

Mineralized Terranes

Mt. Isa Inlier

Introduction:

The Mount Isa Inlier of Northwest Queensland comprises three major tectonic units, which are predominantly north-south trending sedimentological and structural domains:

- Western Fold Belt (Western Succession)
- Kalkadoon-Leichhardt Belt
- Eastern Fold Belt (Eastern Succession)

At Mount Isa, a series of mainly extensional Superbasins, magmatic episodes and shortening events occurred between 1870 Ma and 1480 Ma.

Event	Tectonics	Age
Basin Formation		
Leichhardt	ENE-WSW Rifting	1800 - 1740 Ma
Calvert	N-S Rift-drift	1730 - 1670 Ma
Isa { Pb-Zn-Ag }	Sag	1660 - 1595 Ma
Basin Inversion		
D₁	N-S thrusting	1640 Ma
D₂ { Pb-Zn-Ag }	E-W Compression	1595 Ma
D₃	ENE-WSW Compression	1550 Ma
D₄ { Cu }	ESE-WNW Compression	1530 Ma

Figure 1: Main tectonic events

>1900-1840 Ma: Basement, Barramundi Orogeny, KLB and Cover Sequence 1

- The basement comprises supracrustal sediments and igneous rocks that were deformed and metamorphosed to amphibolite facies during the *ca.*1870 Ma Barramundi Orogeny
- Kalkadoon Granite Suite (1.88-1.82 Ga) shows magmatic arc-type affinities that is the most likely be related to subduction (Wilson, 1978).
- Large scale volcano-magmatic input to the crust (the Kalkadoon Suite and Cover Sequence 1) suggests a magmatic arc above a thickened lithosphere.
- Pilgrim fault might separate different basement elements, and is perhaps a fossil subduction zone.
- Subsequent thinning of lithosphere towards the east may be due to mafic underplating, as reflected in the high gravity responses.
- While there is isotopic similarity in the basement, the relationship of the Kalkadoon Arc to the NAC remains tentative, and an inferred subduction zone is placed along May Downs Fault

1800-1640 Ma: Superbasin development

- In this *ca* 210 Ma period, three successive Superbasins developed. From a geodynamic perspective, a key question is the nature of the switching of extensional modes in different orientations leading to successive basin formation. There is a spread of interpretations in this regard:
 - periodically rejuvenated intra-continental rift (Derrick 1982), punctuated by mild contraction and inversion.
 - continental backarc (Giles *et al.* 2002) related to retreat of a northward dipping subduction zone during LSB and CSB, with the ISB as a sag phase due to ocean basin opening between Australia and Laurentia. Interspersed contraction is related to accretion events along the southern plate boundary.

- Rift to rift-drift and passive margin development (Gibson and Hitchman 2005), *not* punctuated by mild contraction and inversion, but rather by differential uplift and block rotation.
- Ramp and strike slip basins, during ISB, related to far field subduction to the south (Scott *et al.* 2000).
- later foreland basin in the upper part of the ISB in the LHP.

The Superbasins:

- **Leichhardt Superbasin** (1800-1740 Ma): an intra-continental rift focused in LRFT with major north-south graben reflecting ENE-WSW extension (O'Dea *et al.* 1997; Betts *et al.* 2006). O'Dea *et al.* (1997) suggest the influence of a mantle plume or upwelling asthenosphere to generate the thermal energy responsible for the flood basalts. Superbasin ended with development of midcrustal (north-south?) oriented extensional detachment and emplacement of Wonga Granite (*ca* 1745-1725 Ma).
- **Calvert Superbasin** (1740-1670 Ma): following 20 Ma hiatus, renewed extension on WSW-ENE trending growth faults and north-south trending LSB faults. A thinned continental crust is inferred further east (1712-1654 Ma; Giles *et al.* 2004) based on a deep marine depositional setting of the Soldiers Cap Group. An apparent offset between locus of crustal extension (sedimentation in LRFT) and locus of sub-crustal lithosphere extension (magmatic rocks in LHP) is interpreted to indicate asymmetric extension on eastward facing detachment (Betts *et al.* 1998). Progression into deeper marine settings northeastwards, with upward fining cycles and thicker shales, suggests the rift may have evolved (drifted) into a passive continental margin setting (Gibson and Hitchman 2005). End of CSB sedimentation was closely followed by intrusion of the Sybella Granite at 1670 Ma (into the LSB), an "A-type" granite from lower crustal melting (Wyborn *et al.* 1988) in a core complex-model which presumably commenced during sedimentation, with magmatic inflation leading to uplift and cessation of

sedimentation (Gibson and Hitchman 2005). There is no record of erosional breaching of the lower plate rocks during the Calvert sedimentary cycle.

- **Isa Superbasin**, lower part (1670-1640 Ma): Sedimentation closely followed Sybella Batholith emplacement and represents a major series of transgressions. This has been related to decay of a thermal anomaly, initiated at 1710 Ma and culminated at 1670 Ma (Gibson and Hitchman 2005). The Isa and Lower McNamara Groups are interpreted as sag phase sedimentation (1670-1640 Ma) with episodic syndepositional faulting in a fluvial to shallow marine environment. The locus of post-rift subsidence in the LHP (Krassay *et al.* 1997) was where the earlier locus of Calvert magmatism and sub-crustal extension was focused. This argues for an asymmetric, east-facing extensional detachment (Betts *et al.* 1998; Gibson and Hitchman 2005).

1640-1570 Ma: Isan Orogeny to post-orogenic history

- Continental collision is most likely driver of this Isan orogeny. Several deformations and thermal events are recognized.
 - Early (D1) effects involved *ca.* 1640 Ma north-south compression which is variably preserved in the inlier. During this deformation, sedimentation was on-going in the Upper McNamara Group of the LHP and McArthur regions. This may be related to development of a foreland basin (1640-1590 Ma) and a topographic front to the south as the Isan Orogeny propagated (McConachie *et al.* 1993). The change in sedimentation correlates with a hair-pin bend in the APWP (Southgate *et al.*, 1997; Indrum 2000). Generally, crustal over-thickening leads to uplift and widespread exposure of granulite facies rocks. The absence of granulites and of a significant foreland basin is notable. Granulite facies metamorphics, however, occur in the southern Arunta region (Scrimgeour *et al.* 2005) at about this time and may be interpreted as an orogenic front.
 - D2 involved thick-skinned east-west shortening (MacCready *et al.* 1998) in both the EFB and WFB. Folding in the LHP is much less intense, has a

different orientation, and steep strike slip along faults may be dominant here (Scott *et al.* 2000), as well as folding in relation to reactivated normal faults (Betts and Lister 2001). Following the peak deformation and metamorphism at ~1590 Ma, there was no significant uplift and erosion until after 1500 Ma (perhaps 1 kbar of erosion in the EFB). It is suggested that the previously thinned crust was restored to roughly normal thickness, resulting in no significant uplift and erosion.

- Late- to post-orogenic magmatism (1550-1490 Ma) is a characteristic feature of the EFB, but is absent from the WFB. These magmas are interpreted as mantle-derived material which ponded at <30 km depths during early stage of partial melting and granite emplacement. Episodic thermal pulses overlapped with east-west compression. Isotopic data suggest a two component magmatic source: Paleoproterozoic (2.2-2.3 Ga?) crustal mantle or similar material recycled in crustal sequences and a juvenile mantle-derived component (ca 1.5-1.55 Ga). A tonalitic crustal source can generate 20-30 % melting but the volume of granite and periodicity suggest input of mafic magmatism and significant heating (>850°C) in the lower crust. A residence time of 1-10 Ma is suggested for ponding of magmas, with magma escape a function of %melt in an oscillating deformation. This may be related to slab roll-back in a back arc environment.

Overview of the Tectothermal History of the Mt Isa Inlier (after Rubenach 2008)

- High grade and lower grade metamorphic belts alternate EW across the inlier. Although their present dips are unknown, it is proposed that the isograd surfaces originally had shallow dips (Figures 1 & 2).

The isograd patterns on the map (Figure 1) show that:

- The overall isograd pattern is a series of amphibolite facies tongues that are elongate north-south, and which alternate with greenschist facies belts.
- There are no obvious relationships between metamorphic grade and stratigraphy.
- Grade changes occur across major faults such as the Cloncurry and Pilgrim Faults.
- There is a curious relationship between the presence of large granite bodies and amphibolite facies metamorphism, but with no large bodies of granite (as opposed to smaller-scale magmatic rocks in migmatites and as pegmatites) emplaced during the metamorphic peak

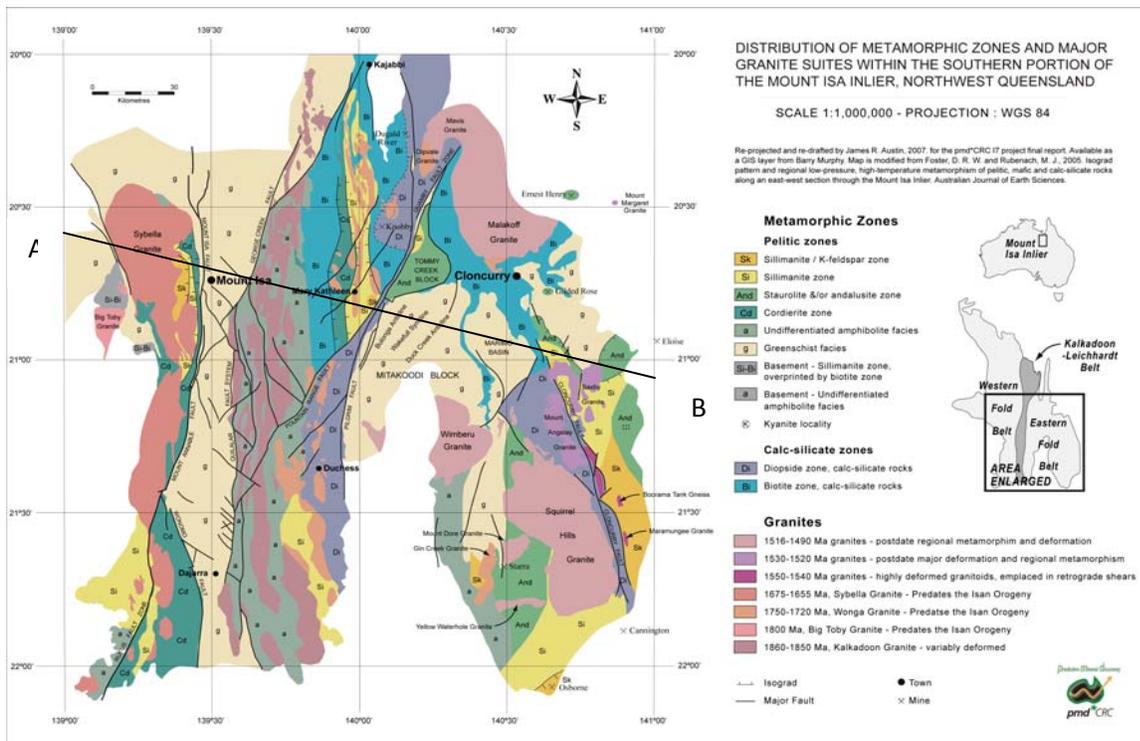


Figure 1. Isograd map of the Mount Isa Inlier, after Foster and Rubenach (2006), made GIS compatible by J. Austin. The section line through Mount Isa (Fig. 2) is shown.

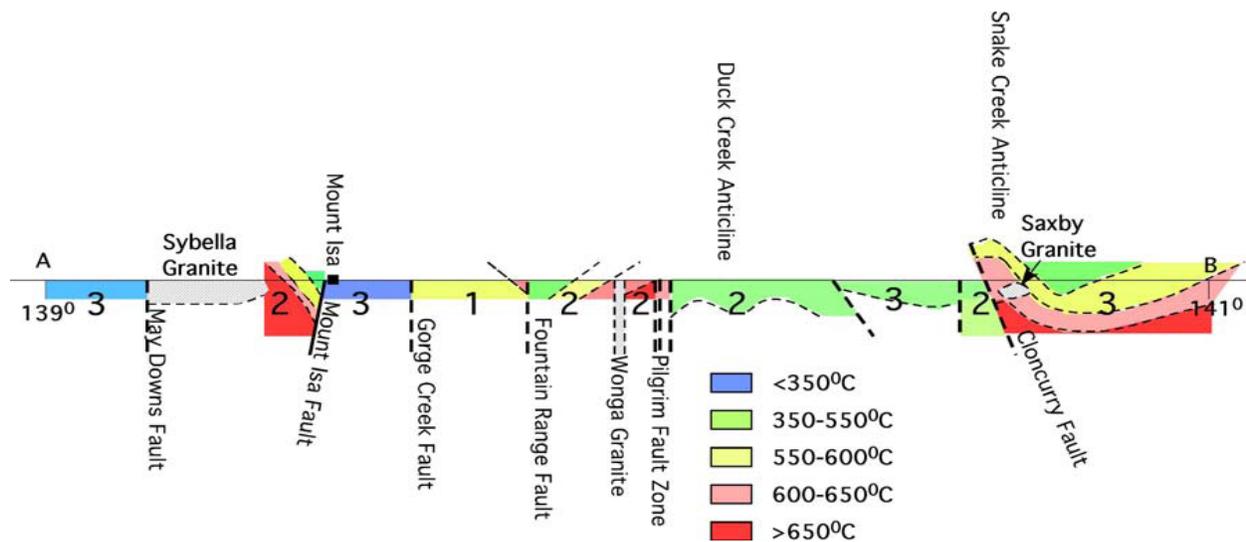


Figure 2. NNW-SSE cross section through the Mount Isa Inlier through Mount Isa. For convenience cover sequences 1-3 are included rather than the more recent superbasins. The dips of the isograd surfaces are unknown, so are schematic.

The metamorphic cross-section A-B (Fig. 2) shows Isan Orogeny peak of metamorphism temperatures rather than isograds. The temperatures are based on the following:

- Greenschist facies, less than 550°C.
 - Amphibolite facies, greater than 550°C. In pelitic rocks, the cordierite, andalusite or staurolite incoming isograds correspond to ~550° at 3-4 kbar
 - The sillimanite isograd, using the Pattison (1992) triple point in the Al_2SiO_5 system, is about 580°C at 4 kbar. This also corresponds approximately to the diopside isograd in regional calcsilicate rocks in the inlier (Foster & Rubenach, 2006).
 - The sillimanite/Kfeldspar isograd is roughly 650°C at 3kbar and 690°C at 4 kbar.
- The Wonga Event (~1740 Ma) and the Sybella Event (~1670 Ma; Figure 3) are significant but localized high-grade shear zone events associated with granite

and gabbro/dolerite emplacement that occurred prior to the Isan Orogeny. New age determinations indicate that two tectonothermal episodes occurred during the Sybella Event in the May Downs Gneiss, with earlier cordierite/Kfeldspar assemblages overprinted by migmatitic biotite/sillimanite/Kfeldspar gneisses.

- A new monazite age determination of 1596 ± 27 Ma for the Mica Creek Pegmatites is consistent with structural interpretations that they formed during D2. Thus pegmatites occur in sillimanite zone metamorphics throughout the Inlier.
- Both the Mary Kathleen/Duchess Zone and the Mount Isa area show anticlockwise P-T-t paths close to the Al_2SiO_5 triple point for the metamorphic peak and post-peak events (Figure 4a). This is also the case for the Selwyn Zone, but in addition the latter also shows early cordierite metamorphism followed by, in D1 and early D2 times, a clockwise medium pressure P-T-t loop (Figure 4b). Although the diversity in bulk compositions in the Selwyn Zone makes this clockwise loop more easily recognizable, the lack of similar loops in the other zones is probably real.
- Part of the thermal budget in the Isan Orogeny is probably the result of elevated values of radioactive heat producing elements in the crust. However, abundant mafic intrusions occur throughout the Isan and pre-Isan metamorphic history, and the highly fractionated nature of these intrusions at the current level of erosion implies large bodies of layered gabbros deeper in the crust. It is proposed that repeated intrusions of gabbros occurred under the higher grade areas, resulting in migmatization of middle crustal rocks and upwards transfer of heat via advection due to rise of pegmatites into what are now the sillimanite zones (Figure 5).

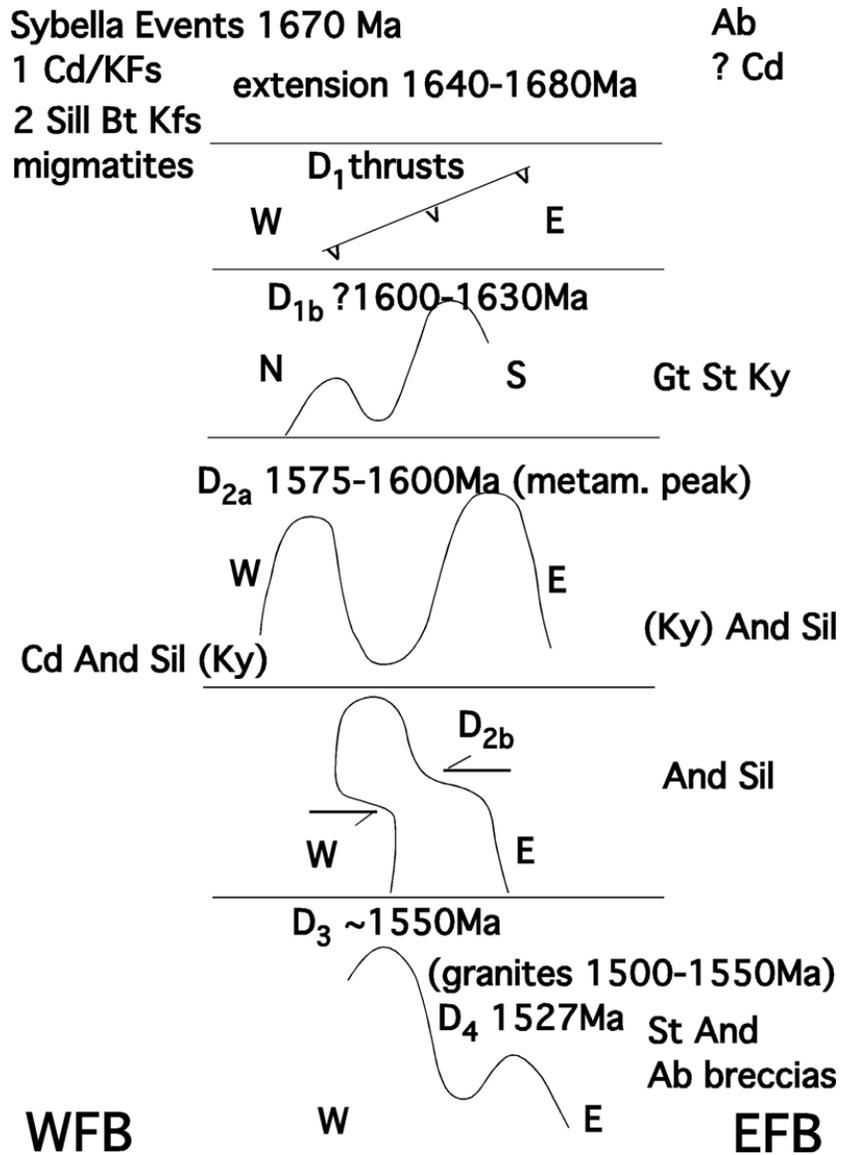


Figure 3. Schematic history of the Mount Isa Inlier during the Isan Orogeny. WFB, Western Fold Belt; EFB, Eastern Fold belt. Deformation events are schematically represented as either plan views or sections. Age dates are based on this report. Mineral abbreviations are after Kretz (1983; also see appendix. The deformation history is based largely on JCU work and other models are discussed in Rubenach et al. (in press; appendix).

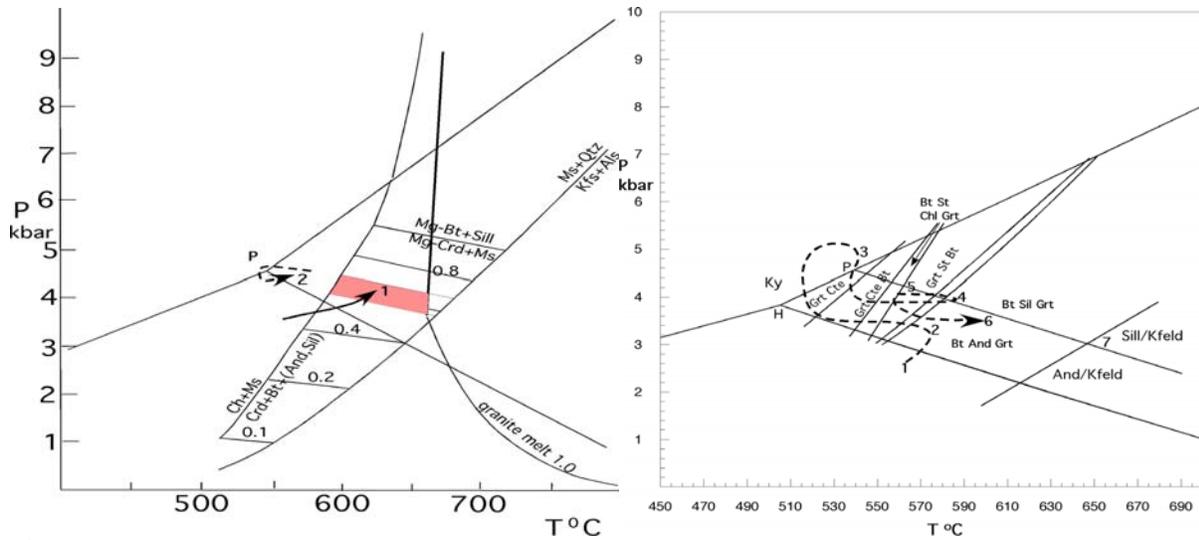


Figure 4.
(a) P-T-t path for the Rosebud Syncline and Wonga Waterhole, Mary-Kathleen- Duchess Zone. “1”, peak of metamorphism (D2) for typical (Crd)-And-Sil schists, Rosebud Syncline (~1575 Ma). “2”, Wonga Waterhole area, And-Sil-Ky rocks (also ~1575 Ma). The Al_2SiO_5 triple point used is from Pattison et al. (2002), and chemical data from Reinhardt (1987) was used in locating the cordierite- Al_2SiO_5 reaction on the isopleths of Pattison et al. (2002).
(b) Composite P-T-t path plotted on a pseudosection THERMOCALC NCMnKFMASH system, Holland & Powell, 1998) for a typical andalusite-garnetbiotite- muscovite schist from the Snake Creek Anticline (on the sillimanite isograd). The path was determined from pseudosections for a variety of compositions, and is modified from Rubenach et al. (in press). 1, Ibitization (not in this sample); 2, growth of cordierite (not this sample) and andalusite; 3, growth of yanite (not this sample) and garnet; 4, growth of andalusite and sillimanite, D2(~1580 Ma); 5, growth of staurolite, probably D3 (~1550 Ma); 6, late overgrowths of andalusite, D4(1527 Ma); 7, illimanite/Kfeldspar schists, aureole of the Saxby Granite only (1527 Ma).

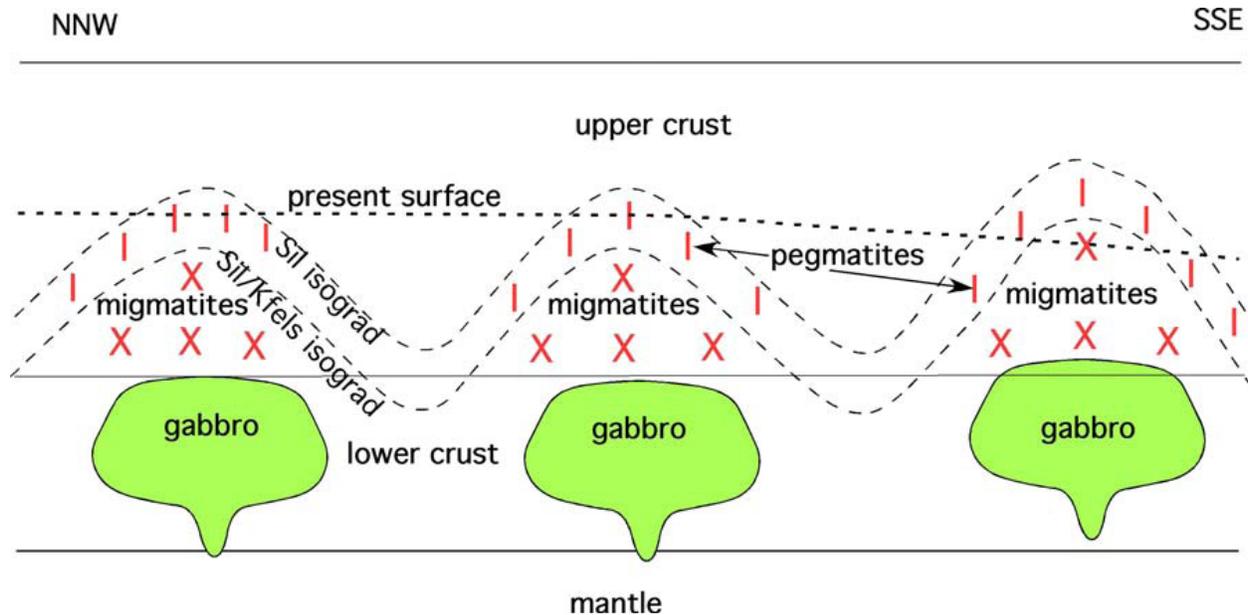


Figure 5. Schematic tectonothermal model for the Mount Isa Inlier, based approximately on the metamorphic section of Figure 2. Although the model has been drawn for the metamorphic peak, metamorphism occurred in multiple events (see text) and multiple episodes of gabbro emplacement are proposed. The pegmatites were derived from partial melting of metasedimentary rocks in the illimanite/Kfelspar zones.

- The Mount Isa Inlier is not only highly endowed with mineralization, but is also extraordinary in the abundance and lithological diversity of metasomatic rocks that formed throughout the tectonothermal history. Epigenetic ore deposits are more abundant in areas of significant metasomatism, regardless of whether they formed contemporaneously. Mixing of metal-rich and barren metasomatic fluids was probably crucial in determining whether particular metasomatic lithologies are mineralised.

Answering the 5 Questions

Q1: What is the role of Geodynamics at the Isa Inlier?

At the Mt Isa Inlier the driving forces for its geodynamic regime are largely controlled by the tectonic processes of vertical and lateral accretion. The interpreted farfield plate geometries suggest a setting of an intra-continental rift through to a distal back arc basin or, perhaps, evolving to a passive margin setting. Extension was accommodated by sedimentary basin development (Leichhardt, Calvert and Isa Superbasins), volcanism and magmatism, with input to the high thermal gradient from both radiogenic felsic rocks and mafic bodies emplaced in the mid to upper crust. The region is modelled in extension as a thin, brittle upper crust above a thermally weakened lithosphere, where connectivity between the two vertically stacked domains appears to be largely along steep crustal scale faults. The Isa Superbasin (ISB) is regarded as a composite of early rift-sag to later foreland basin. The Isan Orogeny is associated with early north-south shortening that overlapped with Isa Superbasin (ISB) sedimentation. The latter is mostly preserved in the Lawn Hill Platform (LHP) and Western Fold Belt

(WFB) and in parts of the Eastern Fold Belt (EFB). The major period of deformation was an east-west shortening and crustal thickening which was most pronounced in the EFB.

Methods of Determining the Geodynamic Setting

There remains considerable uncertainty regarding the geodynamic setting and far-field factors controlling the evolution of the inlier. A synthesis of observations is presented here.

- Constrain the tectono-magmatic history and role of crust/mantle processes in magma generation, with an emphasis on the Western Fold Belt in the first instance, using geological mapping, isotopic dating and radiogenic isotope analysis. This research follows 3 themes on: a) The nature of pre-Barramundi crustal elements, b) Source regions of potassic “A-type” granites and c) Tectonomagmatic evolution.
- Constrain the tectono-thermal and metasomatic evolution, with an initial focus on the Western Fold Belt, through structural and microstructural studies, isotopic dating, PT-t paths and development of a regional thermal model of the inlier.
- Constrain the time-space correlation through a targeted sampling campaign, using isotopic dating and sequence stratigraphic concepts.

Q2: What is the role of Architecture of the system at the Isa Inlier?

Across the WFB and EFB, Superbasin development is interpreted to be interspersed with extensional core complex development and emplacement of syntectonic granites (Wonga, Sybella), and the generation of fault-controlled buttress-like geometries and doming. The rift architecture was founded on a faulted basement substrate which had undergone crustal addition in a volcanic/magmatic arc that focussed along the Kalkadoon-Leichhardt Belt (KLB). Repeated extension occurred during the Leichhardt (LSB) and Calvert Superbasins (CSB). Uncertainty surrounds whether there was an intervening compressional event. The “Cover Sequence 2/3” unconformity is cited as a

compressional event in the literature (Betts *et al.* 2006), but it may instead be related to extension on crustal scale detachments (Gibson and Hitchman 2005). Although the Isan Orogeny has generated complex structuring in places, the regional Superbasin architecture can be modelled in 3D as a sheet-like geometry with relatively flat enveloping surfaces disrupted by a series of mainly steeply dipping faults. These faults were generated during the Isan Orogeny or were re-activated from earlier extensional events. Regions of high temperature-low pressure metamorphism appear to be largely related to magmatic input.

Methods of Determining the Architecture of the system

- Develop 2D and 3D maps of the region, incorporating existing coverage, and blending with models in new areas.
- Examine the camp scale structural controls on metal occurrence and deposit clustering.
- Determine the nature of structural controls on deposits.

Q3: What are the roles of fluids, their sources and reservoirs at the Isa Inlier?

Sedimentary formation waters, magmatic, metamorphic, surficial, and mantle fluids make up the diverse sources. Most of the ore deposits and regional alteration have mixed geochemical signals indicating the involvement of at least two of the fluid endmembers. Where basins are thickly developed, as in the Leichhardt River Fault Trough (LRFT), heterolithic proximal facies sediments are identified as diagenetic aquifers for storage of sedimentary formation waters. These were important fluid sources both for earlier formed Pb-Zn-Ag deposits and the later Cu deposits. In the EFB, recent noble gas and halogen data suggests a lesser role for magmatic fluids regionally than previously thought and strong evidence for the involvement of such fluids has only been obtained for the Ernest Henry IOCG deposit. At other IOCG deposits, halogen data indicates multiple sources of salinity in the ore forming fluids with end member compositions being a halite dissolution fluid and a bittern brine fluid. Noble

gas data is compatible with sedimentary formation waters or locally derived metamorphic fluids being significant fluid sources at Osborne, and contrast with the additional external magmatic fluid component identified at Ernest Henry. As Ernest Henry is the largest IOCG deposit in the district, this may indicate the presence of magmatic fluid components is required to form the richest deposit. Magmatic volatiles have been identified in isolated un-mineralised parts of the Mary Kathleen Fold Belt and there is, as yet, no evidence for the involvement of magmatic fluids in any of the deposits in the WFB.

The Mount Isa Cu deposit is the best example of a hydrothermal system with a large component of basement-derived metamorphic fluids. In particular, high $40\text{Ar}/36\text{Ar}$ values, together with rare CO_2 -rich fluid inclusions, suggest devolatilisation of the Eastern Creek Volcanics (ECV), and mixing with either bittern brines or halite dissolution waters. In the EFB, metamorphic fluids from metasedimentary rocks, such as the Corella Formation, were an important potential source of CO_2 , SO_4 and Cl. The high abundance of CO_2 fluid inclusions in IOCG deposits that formed close to the metamorphic peak (Osborne, Eloise and Starra) is most likely to have had a metamorphic origin.

Methods of Determining the fluids, their sources and reservoirs

- Compile a database of isotopic and geochronological data.
- Examine potential fluid source regions using noble gas and halogen tracers

Q4: What are the fluid flow drivers and pathways at the Isa Inlier?

The metal endowment may be determined by the availability of steep fluid pathways, such as along major faults, connecting different fluid reservoirs. This is manifest by fault control on deposit location at a range of scales. The regional scale faults of the Leichhardt River Fault Trough are modelled numerically (in FLAC) as fluid pathways that, in extension, tend to draw down fluids and perturb relatively stable convection

cells. Storage of such fluids in diagenetic aquifers for ten's of millions of years is a key consideration, as such aquifers may be re-charged by lateral flow and disturbed by topographic and structural influences. In compression, the convection cells breakdown quickly and fluids are expelled upwards, typically ponding in permeable hanging wall positions or (perhaps) at the sea floor. Discrete element modelling (UDEC) at the district to deposit scales indicates complex zoning of stress anomalies in response to the partitioning of stress across fault blocks, and the interaction between rock units of different competencies. A far field ESE stress orientation provides the best correlation with known deposits and suggests regional a D4 stress regime may have been responsible for both Cu and Cu- Au mineralisation in the Eastern and Western Fold Belts. Fault bends, jogs and intersections are regarded as key localisation features. Tools for rapid analysis of remote sensed data, combined with on-going calibration with geology, provide great promise for discriminating mineralisation-related alteration footprints.

Methods of Determining fluid flow drivers and pathways

- Undertake coupled deformation-thermal-fluid flow numerical simulations in relation to scenarios from the Mount Isa Inlier, with a focus on geodynamic history, fluid flow pathways and drivers, thermal modeling, and controls on Cu deposits in the WFB. Simulations of the architecture at the time(s) of mineralisation will be made, based on an understanding of the permeability structure, mineralisation ages and fluid flow histories.
- Examine potential role of hydrocarbons and the broad scale permeability structure of the WFB during Zn-Pb-Ag mineralisation.
- Investigate the potential fluid pathways and alteration signals from detailed analysis of key localities, geochemical modelling and relate to regional scale features.
- Characterise Cu-Au-U deposits, and develop guidelines for exploration targeting.
- Characterise the alteration footprints of mineralised systems using across scale remote sensing techniques with an initial focus in the Mount Isa Valley.

Q5: What are the metal transport and deposition processes at the Isa Inlier?

Depositionally, the mineral system was only active in the latter parts of the evolution. Extension and thermal input during early Superbasin development did not result in the formation of mineral deposits but rather were the storage compartments for fluids drawn down into the system. Fluid mixing and dilation are key ingredients to the hydrothermal deposits studied. In particular, at the Mount Isa Cu and IOCG deposits (Ernest Henry, Osborne), brecciation is classically developed in and peripheral to the ore zone. An analysis of apatite compositions provides some insights to the fluid compositions at the time of mineralisation at Ernest Henry. The apatites record evidence for PO₄-HF₂SO₂-CO₂ fluids that carry As(6+) and/or SO₄ and that have little or no Cl or H₂O. An evolution from SO₄ to As could be related to mixing of external fluids at that time or an in-situ change in the redox state of the carrier fluid. Overgrowth of apatite by titanate might record the transition from volatile CO₂-rich fluids to brine-rich liquids. The extreme nature of the chemistry of the Ernest Henry apatites relative to the regional rocks indicates that there are processes that existed within the deposit that did not occur in structurally similar barren rocks. At the Mount Isa Cu deposit, ore-related brecciation is represented by a “once-off” fluid mixing event. Arguably, the sulphide deposition process was by insitu Thermochemical Sulphate Reduction. The range of δ³⁴S_{sulfide} (~15 to 30 ‰) is consistent with high temperature inorganic reduction of marine sulphate, implying either bittern brines or halite dissolution waters. A geochemical mixing model is developed to explain the enriched C isotopes in carbonates and suggests the introduction of H₂ as a strong reductant with possible mantle affinity.

Methods of Determining the means of metal transport and deposition processes.

- Examine a range of possible geochemical models that may be applicable to the mineralising systems of interest.
- Develop reactive transport and permeability models related to Zn-Pb-Ag (e.g. Century), Cu (Isa), and Cu-Au (Ernest Henry) deposits.

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