are interpreted to represent domains where the deep, reduced fluids in the system have reacted with the ambient fluids. In sections of these faults proximal to the Wallaby deposit the alteration is characterised by a phengitic white mica, reflecting a more alkaline fluid composition. This also corresponds with a zone of elevated W-Mo-Bi, in contrast to the As-Sb signature of the more acid-reduced domain. Hence the Wallaby deposit is proximal to an acidity gradient as well as a redox gradient. The current study will expand the integration of alteration and structural architecture at Sunrise Dam and Wallaby, and upscale regionally to identify further prospective targets.

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Regional architecture of the Tasmanides: the story so far

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Introduction

There has been much discussion recently about 3D modelling workflows and how to deal with complexities of integrating regional 3D datasets. The most widely accepted approach is still to develop a CAD based model based on regional mapping, geophysics and serial cross sections. It seems that one of the main tenets of this approach is to make certain that all the data is available prior to embarking on section drawing and 3D construction. The major argument for this is that CAD based 3D models, particularly complex models with numerous intersecting faults and stratigraphic surfaces, are notoriously difficult to modify if the structural interpretation changes.

When we started building the 3D geological model of the central Victorian geology, as the first phase of the regional 3D architecture component of the T5 Tasmanides project we agreed with these sentiments and began cross section and construction 3D model building using a very similar approach. With the very welcome funding of the T13 Victorian Seismic Traverse project, however, we were presented with a dilemma of sorts. Early in Year 3 of our project (at a point when we had envisaged having the majority of the central and western Victorian model completed) T13 will start to deliver results that will potentially require at least some model surface orientations to be modified or completely redesigned.

In response to this challenge we have done two things. Firstly, we have modified our model workflow, slightly allowing us to integrate the flexibility of a GeoModeller approach to model building with the robustness and ability to handle very large datasets of the traditional CAD approach. Secondly, we have put our necks on the block and have developed our “best guess” model for the major crustal architectural elements in the region of the T13 seismic line, and have produced our “interpretation” of the seismic line before it has been shot.

So far

Our model approach thus far has been to:
Identify critical Phase 1 model region – The central Victorian goldfields region bordered by the Avoca Fault to the west and the Governor Fault to the east was chosen due to its high mineral potential, the location of the T1 western Victorian model to the west, and its coincidence with the proposed location of the T13 seismic line.

Identify locations for major crustal scale sections to be drawn – nine major regional section locations were identified with a number of smaller infill sections providing detail in structurally complex regions (Figure 1).

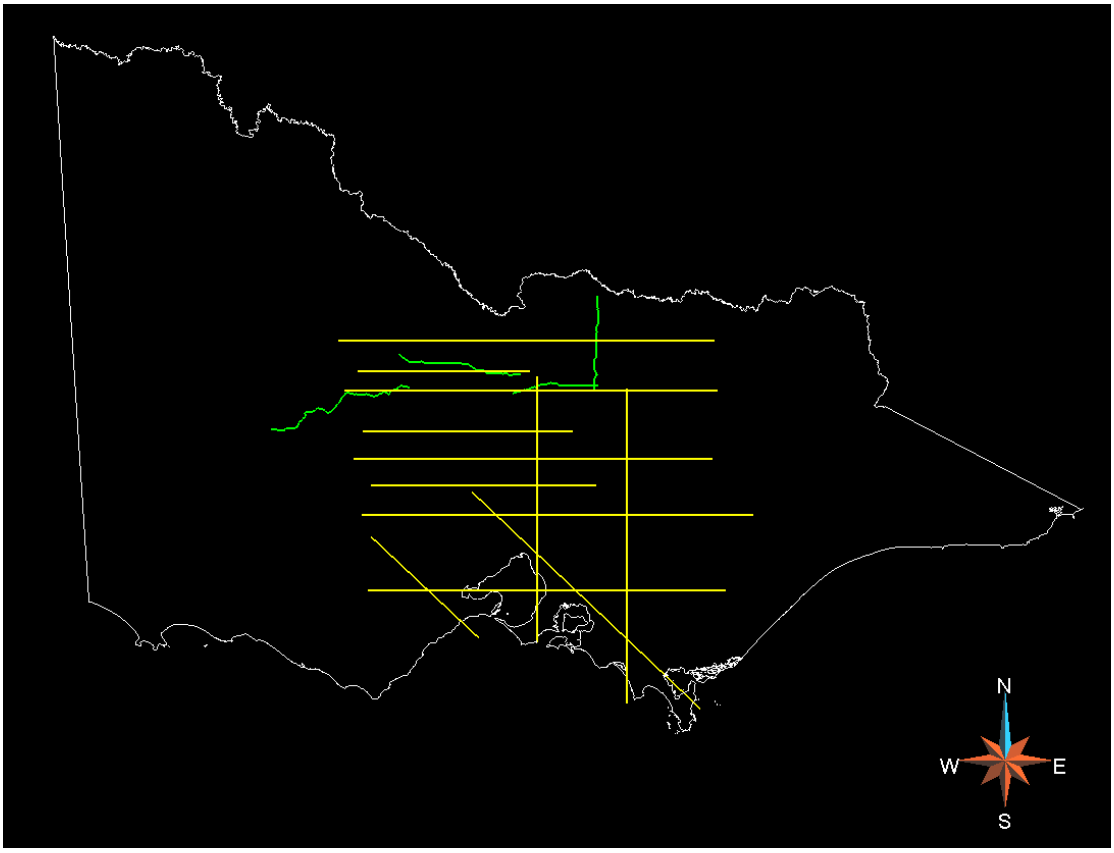

Figure 1: Location of crustal section lines (straight) and proposed T13 seismic lines (meandering lines).

Traditional CAD approach to modelling major architectural elements – all of the major faults and granites within the focus region were using a traditional CAD approach. The geometries of surfaces were constrained by the crustal sections, GSV 1:500 000 regional mapping and Pre-Permian interpretive maps, and locally by more detailed public domain maps and datasets. The 3D geometry was further informed by interpretations of the VIMP potential field data and potential field worms derived from these data.

First order modelling of stratigraphic contacts using GeoModeller – We have chosen to try integrating the use of GeoModeller when building stratigraphic surfaces. GeoModeller has the great advantage in that, when new data are added, the model surfaces can be easily updated to reflect these changes. We are still experimenting with ways to successfully integrate the two approaches but are confident that this approach will provide us with additional flexibility when it comes to updating the models, in particular complex stratigraphic relationships, post T13.

We have currently constructed all of the major architectural elements (faults, detachments, basement blocks, granites) between the Avoca Fault and the Governor Fault and between the Murray River and Melbourne. We have also integrated these structures with the Western Victorian model produced during T1 (Figure 2). The next phases of modelling will involve pushing the model south into the region overprinted by complex Cretaceous and younger basins such as the Ballan Basin, as well as continuing to develop stratigraphic models for the entire region.

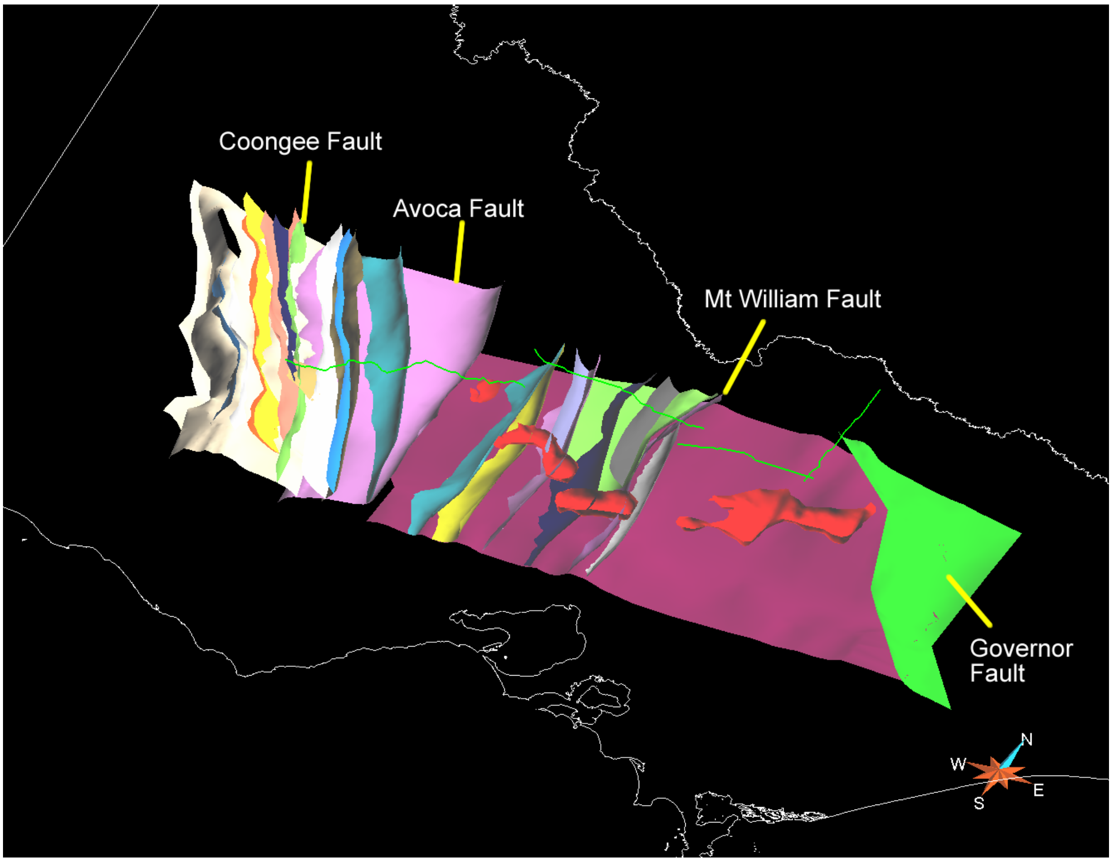

Figure 2; Major architectural elements of the current model region.

As mentioned above, we have also developed our pre-seismic interpretation of the T13 seismic line. This has been a beneficial process for both us and the researchers responsible for acquiring and processing the seismic data in the T13 project, as we at least have a starting point of where we think potential reflectors should be intersected along the line ,as well as their inferred dip. I am sure that more than a few of us will be following with interest the T13 data releases to track just how close our current thinking on the geometries in the region is to reality. Our current best estimate of the geometry along the line is presented in Figure 3.

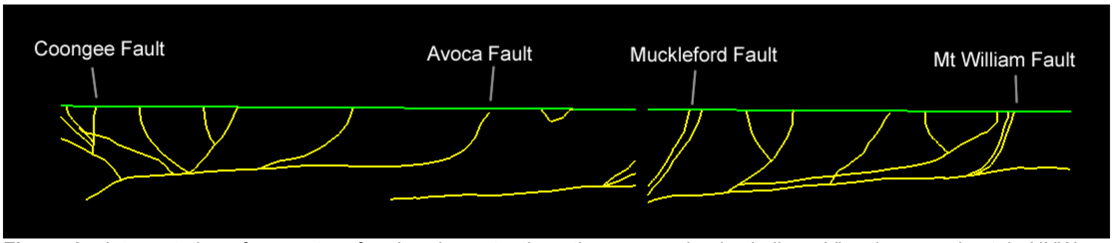

Figure 3: Interpretation of geometry of major elements along the proposed seismic line. View is approximately NNW and line length is 220km. Vertical scale = horizontal scale.

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Computational Simulation as a Practical Tool for Explorationists - a Progress Report

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Computational simulation of geological processes involved in ore formation is being applied successfully to mineral exploration, with several successful case histories already reported within the Predictive Mineral Discovery CRC (***pmd****CRC*).

Rationale

The ***pmd****CRC* was established to generate a change from the industry's current empirical targeting paradigm to a process-driven targeting approach. From the CRC's outset, it was recognised that this change could not be made unless process-driven targeting concepts were evaluated by science-based computational simulation tools. This abstract seeks to explain where we are in the development of such tools and how they can be practically applied to ore discovery.

Many explorers continue to operate exclusively with empirical targeting methods. Three arguments advanced for doing so are:

The experience of many senior explorationists leads them to believe that prioritising targets on the basis of conceptual thinking without reference to empirical criteria rarely, if ever, leads to exploration success.

Ore system geology is very complex and generally poorly understood. Thus the application of conceptual approaches (including computational simulation) which might lead explorers to non-intuitive (i.e. non-empirical) targeting choices is likely to be a worse strategy than sticking with straight empiricism.

In most target areas, the 2D (let alone 3D) geology is poorly understood. Computational simulations of ore systems rely on a 3D understanding of the geology of an area so they cannot be practically applied. In some cases, it is conceded that, if you had a perfect 3D interpretation of the geology, then computational simulation would be useful, although in such cases, the ore would already have been discovered!

The first point can only be addressed by employing a methodology for rating conceptual targets. This begins by eliminating concepts which cannot be supported by a rigorous evaluation of the underlying science. Appropriate use of computational simulation is a critical component in such evaluations.

The second and third arguments are fallacious despite being based on accurate premises. The core assumption is that an empirical approach in a poorly understood ore system and/or in an area of poorly understood geology cannot be improved upon. If this were true, it would be a depressing condemnation of our industry, as discovery efficiency is generally poor and appears to be getting worse (e.g. Schodde, 2003). If we take any empirical model as a starting point, however, we can usually identify areas where providing greater certainty about geological processes would improve the quality of the "empirical" targeting criteria.

One useful example of this last point is in the exploration for Irish-style zinc deposits in the Irish Midlands. Murphy et al. (2006) report that many (but not all) of these deposits are located at the base of the Waulsortian Limestone on north-dipping faults. The largest deposit in the district- Navan, however, is not located at the base of the Waulsortian Limestone. In the Irish Midlands, the 3D geology is not well known and outcrop can be poor, but fault orientations can be estimated from potential field data. So, two questions for explorers are:

- Should south-dipping faults be excluded from exploration targeting when we know that some mineralisation has been found against such faults?
- Under what circumstances are stratigraphic horizons other than the base of Waulsortian Limestone likely to be prospective?

If these questions can be answered with some confidence, it is obvious that targeting efficiency will be improved. Neither question can be simply addressed by the "empiricist", but both can be analysed through carrying out a series of carefully designed computational modelling experiments (e.g. Murphy et al., 2006). Also, the solution to both questions is not dependent on a detailed picture of the geology at a particular target. An answer to either question will lead to both specific data collection strategies and decisions on specific targets (where the geology **is** well enough known to make a drill decision). Thus, for example, assuming that roughly half of the faults are south dipping, a clear conclusion that excludes south-dipping faults would reduce the target population by half and increase the remaining target quality by a factor of 2. This would also lead explorers to focus data collection strategies (e.g. magnetics, gravity or shallow drilling) on recognising fault dip direction.

The fundamental proposition here is that all targeting strategies rely on geological interpretations of one type or another. Our inadequate understanding of how geological processes interact to make ore deposits is one of the most important reasons for the industry's inefficiency in making economic discoveries. So anything that can help us improve such understanding in a testable way will reduce discovery costs. Given that we cannot undertake "live" experiments on geological materials at reasonable scales and time frames, the only way of obtaining rigorous science-based assessments of conceptual targets is computational simulation. But, if we wish to obtain scientifically valid and practical targeting outcomes, we need:

- The process of developing conceptual models to be both rigorous and take consideration of all viable process ideas.
- The required simulation experiments to be done sufficiently quickly so that the results can be used in the time frames of mineral exploration programs.
- To translate the underlying science into algorithms and code which is robust enough to provide predictive value for the range of ore forming processes which are being assessed.
- The approach to be used effectively across various scales, and
- To demonstrate success sufficiently often so that the value of the approach is recognised.

The remainder of this abstract addresses progress on those issues within the ***pmd****CRC*'s Modelling Program.

Progress Report

Developing conceptual models

The process of developing conceptual models in the ***pmd****CRC* begins with an assessment of the "5 Questions", which were formulated within the Australian Geodynamics CRC by a group including Tom Loutit, Alison Ord, Bruce Hobbs, Greg Hall and John Walshe, viz.:

1. What is the geodynamic history?
2. What is the architecture of the system?
3. Where are the fluid reservoirs?
4. What processes drive fluid flow?
5. What are the processes of ore deposition?

Assessment of these questions allows team members to gather all the critical information about the mineral system in question and guides the discussion about both the processes which formed the target ore systems and their timing.

In addition, the modelling team seeks information about current empirical models and hence the critical geological uncertainties which require resolution by computational simulation. An important point here is that this part of the assessment almost always focuses on data types that are either available or collectable at the scale under consideration. This generally means that the numerical simulation experiments do not need to address all aspects of the ore system and may not require fully coupled modelling (deformation-fluid flow-thermal evolution-chemical reaction).

Speeding up the simulations

The focus of the CRC's software development program has been to speed up the efficiency of the entire process of generating, visualising and interpreting computational simulations. Optimisation of these activities has been planned around the modelling team's workflow, which consists of the following key steps (Woodcock et al., 2004):

- Determine scale and type of investigation.
- Use the "Five Questions" to describe the mineral system, then determine what questions need to be answered by numerical modelling.
- Build the geometry for the model family.
- Choose properties appropriate for model sophistication and boundary conditions.
- Run the models.
- Visualise and interpret the results.

Activities which had contributed to a 10 times improvement in computational simulation efficiency by mid-2005 and will result in a further 10 times lift in efficiency by the end of the CRC in mid-2008 include:

- Streamlining of the processes of mineral system assessment, proposal development and reporting to clients.
- Development of a user interface and software architecture to enable expert users to access and (where necessary) couple various simulation codes without needing to work with them separately.
- Development of several parameter search ('inversion") tools.
- Mesh building improvements using templates, GOCAD wizards and PATRAN.
- Large "parameter sweeps" (multiple models in which we experiment with varying parameters) on CSIRO's Melbourne high performance computer ("HPC").
- Porting reactive transport and mechanical modelling codes to Finley/eScript in order to enable fast (parallelised) simulation runs on the new iVEC HPC in Perth (in progress).
- Effective and efficient coupling of deformation, fluid flow, thermal evolution and chemical reaction in complex 3D meshes (to be completed in 2007).

Translation of the underlying science into algorithms and code

Research in this area has proceeded across a number of fronts, viz:

- Calibration of fracture modelling simulations with experimental data.
- Addition of advective transport of heat into FLAC and FLAC3D, thereby enabling simulation of convective behaviour.
- Introduction of additional mechanical behaviours (constitutive models) into FLAC3D.
- Development of new algorithms for high strain deformation involving thermal feedback. This work builds on studies outside of the ***pmd****CRC* by research team members, Klaus Regenauer-Lieb and Regan Patton (e.g. Patton and Watkinson, 2005; Regenauer-Lieb et al., 2006) The research aims (inter alia) for new codes which will allow self consistent simulation of rock behaviours at the brittle-ductile transition (that is, without the need for imposing two different constitutive models for brittle and ductile materials)
- Development of a new reactive transport code capable of dealing with large, irregular 3D meshes and complex chemistry suitable for experiments at the high temperatures and pressures prevailing in hydrothermal ore systems, and building on the HCh developments of Yuri Shvarov and Evgeniy Bastrakov.

All of this work is enabling us to deliver predictive value in the simulation of geological behaviours for a range of hydrothermal ore systems in the shallow crust. There is still much work to be done, however, to enable accurate simulation of all such behaviours. While we aim to offer predictive value for most shallow crustal hydrothermal ore systems by the time the CRC ends, much will remain to be done in the areas of simulating magmatic behaviours and coupled deformation-fluid flow below the brittle-ductile transition.

Across scales

Simulation of geological behaviours is possible at all scales – from the growth of crystal defects to whole earth geodynamics. Nevertheless, the nature of application to targeting changes as we move “upwards” in scale.

At the ore system scale (e.g. a cube 5-10km on each side), the entire simulation can be confined to the upper brittle crust, where the reliability of deformation and fluid flow predictions are highest. In these situations it is possible to make predictions about the localisation of fluid flow and, by inference or through coupling with chemistry, mineral deposition. Most of the current application work with mining industry clients focuses at this scale. An interesting variation at the terrane scale is currently being applied in the PIRSA Central Gawler Gold Province project. Here, we are simulating a range of known and possible ore systems at the ore system scale to predict “what could exist” somewhere else in the terrane.

In general, however, at larger scales, the approach changes because both the science of deep rock and fluid behaviour and our knowledge of 3D geology become more uncertain. The use of simulation here is primarily to test ideas for their relative likelihood. Thus, predictive targeting is fundamentally dependent on the formulation of conceptual ideas inferred from data derived from deep geophysical studies, exhumed deeply buried rocks and xenoliths. Computational simulation at this scale provides a platform for testing ideas but is generally incapable of putting an “x” on a map.

Successful application

Since the ***pmd****CRC* began in July 2001, there have been many examples where the application of simulation to ore system studies has added value to conceptual thinking. Examples are located in the Yilgarn and Gawler Cratons, the Mt Isa Inlier, the Lachlan Orogen, the Athabasca Basin in Saskatchewan, the Great Basin in Nevada and the Outokumpu District in Finland. In some cases, the contribution to direct mineral discovery has been publicly acknowledged, for example at Stawell in Victoria (Rawling et al., 2004) and Kundana in Western Australia. In others, the work has contributed to ongoing exploration thinking. The need is for many more case histories in which the direct contribution to discovery is recognised. To this end, the CRC’s modelling team is currently focused on applying these technologies to a plethora of short term targeting projects, both in Australia and overseas.

Acknowledgements

This abstract draws on decades of work by researchers both within CSIRO and elsewhere in the ***pmd****CRC*. Many people have contributed towards the achievements covered herein, beginning with Bruce Hobbs who set us all on this course, and including Alison Ord, Peter Hornby, Robert Woodcock, Heather Sheldon, Klaus Regenauer-Lieb, Regan Patton, James Cleverley, Evgeniy Bastrakov, Yanhua Zhang, Peter Schaubs, Warren Potma, John McLellan, Andy Dent, Simon Cox, Gordon German, Thomas Poulet, Chongbin Zhao, Robert Cheung, Ryan Fraser, John Walshe, Andy Barnicoat, Lesley Wyborn, Barry Murphy, Jon Dugdale, Tim Rawling, Chris Wilson, Greg Hall, Scott Halley, Nick Fox, Bob Haydon, Klaus Gessner and Fabio Boschetti.

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Using time-constrained facies belts and sequence architecture to correlate the Western and Eastern successions of the Mt Isa Inlier: implications for fluid migration

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Introduction

In order to provide more precise correlations between the Eastern and Western Successions of the Mt Isa Inlier it is necessary to determine:

1) a chronologic framework for the interval 1800-1500 Ma, and
2) a physical or architectural framework for the basin fill.

Sequence stratigraphic analysis permits the identification of depositional sequences and their bounding stratal surfaces that are amenable to correlation. The chronologic framework provides an absolute age for the sediments and magmatic rocks. It permits the identified sequences to be arranged in their appropriate order and the temporal significance of unconformity surfaces and their correlative conformities to be realised.

Mapping during the 1950's and early 1960's at a scale of 1:250,000 established the broad, lithostratigraphic framework for the Mt Isa Inlier and provided initial insights into the regions structural complexity. Subsequent mapping at a scale of 1:100,000 in the 1970's and early 1980's improved our understanding of the regional stratigraphy as lithostratigraphic subdivisions were refined. The mapping programs also identified the principal tectonic units of the Mt Isa Inlier, including the Lawn Hill Platform and Leichhardt River Fault Trough of the Western Succession, the central Kalkadoon Leichhardt Block and Mary Kathleen Zone, and the Eastern Succession, including the Mitakoodi Block, Marimo Belt and Soldiers Cap Group. During the 1:100,000 mapping program, logistic requirements resulted in three separate BMR-GSQ field parties mapping the Mt Isa Inlier. Although each party recognised the need to correlate their lithostratigraphic packages and metamorphosed equivalents, the lack of high quality age information, combined with an absence of depositional facies models, inhibited regional correlations across the Inlier. Working largely as independent units, the field mapping parties developed lithostratigraphic subdivisions for each tectonic unit and attempts to correlate between these units met with limited success. In consequence, the current lithostratigraphic and tectonic subdivisions of the Western and Eastern Successions have become entrenched in the literature and attempts to formulate holistic geodynamic models to explain the evolution of the Mt Isa Inlier and its mineral systems have met with mixed success.

In the mid 1990's AGSO, in conjunction with the GSQ and NTGS initiated a multidisciplinary basin analysis project for the McArthur and Mt Isa Basins, with the aim of providing a chronostratigraphic subdivision for the ore-hosting rocks of the Mt Isa, McNamara, Fickling, McArthur and Nathan Groups of northern Australia. This project involved the identification of depositional facies, the bundling of facies belts into depositional sequences and recognition of the respective bounding surfaces (sequence boundaries, maximum flooding and transgressive surfaces). The project benefited from a significant investment in palaeomagnetism research and SHRIMP geochronology which resulted in an additional 50 ages to support correlations across northern Australia (Page et al., 2000). The new chronostratigraphic subdivision identified nine supersequences and correlated these packages between the Western Succession of the Mt Isa Inlier and the southern McArthur Basin (Southgate et al., 2000; Jackson et al., 2000, Jackson et al., 2005). More recently, similar techniques have been used to provide a chronostratigraphic subdivision for mafic volcanic and sandstone-rich successions of the Haslingden Group (Neumann et al., 2006). Importantly, the chronostratigraphic event charts for the Haslingden, Mt Isa and McNamara Groups, Surprise Creek Formation and Fiery Creek Volcanics can now be combined to provide a time-based synthesis for accommodation history and magmatism for the entire Western Succession covering the interval 1800-1575 Ma. Such a synthesis provides a template for chronostratigraphic correlations across the entire Mt Isa Inlier, ultimately uniting West and East.

Facies Models

In order to provide a physical or architectural framework for sediments of the Western and Eastern successions, it is necessary to identify the principal depositional facies belts of the Inlier and use sequence stratigraphic concepts to identify time equivalent packages. SHRIMP geochronology can then be used as a means of testing the proposed correlations and better understanding the significance of identified unconformities.

Western Succession Facies Models

Sedimentary rocks of the Western Succession can be grouped into two depositional systems each composed of linked:

- siliciclastic facies, or
- carbonate facies.

Rocks of the siliciclastic depositional system are grouped into six facies belts:

- Trough cross-bedded quartzite facies
- Cross-bedded, sandy carbonate and stromatolite facies
- Thinly-bedded, wavy to hummocky very fine sandstone facies
- Medium to thickly-bedded, very fine sandstone facies
- Very fine sandstone, siltstone and mudstone rhythmic laminite facies
- Carbonaceous shale and rhythmic laminite facies.

Rocks belonging to the carbonate depositional system are also grouped into six facies belts:

- Shoreface, cross-bedded sandy carbonates
- Peritidal/lagoonal cycles, consisting of thin to thick bedded units of microbial laminate, intraclast grainstone, dolomudstone and quartz peloid grainstone
- Domal and columnar stromatolite bioherms
- Proximal tempestites, consisting of 1-10 m thick shallowing upward cycles of wavy bedded quartz peloid grainstone and packstone, dolomudstone and domal stromatolites.
- Distal tempestites consisting of thinly bedded calcareous quartz siltstone, wackestone, mudstone with current ripples and hardgrounds.
- Organic matter rich shales

Facies identified in the siliciclastic and carbonate depositional systems of the Western Succession developed in response to storm-dominated sediment transport and dispersal mechanisms on a relatively shallow water platform or shelf. The siliciclastic facies belt developed on the landward portions of the shelf; the carbonate facies belt developed basinward of the nearshore siliciclastics (Sami et al., 2000; Jackson et al., 2005).

Eastern Succession Facies

Fieldwork in the Mary Kathleen Zone, Mitakoodi Block, Marimo Belt and Snake Creek aimed to identify the principal depositional facies belts in each tectonic element for sediments of the Ballara Quartzite, Corella Formation and Deighton Quartzite (Mary Kathleen Zone), the Marraba Volcanics, Mitakoodi Quartzite, Marimo and Answer Slates and Roxmere Quartzite (Mitakoodi Block and Marimo Belt), and the Soldiers Cap Group (Snake Creek). The fieldwork also aimed to identify changes in the stacking patterns of depositional cycles in each facies belt with the intention of identifying surfaces of potential stratal significance across which geochronology samples would be collected for subsequent age determinations.

With the exception of the Soldiers Cap Group, Kuridala Formation and possibly the Roxmere Quartzite, all of the facies identified in the Eastern Succession fall within the twelve facies recognised from the earlier work in the Western Succession. Furthermore, sediments deposited in the east are characterised by deeper water facies when compared with their time equivalent rocks to the west. This observation suggests that, like their Western Succession counterparts, sediments of the Mary Kathleen Zone, the Mitakoodi Block and Marimo Belt accumulated on a platform or shelf, with more open water and deeper water environments located to the east.

Thick turbidite successions characterise the Soldiers Cap Group, Kuridala Formation and possibly the Roxmere Quartzite. These rocks accumulated as metre to decametre thick beds of amalgamated, reverse and normally graded, often poorly sorted sandstones and pebbly sandstones with interbedded siltstones and shales. These sediments are interpreted as deep water basinal facies. Unlike other sediments of the Eastern Succession, these rocks lack counterpart facies in the Western Succession. Sediment volumes responsible for the accumulation of these deposits were large, and much greater than those responsible for the centimetre thick rhythmically laminated turbidites of the platform.

The rhythmic laminites are interpreted as the product of highly repetitious storm events on the platform. Storms moved sediment onto and across prograding deltaic systems. Increased sediment loads caused partial collapse of the deltas facilitating the transport of sediment, via turbidity currents down the depositional slope onto the sea floor, to accumulate as delta front and prodelta rhythmic laminite facies. The grainsize, bed thickness and large volumes of sediment present in the Soldiers Cap and Kuridala Formation turbidites imply different sediment transport and dispersal mechanisms to those identified for rhythmic laminites on the platform. In order to understand the differences in these depositional systems and the significance of the basinal turbidites it is necessary to consider the sequence architecture of the platform and basinal successions.

Architectural Framework

The petroleum industry routinely uses sequence stratigraphic models as a tool for predicting the distribution of facies and reducing exploration risk. These models are based on the interpretation and integration of thousands of kilometres of seismic, outcrop, drill core and wireline-log datasets from a wide range of sedimentary basins from around the world. Sequence stratigraphy is based on:

- the recognition of depositional facies,
- bundling of these facies into depositional cycles,
- determining the stacking patterns of the respective cycles and identifying genetically related depositional systems or systems tracts (lowstand, transgressive and highstand deposits)
- identifying key surfaces (sequence boundaries, maximum flooding surfaces, transgressive and ravinement surfaces) that bound the respective systems tracts.

Transgressive and Highstand Deposits.

Southgate et al. (2000) and Neumann et al. (2006) grouped platform facies from the Western Succession into a series of supersequence cycles each consisting of a transgressive and highstand suite of deposits. Facies and cycle stacking patterns observed in platform sediments from the Mary Kathleen Zone, Mitakoodi Block and Marimo Belt indicate that these sediments can also be characterised by transgressive and highstand depositional systems. For example, in the Leichhardt River Fault Trough, rocks of the basal Quilalar Formation accumulated as a series of shallowing upward cycles, with successive cycles recording progressively deeper water facies indicative of regional transgression (Jackson et al., 1990). In the Mary Kathleen Zone, the same transgressive trend is observed in the Ballara Formation and basal parts of the Corella Formation. SHRIMP zircon ages from detrital and tuffaceous sediments of the Quilalar and Ballara Formations are consistent with both units being deposited in response to the same transgressive event, with onlap related to regional basin subsidence or sag. Likewise the overlying siliciclastic and carbonate–rich deposits of the Quilalar and Corella Formations accumulated as aggradational and progradational cyclic sequences collectively termed highstand deposits. Hence, the Quilalar, Ballara and Corella Formations represent a linked depositional system with transgression resulting in onlap to the west and deposition of a deepening-upward suite of sediments. As the siliciclastic facies belts migrated westward, clear water conditions permitted the formation of an offshore carbonate depositional system in the east. The deepest water conditions are associated with organic-matter rich shales in the lower parts of the Quilalar and Corella Formations. Sami et al. (2000) and Southgate et al (2000) interpreted similar depositional systems for siliciclastic and carbonate facies belts of the Gun Supersequence on the Lawn Hill Platform and Leichhardt River Fault Trough.

Lowstand Deposits

Turbiditic sediments of the Soldiers Cap Group, Kuridala Formation and possibly the Roxmere Quartzite are interpreted as accumulating in supersequence lowstand depositional systems located basinward of the former platform margin. Importantly, these sediments accumulated during those intervals when large parts of the platform became subaerially exposed, leading to widespread erosion and the development of major unconformity surfaces or supersequence boundaries.

SHRIMP zircon ages for the Llewellyn Creek Formation and Mount Norna Quartzite of the Soldiers Cap Group and Kuridala Formation identify maximum depositional ages of ~1680-1685 Ma for these turbidites. These ages are consistent with the interval of time represented by the Gun Unconformity on the platform and hence the interval of missing rock record at the base of the Isa Superbasin. Importantly, volcanism responsible for the influx of these zircons took place immediately preceding and possibly coeval with intrusion of the Sybella Granite and extrusion of the Carters Bore Rhyolite in the Western Succession. Detrital populations in Soldiers Cap samples also identify 1710-1730 Ma zircons, related to erosion of the Fiery Creek Volcanics, as well as populations that indicate recycling of Quilalar and Ballara age lithologies. Detrital populations in the Roxmere Quartzite suggest that these lowstand deposits may equate to missing rock record at the base of the Prize Supersequence.

Implications for Metallogenesis

Palaeoproterozoic rocks of the McArthur-Mt Isa-Cloncurry region host the world's premier zinc repository. Because supersequence lowstand deposits onlap at and below the platform margin these sediments will lack geometric connectivity with their counterpart supersequence transgressive and highstand deposits of the platform. Hence the evolutionary pathway of fluids hosted in supersequence lowstand deposits located basinward of the platform margin will most likely differ from fluids found in the supersequence transgressive and highstand deposits of the platform. Facies belts and basin architectures identified in this study restrict the Mt Isa style of Pb-Zn-Ag deposits to the supersequence transgressive and highstand depositional systems of the platform. These settings contrast with the deep-water and basinal, turbiditic hosts of the Broken Hill type deposits, which occur in supersequence lowstand deposits. Hence the palaeogeographic models developed from improved correlations between the Western and Eastern successions also provide a geometric separation for fluids potentially associated with the Mt Isa and Broken Hill types of deposits.

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Testing predictive exploration models for the Yilgarn by computer simulation

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Introduction

Numerical modelling, or computer simulation, is a powerful tool for understanding the processes that lead to commonly-observed features of mineralised regions, and for testing conceptual models of mineralisation. Here we present results of numerical modelling studies that were carried out to address two issues concerning mineralisation in the Yilgarn:
Why is mineralisation commonly located close to the unconformity between greenstones and the "late basins"? What is the role of granite domes in this system?
Do fluids produced by metamorphic dehydration (devolatilisation) reactions play an important role in mineralisation?
These numerical models address generic questions on a regional scale. They are not intended to produce precise results that enable us to say "drill here"; rather, they lead to a better understanding of the operating geological processes.

Late basins and domes – critical architecture for mineralisation?

Many gold deposits in the Yilgarn occur within greenstones, close to the unconformity with the overlying "late basins" (e.g. Hall, 2005). It would be helpful to understand why this occurs, especially if one could identify specific locations that are more favourable for mineralisation. The role of late basins could be chemical (e.g. basinal fluids reacting with greenstones), physical (e.g. through a sealing effect of the shale, which in turn affects fluid pressure), or a combination of both. This study focuses on the physical processes that take place at or close to the unconformity. Mechanisms for driving fluid from the basins into the greenstone are of particular interest.
Two generic architectures were used for the late basin models: one with flat stratigraphy (Figure 1a), and the other with a "dome and basin" geometry (Figure 1b), similar to the architecture that is seen in the Yilgarn at the present day. The models consist of layers of granite, greenstone, conglomerate and shale, with a fault cutting through the model that is weaker and more permeable than the surrounding rocks. The granite is assumed to be cold and strong. The models were tested in extension and contractions, with initial fluid pressure between hydrostatic and lithostatic.

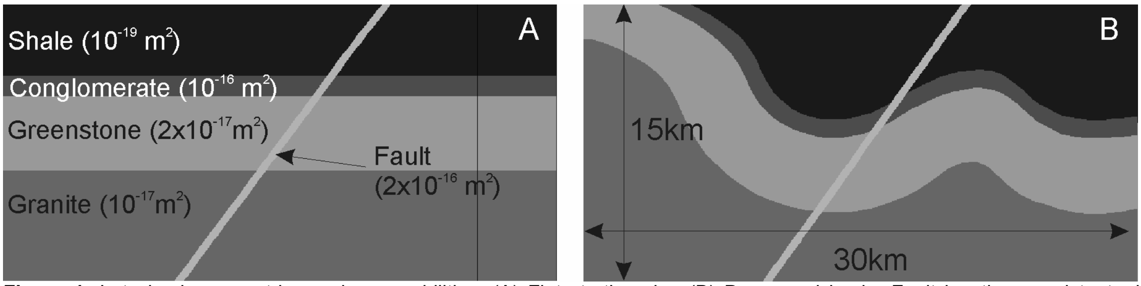

Figure 1: Late basin geometries and permeabilities. (A) Flat stratigraphy. (B) Dome and basin. Fault location consistent with observed relationship between major shear zones and domes.

Key results can be summarised as follows:
To move fluid from the basin into the greenstone requires downward flow, or lateral flow from the side of the basin in the case of the folded stratigraphy. Downward flow is favoured by extension; contraction/shortening leads to upward flow, although it may eventually switch to downward flow if sufficient sub-aerial topographic elevation is achieved.
Extension resulted in downward flow in the upper part of the model, with fluid accumulating at the level where upward flow from the base converges with downward flow from the top (Figure 2). High strain rate, high permeability and low fluid pressure promote downward flow to greater depth. A permeable fault has the potential to transport fluid from the surface down to several kilometres depth.
Extension of the folded stratigraphy model resulted in fluid moving from the greenstone into the conglomerate, then back into the greenstone again, on the left-hand side of the basin (Figure 2).
In all cases. there was little, if any, movement of fluid from the shale into the other lithologies. The shale has low permeability and acts as a seal. Increasing permeability with shear or tensile failure could allow fluid to be extracted from and/or to escape through the shale.
Prompted by observations of the pattern of volumetric strain associated with domes in the folded stratigraphy model, some further tests were run using a simplified geometry comprising a symmetrical granite dome overlain by greenstone. These models showed development of shear zones along the flanks of the dome, and a dilatant region above the dome, but only if the greenstone was weaker than the granite. This seems consistent with field observations of shear zones in greenstones anastomosing around granites.

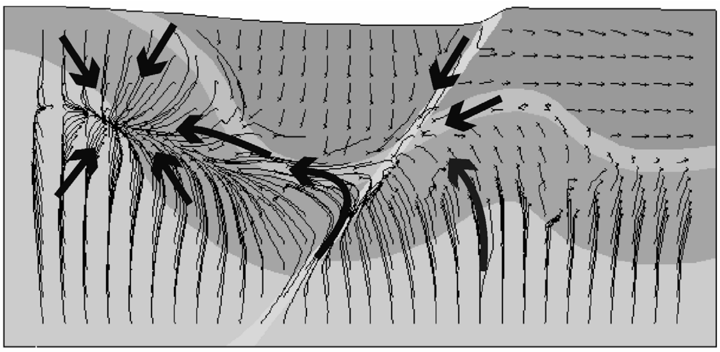

Figure 2: Fluid pathways after 4.5% extension, initial fluid pressure gradient = 1500 x 9.81 Pa/m. Strain rate ~$1.2x10^{-13}$ s^{-1}. Black lines indicate pathways of passive fluid markers. Arrows indicate general direction of fluid flow. Note downward flow near top of model, upward flow from base.

Devolatilisation as a fluid source for mineralisation

Some of the late basin models were initialised with fluid pressure greater than hydrostatic and fluid pressure was fixed at the base of the model during each run, implying a constant supply of fluid from below. This is intended to represent fluids released by regional metamorphic dehydration, the composition of which is similar to that inferred for gold deposits in Archaean greenstone belts (e.g. Powell et al., 1991). It is important to validate this approach by estimating the fluid flux due to regional metamorphism, and evaluating the degree of overpressure that could be attained and sustained by such a flux.
In order to calculate the fluid flux due to regional metamorphism, we need to know how the water content of crustal rocks changes with temperature, and how the temperature evolves over time. This has been achieved by using the thermodynamic code Perple_x

(http://www.perplex.ethz.ch/perplex.html) to calculate the water content of granite and basalt over a range of pressures and temperatures, then using this information to calculate the rate of fluid release during a crustal heating event. The model assumes a 1D column of crust, 40 km deep, which is initialised with a stable geothermal gradient and is subsequently heated by raising the temperature to 1200 °C at the base. This sudden heating could, for example, represent a delamination event. Effects of melting and latent heat are ignored. It is assumed that the column is fluid saturated, and that all fluid is removed from the column as fast as it is produced. Effectively we are assuming that permeability adjusts instantaneously to allow fluid to escape as fast as it is produced. These assumptions mean that the flux calculated by our model represents an upper limit on the rate of fluid release.

Figure 3 shows results obtained for granitic crust. It takes ~25 million years for the temperature to reach a new steady state. The instantaneous fluid flux decays exponentially over time; fluctuations are a numerical artefact associated with reactions that take place over a narrow temperature interval, but the net effect is a smooth increase of the integrated flux over time. The integrated flux increases with decreasing depth, because rock at shallow depth receives fluid from a greater volume of underlying rock. The final value of the integrated flux is comparable to that estimated by other workers (e.g. Ague, 2003).

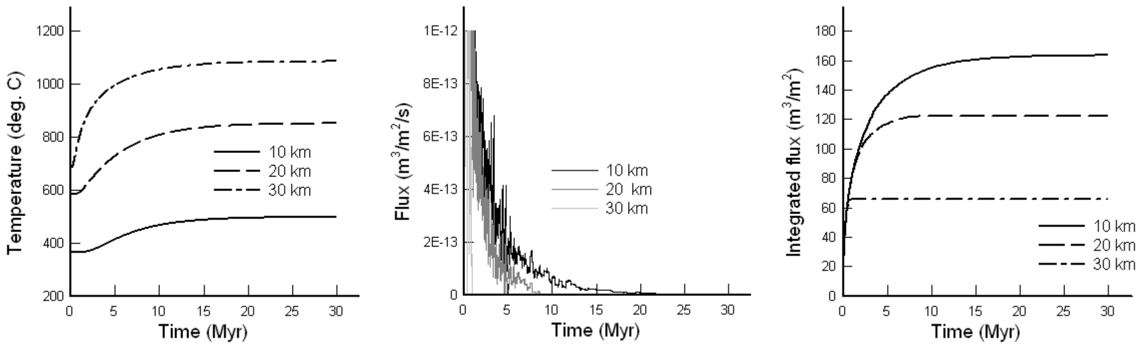

Figure 3: Evolution of temperature, fluid flux and integrated fluid flux in a 40km column of crust undergoing heating from the base, assuming the crust is water-saturated granite.

Information from the 1D devolatilisation model can be used to derive a fluid flow boundary condition for the late basin model. This was achieved by identifying a function which approximates the evolution of fluid flux due to devolatilisation at 15 km depth (the depth of the late basin models). By doing this we are ignoring any devolatilisation that takes place *within* the 15 km model, but it is a useful starting point. Applying this boundary condition to the base of flat stratigraphy model (Figure 1a), starting with hydrostatic fluid pressure and no deformation, resulted in negligible change in the fluid pressure, although fluid pressure would increase more if the permeability was lower (see Figure 1a for permeabilities). The regional fluid flux is enhanced by focusing into the permeable fault (Figure 4), especially where it cuts through the low-permeability shale (flux in fault ~10 x regional flux). The degree to which the regional flux is enhanced by focusing depends on the width of the fault, and the permeability contrast between fault and host rock (narrow faults and high permeability contrast result in higher fluid flux).

Figure 5 illustrates the effect of deformation (shortening, in this case) on fluid flow, comparing the fluid flux in the fault for 2 different strain rates (shortening), with that due to focusing of the regional metamorphic flux without deformation. Deformation produces fluxes that are orders of magnitude larger than the flux due to focusing alone, even at relatively low strain rates. Note, however, that the deformation-driven flux is transient; it cannot be sustained once fluid from the immediately surrounding wall rock has been drained into the fault. At this point, permeability of the wall rocks becomes the rate-limiting factor.

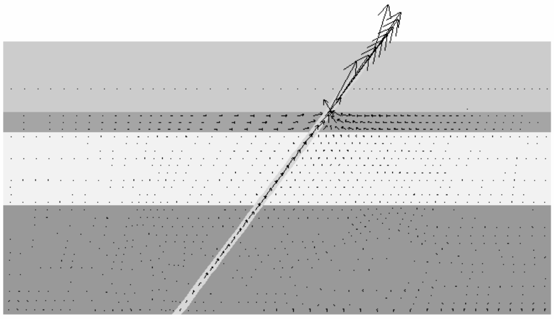

Figure 4: Passive focusing of regional fluid flow through a permeable fault. Maximum flux in fault ~2x10^{-11} m^3/m^2/s; maximum regional flux = 10^{-12} m^3/m^2/s.

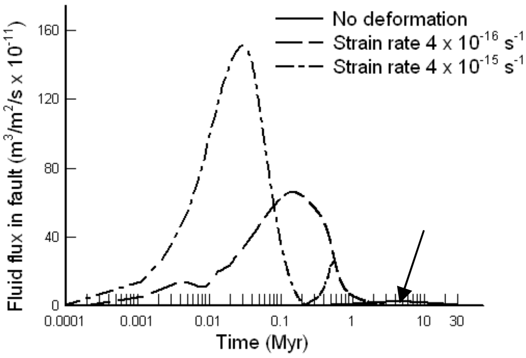

Figure 5: Effect of deformation on fluid flow, compared with passive focusing of regional metamorphic flux (highlighted by arrow). Plot shows fluid flux in fault as a function of time. Note log scale on time axis.

Conclusions

Numerical models have been used to explore two aspects of mineralisation in the Yilgarn, namely the role or late basins and domes, and the significance of fluid release during regional metamorphic dehydration. The late basin models suggest that extension may be a key requirement to drive fluid from the late basins into the underlying greenstone. Fluid may penetrate the greenstone where a permeable fault crosses the unconformity, or on the margins of the basin. Extension can lead to the development of shear zones around granitic domes, and dilatant regions above the domes, if the greenstone is weaker than the granite.

Metamorphic dehydration produces a relatively small fluid flux over a wide area, which can be enhanced by focusing into permeable faults. The regional flux appears to be insufficient to generate or sustain significant fluid overpressure, at least for the permeabilities used in our models. Fluid produced by regional devolatilisation may be an important component of the mineralising system, but it must be focused into narrow, permeable pathways before it can play a significant role in mineralisation. Deformation can enhance the flux relative to that produced by passive focusing, but this is a transient effect. Devolatilisation may be more important on a small scale around intrusions, where rapid heating leads to rapid release of volatiles from the wall rocks. Further work is needed to address this issue and the related issue of volatile exsolution during crystallisation of granitic magmas. The thermal effects of late granitic intrusions will also have an impact on fluid flow (see Cleverley et al., 2006).

Acknowledgements

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Metal Transport & Deposition in the Mount Isa Western Fold Belt and Lawn Hill Platform

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Introduction

Consideration of aspects of the transport and deposition of metals forms a key part of the “five questions” philosophical approach to mineral systems. In this paper under the headings “when” and “what” I review evidence of multiple fluid flow events in the Mount Isa Western Succession and Lawn Hill platform, and explore processes of metal transport and deposition.

Mapping flow paths and distinguishing “fertile” flow related to ore formation from “infertile” flow is potentially a crucial development for mineral exploration. Under the heading “where” I discuss progress towards defining the infra-red responses of various alteration types and how they can be mapped using multi- and hyperspectral mapping systems.

When

The Proterozoic Mount Isa terrane has undergone a complex, multistage evolution, which implies numerous fluid flow events. The major Sybella event at approximately 1680 Ma generated a major sequence stratigraphic boundary at the base of the Mount Isa Group, voluminous bimodal magma (Sybella batholith) and contact metamorphism and local melting (M1 event). Deposition in the Mount Isa Group probably resulted in fluid movement during sediment loading and basin dewatering. The Isan Orogeny, which attained its thermal maximum at prior to 1565 Ma (M2 event), resulted in folding of these basinal rocks and probably flow of fluids, including those generated by metamorphic devolatilization.

Rocks of the basal South Nicholson Group (Lawn Hill platform) dated at 1495 Ma (Jackson et al., 1999) unconformably overlie rocks deformed during the Isan event. This demonstrates that Isan rocks had been exhumed and eroded prior to 1495 Ma. Cooling as a result of exhumation may be reflected by published Ar-Ar ages from biotite and muscovite in the range 1530 to 1500 Ma (Perkins et al., 1999). This age range is also that of the Williams batholith and comparable intrusions that crop out in the eastern part of the Mount Isa Inlier and which are implicated in copper ore formation. Unmetamorphosed mafic dykes that abound in the vicinity of Mount Isa may have been emplaced at this time.

Published Ar-Ar, K-Ar and Rb-Sr ages from the vicinity of Mount Isa township and from the Lawn Hill platform have distinct maxima at 1300-1350 and 1150-1200 Ma (McDougall et al., 1965; Page, 1978; Kralik, 1982; Perkins et al., 1999; Spikings et al., 2002). These age ranges may correspond to early Grenville events and to the assembly of supercontinent Rodinia. The tectonic expression of these age ranges at Mount Isa is as yet uncertain.

The presence of a major unconformity at the base of the Cambrian shows that the Proterozoic sequence had been eroded to close to its present distribution by Cambrian times, and that only minor vertical movement have occurred subsequently. Widespread base-metal anomalies at the base of the Cambrian attest to another major Cambrian or younger event or events, possibly under near-surface conditions.

What

Pre- and syn-Isan fluid flow is recorded in various rocks from west of Mount Isa township, characterised by magnesium metasomatism, including cordierite-anthophyllite schist, massive tremolite rocks and quartz-albite-tremolite rocks. A number of pre-M2 uranium deposits occur north of Mount Isa, notably Valhalla (the second largest undeveloped resource in Australia), Skal and Anderson's Lode. The mineral assemblages in these deposits include albite, magnetite, amphibole and calcite, similar to those in widespread albitites of the Cloncurry district. This is the first indication that regionally-extensive albitisation is not restricted to the Eastern Succession. At Valhalla, uranium is associated with Zr (in zircon lattice sites), P (in apatite as discrete inclusions) and Ti, as brannerite and spatially associated with spongy-textured Ti oxides. This is suggestive of the input of carbonatite or alkaline magmatic fluids. Red coloration of the albitites is due to a secondary process that caused development of hematite along grain boundaries. There are as yet no absolute age determinations for the deposits and associated albitites, and it is not yet clear whether there is a genetic link with the unconformity-type uranium deposits of the Alligator Rivers region (which are associated with magnesian metasomatism).

Models for lead-zinc ore formation are divided between those which advocate formation during or soon after deposition of the host rocks (i.e. between 1670 and 1650 Ma) and those that espouse emplacement during much later deformation events. The McArthur River deposit is the clearest example of the former category, having been relatively unaffected by late deformation. To many, this deposit provides compelling evidence that ore emplacement was either exhalative or occurred soon after deposition. This timing is supported by published lead isotopic ages, although paradoxically there is evidence at Mount Isa for spatial association of lead and zinc with post-Isan deformation features and a temporal link with copper. These seemingly disparate views can be reconciled by proposing two distinct Pb-Zn events. Indeed, there is textural and geostatistical evidence suggesting separate Zn and Pb-rich events at Century. Alternatively, local-scale reconfiguration of early orebodies during deformation may account for some of the features of the Mount Isa Pb-Zn orebodies.

Fluid flow paths related to early Pb-Zn should be influenced by metamorphic re-equilibration and geometric reconfiguration during the Isan shortening event (D_2). These flow paths have yet to be clearly identified. Tourmalinites, quartz-tourmaline rocks and tourmaline-bearing pegmatites are common west of Mount Isa township. Duncan et al. (2005; 2006) have obtained 1570 Ma ages from tourmalines using Pb-Pb step leaching. Fine-grained inclusions of sphalerite have been found in some of their samples, and fluid inclusions in tourmaline are rich in Zn and also U. At Century, hosted by lower grade metasediments, alteration includes a smectitic halo (defined by X-ray diffraction) and abundance of iron-bearing phases such as siderite, pyrite, sideroplesite and pistomesite.

The sources of Cl, S and metal are poorly-constrained aspects of these deposits. A possible source of Cl for Century is in evaporitic rocks of the Paradise Creek and Esperanza formations. These rocks may also have provided S through dissolution of anhydrite or as H_2S gas through thermochemical sulphate reduction. Sulphur may also have been derived from seawater or from a more deep-seated (mantle) source, although sulphur isotopic data provide little support for the latter hypothesis. A magmatic source is rendered implausible by the paucity of outcropping intrusions or of geophysical evidence for buried bodies. The rocks of the Lawn Hill Formation are enriched in Pb and Zn compared to Cu, and enriched in Pb and Zn relative to all other units of the McNamara Group. This may indicate that the Lawn Hill Formation represents a good source of these metals, or that metal enrichment is of regional extent, or that other units have been more substantially depleted during fluid flow. Clearly, more work is required in order to establish the likely source of base metals.

Depositional mechanisms for deposition of lead and zinc are poorly understood and various models are being tested as part of ongoing research in pmd*CRC projects, G14 and I7. The intimate association of metal and carbon is noteworthy, and may reflect the role of carbon as a mediator of chemical reaction (e.g. chemical or biochemical reduction), introduction of metal in a liquid hydrocarbon phase, or input of hydritic fluids.

The relative timing of copper ore formation is less controversial, with most workers agreeing that it took place after peak M2 metamorphism. Currently, the best estimate of the absolute age of ore formation at Mount Isa comes from imprecise Re-Os dating of breccia ore at 1367 ± 80 Ma (Gregory et al., 2005). This age is consistent with published Ar-Ar, K-Ar and Rb-Sr data (McDougall et al., 1962; Page, 1978; Kralik, 1982, Perkins et al., 1999; Spikings et al., 2002) and suggests that ore formation occurred after deposition of the South Nicholson Group and equivalent Roper Group had commenced. A complicating factor, however, is the recent identification of two phases of copper emplacement (breccia- and quartz-vein hosted) under different stress fields (Miller, 2006.). While these stress fields may represent an evolving tectonic event, additional Re-Os data will be acquired in order to resolve the time gap between the two events.

Several lines of evidence confirm the influx of oxidised, iron- and sulphur-rich brines, probably sourced from an overlying sedimentary basin. These include the textural association between chalcopyrite and anhydrite-barite-hematite rocks, evidence of bulk sulphur addition, stable isotopes of sulphur and halogens from fluid inclusions (Kendrick et al., submitted). The South Nicholson Group is a possible brine and metal source, and contains at its base purple ferruginous coarse clastic rocks (Constance Sandstone) and hematite ironstones (Mullera Formation). The older Eastern Creek Volcanics are traditionally regarded as the main source of copper for the deposits at Mount Isa, and Gregory (2006) provided evidence of copper depletion along northwest-southeast faults where mica alteration and massive hematite breccia fill have also been observed. The possible contribution of other rocks, including younger sediment of the South Nicholson and Roper Group, has yet to be evaluated.

Reduction is a plausible mechanism for depositing copper (and indeed lead and zinc) from oxidised brines, and explains the association of copper with carbon-rich rocks. Replacement of carbonate or sulphide is unlikely to have been an important depositional process. Presence of dolomite and ferroan carbonate would have buffered the pH of the brines, but would not necessarily have precipitated significant amounts of copper unless the oxidation state of the brine was close to the sulphate-sulphide buffer. There is clear evidence that the incoming fluid at Mount Isa carried abundant sulphur (locally anhydrite-saturated) and there is no textural evidence for pyrite replacement by chalcopyrite. Many other rock-types in the region could precipitate copper through reduction, and the key factor in whether an ore deposit was generated is likely to have been whether the requisite porosity and permeability existed during brine flow, rather than host-rock chemistry.

The foregoing requires two principal assumptions. One is that wallrock reaction is the key depositional mechanism. Numerical simulations suggest that cooling is much less efficient than either mixing or wallrock reaction. Rock-absent mixing simulations precipitate copper, but generally generate mineral assemblages that differ substantially from those observed at Mount Isa. Second, is the assumption that carbon at Mount Isa (and other similar deposits such as Mount Gordon, Mount Kelly, Kuridala) is synsedimentary or the remnants of a mobile hydrocarbon liquid valid? On the other hand, proponents of a hydritic flux from the mantle argue that the carbon could be the product of mixing of these highly reduced fluids with a more oxidised and CO_2-bearing fluid, such as the basinal brine discussed above. This hypothesis has yet to be tested, but acquisition of He and additional Re-Os isotopic data may provide evidence for mantle-derived components. Indeed, existing Re-Os data for the Mount Isa copper ores suggest minimal involvement of crustal material.

Where

Identifying fluid pathways and confidently ascribing them to particular flow events is of considerable importance for mineral exploration. In the I7 project a focus has been on establishing the spectral response of different lithologies and alteration types. There is now a library of nearly 3,000 spectra, including those collected in other pmd*CRC projects (I1, I4, G14) and by CSIRO.

Use of mineral maps from ASTER data generated in project I1 has not been encouraging. This is because ASTER lacks the spectral resolution to permit confident extraction of mineral end-members. This is clearly illustrated by comparison with HYMAP data for the same areas. Vegetation is also a major problem in parts of the Mount Isa region, with responses of common vegetation types (e.g. Snappy Gum) partly overlapping those of carbonates and mica. Nevertheless there is a large amount of information in the ASTER data that will be assessed using supervised and unsupervised classification techniques.

Better differentiation between mineralized and unmineralized rocks can be achieved by parameterizing the mineralogical data. Parameters such as mica crystallinity appear to be valuable in distinguishing visually similar altered and unaltered rocks, even when the rocks are dark and generate poor quality spectra. Support for this concept comes from illite crystallinity determined by conventional XRD, which maps a distinct mineralogical anomaly in the vicinity of the Century mine. GADDS (general area diffraction detection system) permits rapid and very low cost acquisition of XRD data without sample preparation making this a viable exploration tool. In the light of these results, the feasibility of mapping specific features such as illite crystallinity at Mount Isa and on the Lawn Hill platform using hyperspectral systems needs to be assessed.

FTIR (Fourier transform infra-red) spectra are required in order to examine the feasibility of mapping minerals that do not have a strong response in VNIR and SWIR with ASTER thermal bands 10 – 14 (e.g. feldspar and quartz).

Conclusions

The complexity of Proterozoic geology, specifically multiple hydrothermal fluid flow events, in the western Mount Isa Fold Belt and Lawn Hill platform presents a challenge for research and for cost-effective mineral exploration. Progress has been made towards defining various hydrothermal alteration assemblages and to establishing their infra-red characteristics in order to map them using multi- and hyperspectral imagery.

Transport of copper in the Western Succession appears to have been facilitated by the development of clastic rocks, with high porosity and permeability capable of storing and transmitting oxidised bittern brines. The role of these rocks as a source of metals needs to be investigated. The source of Pb, Zn, S and Cl currently resident in Zn-Pb deposits is also uncertain as are the implications that source might have for exploration.

Wall-rock reaction (reduction) is proposed as the key depositional mechanism for generation of Mount Isa copper. This has crucial implications for exploration, namely that economic copper could occur in a range of rock types, provided that adequate porosity and permeability existed during ore formation. Reduction may also be a key control on deposition of lead-zinc deposits, but scenario testing is in progress. Research will also attempt to determine whether reduction was effected not by wall-rock reaction, but by a hydritic flux from the mantle. In this case the abundant carbon that is a common feature of many Proterozoic Cu and Pb-Zn deposits could be the product of interaction of such fluids with oxidised shallow crustal fluids and not the reductant itself. The implications that this may have for exploration are as yet uncertain, but presumably would place emphasis on identification of pathways capable of tapping the upper mantle and their recognition in potential field and other datasets.

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