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Genesis, Tectonic Setting- and Exploration Considerations for Fe-oxide Cu Au Deposits, Mount Isa Eastern Succession

Thesis Submitted by
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For the degree of Doctor of Philosophy
In the School of Earth Scienecs
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ABSTRACT

Based on the geochemistry of mafic rocks, the Palaeo-Mesoproterozoic eastern margins of the North and South Australian Cratons can be classified into the Eastern Domain (Mount Isa Eastern Succession, Curnamona Province and Georgetown Inlier) and Western Domain (Mount Isa Western Succession, Kalkadoon-Leichhardt Belt and McArthur River Basin). Basaltic magmatism of the Eastern Domain was synchronous with back arc basinal development, while Western Domain magmas were emplaced into a thicker continental crust. This difference is reflected in the metallogenic nature of the domains, whereby Fe-oxide-Cu-Au (IOCG) and Broken Hill Type (BHT-type) deposits dominates the Eastern Domain, and stratiform Pb-Zn-Ag and Mount Isa Style Cu-Pb-Zn(Ag) are found in the Western Domain. Based on the distinct evolutionary trends for mafic magmas of the domains of Mesoproterozoic Australia, we suggest that the Mount Isa Western Succession and McArthur River Basin continue to be recognised as part of the North Australian Craton. While the Mount Isa Eastern Succession, Curnamona Province and the Georgetown Inlier be referred to as the East Australian Craton. An actively or formerly subducted slab sitting in the mantle lithosphere to the east of the eastern margin of the East Australian Craton may have provided the appropriate mantle chemistry to contribute to subsequent generation, in an extended continent, of magmas and volcano-sedimentary input that led to the formation of Mesoproterozoic IOCG and BHT deposits.

In the Mount Isa Eastern Succession, mafic rocks and magmas contributed sulphur and metals to IOCG ore deposition over a protracted (~170My) period. Between 1686 Ma and 1660Ma, S and metals (Cu, Au, Zn, Fe, Ni, Co) were exsolved

from crystallising strongly fractioned back-arc tholeiitic magmas into active extensional faults, and surrounding country rocks. During Isan peak-metamorphism, at ~1600Ma-1580Ma, significant amounts of S, Cu, Au, Zn, Ni, Co and Cr were leached from mafic rocks and crustal accumulations, and led to the deposition of early IOCG and base metal deposits. Subsequent albitic alteration associated with the hydrothermal fluids of the ~1550Ma-1490Ma Williams-Naraku Batholith may also have sequestered sulphide material from mafic rocks. This study highlights the possibility that the previously held consensus that the Williams-Naraku Batholith of felsic-intermediate magmas contributed the bulk of the metals to the Eastern Succession mineral deposits, may not necessarily be the case, but rather, fluids derived from these magmas remobilised previously existing mafic derived metal accumulations.

Protracted metal and sulphur contributions to the Mount Isa Eastern Succession Iron oxide-Cu-Au (IOCG) province occurred primarily as a consequence of long-lived fluid and melt fluxes from the base of the crust, stimulated by initial back-arc emplacement of voluminous mafic magmas. The concentration of sulphur, iron, copper and gold into the presently observed mineral deposits involved a significant component of remobilisation and reworking of early initial enrichments (pre- to syn-Isan Orogeny) by later fluids (syn- to post-Isan and syn-Williams/Naraku Batholith). Osborne (eastern domain) and Eloise-type ores formed or were strongly remobilized at c. 1600 Ma by reduced, mafic-derived fluids, whereas oxidised brines released by the Williams/Naraku granitoids overprinted magnetite ± sulphides at Osborne (western domain) and Starra to produce younger (c. 1530 Ma) hematite-chalcopyrite associations. CO_2-rich, potentially mantle-derived fluid may have periodically pulsed through the system, manifest now as pyrrhotite-stable carbonate veins and pods. Exploration for Ernest Henry and Starra style deposits should focus on recognition of oxidised corridors in relation to mafic- proximal and structurally-defined targets, However, the possibility remains that large, early mafic rock related Cu-Au ± (Fe, Co, Ni, Zn) deposits are preserved distal to the oxidising effects of the Williams-Naraku hydrothermal system, and may also present exploration opportunities.

Within the southern portion of the Mount Isa Eastern Succession, mafic rocks, and faults that intersect areas of mafic rocks, exhibit the strongest spatial relationship to IOCG mineralisation than any other geological unit. In contrast, felsic rocks, of which both genetic and exploration models have relied heavily upon in the past in order to explain the final localisation controls on IOCG deposits, do not display a significant relationship to mineralisation. The results attained call for an immediate review of exploration practices in the Eastern Succession, and call upon more mafic-related models in order to achieve sustainable IOCG mineral discoveries.

CONTENTS

STATEMENT OF SOURCES

Declaration

I declare that this thesis is my own work and has not been submitted in any form for another degree or diploma at any university or other institution of tertiary education. Information dervided from the published or unpublished work of others has been acknowledged in the text and a list of references is given.

15 June 2010

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Kris Butera Date

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Thanks Fiona, the 7 kids and my family for all your love and support over the last few years.

PREFACE

This thesis has been written as concisely as possible in order to fulfil its objective as an industry “friendly” document, with the specific purpose of helping explorers discover unidentified Fe-oxide Cu Au mineral resources, under the philosophies and logic of the predictive mineral discovery cooperative research centre (pmd*CRC).

The thesis is written as four exclusive papers/articles with the intention of publication in relevant journals/newsletters, and as such, there may be some repetition of crucial topics from paper to paper. Each paper has been contributed to by one or more co-authors.

The papers, in individual chapters, form a logical geological progression from beginning to end:

Chapter 1:
Back-arcs, mafic rock geochemistry, metallogenesis and a reinterpretation of the Paleo- to Mesoproterozoic assembly of Northern and Eastern Australia.
Butera, K.M., Oliver, N.H.S., Foster, D.R.W., Rubenach, M.J.R., Collins, W.C. and Nortje, G.S.

This chapter sets the tectonic framework for the metallogenic studies contained further in the thesis. The geochemistry of the mafic rocks units from within the Mount Isa Inlier and surrounding Proterozoic domains was studied in order to explain the distribution of different metallogenic styles that are temporally and spatially associated with those domains.

Chapter 2:
The role of mafic rocks in the genesis of Iron oxide-Copper-Gold deposits, Mount Isa Eastern Succession, Northwest Queensland.
Butera, K.M., Oliver, N.H.S., Cleverley, J.S., Rubenach, M.J. and Collins, W.C.

Chapter 2 examines the geochemical relationships between Fe-oxide Cu Au (IOCG) deposits and mafic rocks and magmas in the Mount Isa Eastern Succession. Topics studied and discussed include both primary (fractionation) and secondary (metamorphic leaching) processes enacted upon mafic rocks/magmas that led to IOCG genesis.

Chapter 3:
A protracted multi-staged model for Fe oxide-Cu-Au mineralisation, Mount Isa Eastern Succession, NW Queensland.
Butera, K.M., Oliver, N.H.S. and Nortje, G.S.

Chapter 3 takes the data and interpretations from Chapter 2 and puts them in a broader context for overall IOCG Genesis models in the Mount Isa Eastern Succession, discussing previous models and highlighting the need to incorporate the new data into current genetic and exploration models for IOCGs. A reworked version of this paper was published in Precambrian Research, with a siginificant component of the work being contributed by Nick Oliver. This reworked paper is included in Appendix III for comparsion, outlining the various authors contributions.

Chapter 4:

Spatial Associations of mafic rocks and Fe-oxide Cu-Au deposits, southern Mount Isa Eastern Succession: implications for exploration

Butera, K.M. and Oliver, N.H.S.

This chapter examines the spatial association of geological units to IOCG deposits, and specifically the strength of the spatial relationship of mafic rocks to IOCGs. Utilising Weights of Evidence and Fractal Analysis, this work provides exploration indicators/strategies for IOCG deposits, and with the previous discussed geochemical relationships of mafics to IOCGs, adds a set of tools and greater confidence for mineral explorers to engage in IOCG mineral discovery.

CHAPTER 1

Back-arcs, mafic rock geochemistry, metallogenesis and a reinterpretation of the Paleo- to Mesoproterozoic assembly of Northern and Eastern Australia.

Back-arcs, mafic rock geochemistry, metallogenesis and a reinterpretation of the Paleo- to Mesoproterozoic assembly of Northern and Eastern Australia.

Butera, K.M.[1*], Oliver, N.H.S. [1], Foster, D.R.W. [1], Rubenach, M.J.R. [1], Collins, W.C. [1] and Nortje, G.S.[1]

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Abstract

This work presents the Mesoproterozoic evolution of the eastern margins of the North and South Australian Cratons. Using the geochemistry of mafic magmas and their tectonic emplacement environments the cratons can be classified into the Eastern Domain (Mount Isa Eastern Succession, Curnamona Province and Georgetown Inlier) and Western Domain (Mount Isa Western Succession, Kalkadoon-Leichhardt Belt and McArthur River Basin). Basaltic magmatism of the Eastern Domain was synchronous with back arc basinal development, while Western Domain magmas were emplaced into a thicker continental crust. This difference is reflected in the metallogenic nature of the domains, whereby Fe-oxide-Cu-Au (IOCG) and Broken Hill Type (BHT-type) deposits dominates the Eastern Domain, and stratiform Pb-Zn-Ag and Mount Isa Style Cu-Pb-Zn(Ag) are found in the Western Domain. Based on the distinct evolutionary trends for mafic magmas of the domains of Mesoproterozoic Australia, we suggest that the Mount Isa Western Succession and McArthur River Basin continue to be recognised as part of the North Australian Craton. While the Mount Isa Eastern

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Succession, Curnamona Province and the Georgetown Inlier be referred to as the East Australian Craton. An actively or formerly subducted slab sitting in the mantle lithosphere to the east of the eastern margin of the East Australian Craton may have provided the appropriate mantle chemistry to contribute to subsequent generation, in an extended continent, of magmas and volcano-sedimentary input that led to the formation of Mesoproterozoic IOCG and BHT deposits.

Keywords: Mount Isa, Proterozoic, Back-arcs, Metallogenesis, Curnamona, Georgetown

Introduction

Mesoproterozoic geological provinces of Australia are very well endowed with mineral deposits. Despite recognition of some commonality of tectono-stratigraphic evolution of these different terrains (Fig. 1), previous tectonic reconstructions do not adequately explain the paradoxical distribution of the different types of mineral deposits contained within them.

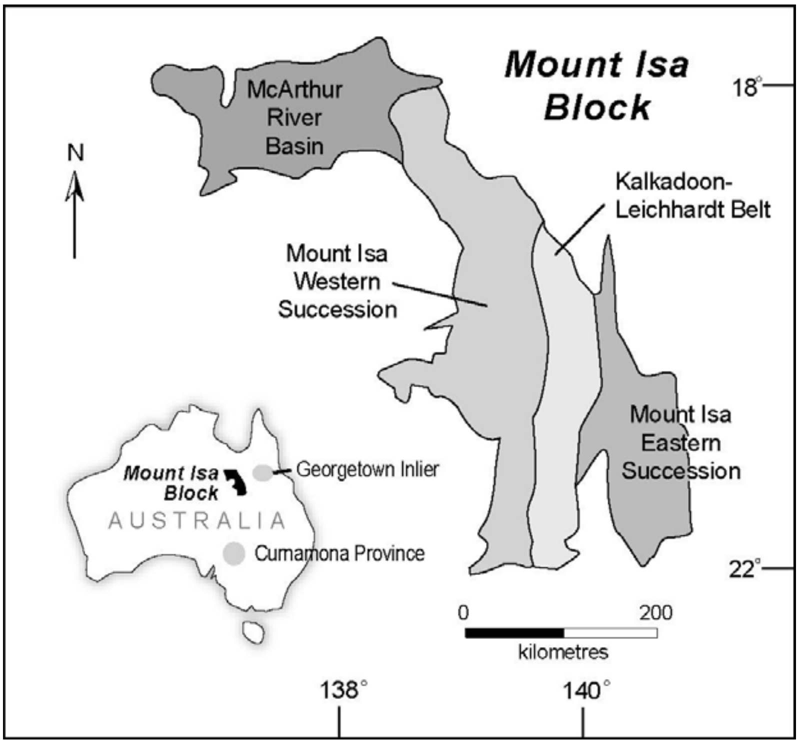

Figure 1. Map of the N-S trending successions of the Mount Isa Block, Australia (after Blake (1987); Blake and Stewart (1992); O'Dea et al. (1997).

Globally, the Proterozoic was a significant era in the geological history of the Earth. Karlstrom et al. (1999; 2001) suggested a globally significant Proterozoic orogenic system that extended from Australia, across southern Laurentia, to Baltica. This reconstruction proposed the possible connection of the south-western United States portion of western Laurentia with the southern edge of the North Australian craton (AUSWUS). It explains similar metamorphic and tectonic histories in the Cheyenne Belt of Laurentia, and the North Australian craton (1.7 to 1.55 Ga), where crustal thickening followed by decompression and two near-orthogonal shortening events have recently been recognized (Dalziel, 1992; Williams and Karlstrom, 1996; Ilg and Karlstrom, 2000; Karlstrom et al., 2001; Cihan, 2004; Sayab, 2005).

Myers et al. (1996) first divided the Proterozoic Australian continent into three possibly distinct cratons (North, South and West), based on the amalgamation of late Archaean to Paleoproterozoic blocks between 1.95Ga and 1.83Ga. Pb and Nd isotopic data from mineral deposits and rocks of the eastern margins of the North and South Australian craton show a similar isotopic pattern to those of south western Laurentia (Mojave province). The isotopic data suggest much more juvenile material on the eastern margin of the Mesoproterozoic Australian continent, analogous in age to rocks and mineral deposits of south western Laurentia, with older crust to the west (Wooden and DeWitt, 1991; Wooden et al., 1994; Zhao and McCulloch, 1995; Hawkins et al., 1996; Ramo and Calzia, 1998; Karlstrom and Williams, 1998; Karlstrom et al., 2001; Mark et al., 2005a; Foster and Austin, 2005).

Numerous researchers have refined the tectono-metamorphic and stratigraphic frameworks of the Australian cratons (Wilson, 1978; Laing and Beardsmore, 1986; Laing, 1990; Laing, 1996; McDonald et al., 1997; O'Dea et al. 1997; Scott et al., 2000; Betts et al., 2002; Giles et al., 2004). Previous work suggests that the crustal sequences of Australian cratons share a depositional history of episodic intracontinental rifting between *ca.* 1800 and *ca.* 1610Ma (Beardsmore et al., 1988; Page et al., 1997; Page, 1998; Page and Sun, 1998). Toward the eastern margin of the North Australian Craton, along with the Georgetown Inlier, is the metallogenically enriched Mount Isa Inlier (Fig. 1), divided into three north-south trending fold belts: the Western Succession, the central older exposed basement Kalkadoon-Leichhardt Belt, and the Eastern Succession, (Blake, 1987; Blake and Stewart, 1992; O'Dea et al., 1997; MacCready et al., 1998). The Broken Hill-Olary domains (Curnamona Province) lie on the eastern margin of the South Australian craton (Myers et al., 1996).

Scott et al. (2000) and Giles et al. (2002) suggested that the 1.8Ga to 1.6Ga extensional basins of the North Australian craton formed in response to far-field subduction in the Arunta inlier in central Australia. Scott et al (2000) made a number of interpretations for the nature and source of mafic magmas in the Mount Isa Western Succession and McArthur River Basin. They concluded that although the chemistries of these magmas were typical of continental flood basalts, they were not derived from plume-, rift- or direct arc-related processes, but rather, were generated by a long-lived convection cell coupled to distant subduction events in the Arunta Inlier, melting the lithospheric mantle. Both the long-lived nature of the magmatism (225 m.y.), and the low concentrations of Ti, P and Nb in the mafic rocks was thought to be inconsistent with decompression melting of a plume head. Most recently, Giles et al (2004) concluded that the North and South Australian Cratons were a single entity prior to ca. 1.50Ga. In their reconstruction the Curnamona Province was thought to be aligned with the Mount Isa-Georgetown depositional basins between 1.80Ga and 1.50Ga Ma, They postulated that the two cratons were separated at ca. 1.50Ga, then subsequently rejoined during the 1.33-1.10Ga Albany-Fraser and Musgrave orogenies.

The geochemistry of tholeiitic intrusive and basaltic mafic rocks gives an insight into the nature of the underlying mantle to these crustal blocks, which in turn helps to constrain fundamental geodynamic, tectonic and deep metal source region controls for the varying mineralisation types. The geochemistry of mafic rocks has been widely used to infer the tectonic environments in which the magmas were emplaced (Pearce and Cann, 1973; Pearce and Norry, 1979; Meschede, 1986), although common geochemistry may potentially be achieved in a number of environments (e.g. Cox, 1992). A number of researchers studying the nature of basic magmatism in the Mount Isa Block have failed to reach a consensus on the tectonic/geochemical connections. Glikson et al (1976) and Glikson and Derrick (1978) concluded that the magmas of the Western Succession of the Mount Isa Inlier were compositionally typical of continental tholeiites, whereas those of the Soldiers Cap Group of the Eastern Succession were similar to ocean floor basalts or arc basalts. Wilson (1978) postulated that the tholeiitic lavas of the region are geochemicaly similar to post Cretaceous? basalts formed in a mature continental margin setting in the western United States. Bultitude and Wyborn (1982) and Ellis and Wyborn (1984) suggested that the geochemistry of the mafic magmas (and dolerites) of the Mount Isa Inlier is consistent with continental rifting, but interpreted the change in chemistry from west to east as reflecting the depth of the mafic melt source region. The geochemical differences between the mafic rocks of the Western and Eastern Successions of the Mount Isa Inlier is thus variably interpreted as having either fundamental plate tectonic significance (Glikson and Derrick, 1978; Wilson, 1978) or a subdued significance within an overall intraplate rift environment (Ellis and Wyborn, 1984). Very little work has since occurred that compares Western and Eastern Succession mafic rock geochemistry.

Within the previously defined parts of the North Australian craton, there is an irregular distribution of mineral deposit types between the internal domains. The Mount Isa Western Succession and McArthur Basin are typified by shale-hosted Mount Isa-style Pb-Zn-Cu-(Ag) and stratiform Pb-Zn-Ag deposits, whereas the Eastern Succession and Broken Hill-Olary Domains of the Curnamona Province contain IOCG, Cu-only and Broken Hill-Type Ag-Pb-Zn mineralization. In order to explain these metal distributions and rationalise some of the problems of previous tectonic reconstructions, we utilise the geochemistry of mafic rocks and new age data to reinterpret the distribution of Proterozoic Australian cratons and blocks. Our new model explains key aspects of the regional metal zonation, particularly in the Mt Isa context, and defines new tectonic and metallogenic interpretations that impact on global reconstructions at this time.

Data

Wholerock XRF and ICP_MS analyses for Major, Trace and REE were obtained for this study on mafic rocks of the Mount Isa Eastern Succession, sampled distal to known mineralisation and alteration. The new geochemistry supplements existing wholerock geochemical data for the Eastern Succession, Western Succession, Kalkadoon-Leichhardt Belt, Curnamona Province and Georgetown Inlier, sourced from previous published and unpublished research (see below), and Geoscience Australia's Ozchem database (www.ga.gov.au). Newly obtained data of rocks that had obviously been influenced by alteration were discarded: results were rejected if they did not have SiO_2 between 46 and 52 wt %, Na_2O < 3.5 wt % and K_2O < 2 wt %. Na and K are mobile elements known to affect rocks during regional metamorphism and/or hydrothermal alteration in the Mount Isa Eastern Succession (Oliver et al, 2004). For previously published data (consisting of datasets rather than data averages) only samples with MgO between 4 and 8 wt% were considered, in addition to the aforementioned filtering mechanisms, to minimise the effect of crystal fractionation on HFSE ratios, and to provide the best point of comparison for different datasets. For the broader Mount Isa Block, data for the Eastern Succession, the Calvert and Leichhardt Associations of the Western Succession, Kalkadoon-Leichhardt Belt, and McArthur River Basin were gathered from Ellis and Wyborn (1984) and Scott et al (2000). Slaughter Yard Creek Dolerites (Western Succession) were drawn from Sisois-Pizanias (2001). Global geochemical data for continental flood basalts and back arc basinal basalts was collected from the online GEOROC database (http://georoc.mpch-mainz.gwdg.de/georoc/).

Geochronological data was taken from Geoscience Australia's Ozchron database, and from previously published work (Nutman and Ehlers, 1988; Black et al, 1998; Page and Sun, 1998; Scott et al, 2000; Connor and Fanning, 2001; Raetz et al, 2002). Age data for 1686±6Ma mafic rocks (gabbros and dolerites) from Snake Creek Anticline is from Rubenach (2005).

Mount Isa Eastern Succession

The oldest mafic rocks exposed in the Eastern Succession are those of the Marraba Volcanics and the 1740 Ma Lunch Creek Gabbro (Page 1983). The age of the Marraba Volcanics can be constrained to ca. 1760 Ma as it overlies Argylla Formation felsic volcanics erupted at ca. 1762 Ma and is in turn overlain by the Mitakoodi Quartzite deposited at ca. 1755 Ma (Page, 1998). These magmas may have been related to the ~1760Ma - 1740Ma Wonga extensional event, in which voluminous bimodal magmatism occurred in the Wonga Belt and broader Mary Kathleen Fold Belt on the western margin of the Eastern Succession (Holcombe et al, 1991; Oliver et al, 1991; Pearson et al., 1992).

The next major mafic magmatic event is constrained by a U-Pb SHRIMP zircon age of 1686±8 Ma for tonalite from the Snake Creek Anticline, toward the eastern margin of the Eastern Succession (Rubenach, 2005). Tonalite sheets, lenses and small bodies are abundant within the mafic-tonalite complex, a sill-like body that intruded near the top of the Llewellyn Creek Formation. The tonalites generally preserve igneous textures, whereas the mafic rocks, which include massive gabbro, layered gabbro and dolerite, have been largely converted to hornblende-plagioclase amphibolites, locally preserving igneous textures but are commonly foliated. Mingling/mixing relationships between tonalite and gabbro indicate coeval emplacement, so that the above age is the likely age of intrusion of the mafic rocks and a minimum age for the Llewellyn Creek Formation. SHRIMP zircon ages of 1658±8 and 1654±4 Ma have been determined for the Toole Creek Volcanics and Mt Norna Quartzite respectively, of the Soldiers Cap Group (Page & Sun, 1998). Both these units overly the Llewellyn Creek Formation, implying that there is a significant, previously unrecognised depositional hiatus between them. Significantly, the typical turbidite sedimentary structures in the Llewellyn Creek Formation are not seen in the overlying units.

Ages similar to the Toole Creek Volcanics are apparent also for the nearby Ernest Henry Diorite (1660 ±13Ma, 1658 ±10Ma, 1657±7Ma; Pollard and McNaughton, 1997; Page and Sun, 1998), and an albitized granite near Cloncurry (1679±7 Ma; Pollard & McNaughton, 1997) is similar to the age of the c. 1686 tonalites at Snake Creek. All indicate significant igneous activity during deposition of the Soldiers Cap Formation, probably in discrete events. The bulk of the remaining mafic units in the south and eastern parts of the Eastern Succession also appear to be related to either the 1686Ma or 1660Ma magmatic events. Dolerite sills from the Hampden Synform, for example, show similar folding patterns to those in the Snake Creek Anticline, suggesting that they were emplaced prior to an inferred N-S shortening event associated with regional albitisation at ~1640Ma (Rubenach, 2005). These mafic rocks, and similarly, those that have a spatial relationship to economically significant mineral deposits at Osborne (IOCG), Selwyn-Starra (IOCG), Eloise (IOCG), Mount Elliot (IOCG-skarn), Cannington (BHT), Pegmont and

Marramungee (BHT-skarn), also display a strong geochemical relationship to the 1686Ma generation of magmas (Butera et al, 2005; see below).

Other, volumetrically insignificant mafic magmatic episodes within the Eastern Succession are interpreted to have occurred at ~1600-1580Ma and ~1530Ma. The 1600-1580Ma generation of mafic rocks are present as thin dolerite dykes, generally less than 100m in width, and lie parallel to the axial plane of the Snake Creek Anticline. The syn- peak metamorphic timing is suggested by a) their orientation, b) lack of boudinage, c) they postdate earlier, folded mafic sills (and/or metabasalts), and d) they commonly preserve their igneous texture and some of their primary mineralogy (although partly foliated and amphibolitised along margins).

The ~1530Ma magmas are unfoliated gabbroic bodies that are mostly confined to west of the Cloncurry Fault, and are intimately associated (mixed and mingled) with granitoids of the ~1530-1500Ma Williams-Naraku Batholith (Page and Sun, 1998; Wyborn et al, 1998; Perring et al., 2001; Pollard et al., 1998; Mark et al, 2005b; Rubenach, 2005).

Averaged geochemical data for the 1686Ma, 1660Ma (Toole Creek Volcanics), ~1600Ma and ~1530Ma generations of mafic magmas are presented in Table 1. They all display strong Fe enrichment, similar to the high Fe tholeiites of the Curnamona Province. Correlation of iron enrichment with silica increase has been suggested to indicate a primary igneous fractionation trend (Williams, 1998; Butera et al, 2005)

	1686Ma		1660Ma (TCV)		1600Ma		1530Ma	
# samples	7		6		13		4	
	Average	*st. dev.*	*Average*	*st. dev.*	*Average*	*st. dev.*	*Average*	*st. dev.*
SiO2	48.32	1.07	49.13	1.39	49.23	0.79	47.38	0.45
TiO2	1.26	0.33	1.19	0.54	1.31	0.24	1.52	0.50
Al2O3	14.59	1.40	13.75	0.90	14.07	0.47	14.28	1.38
Fe2O3T	14.77	3.12	12.85	2.07	14.06	1.15	15.05	3.10
MnO	0.23	0.05	0.21	0.07	0.21	0.04	0.18	0.04
MgO	6.98	1.33	7.25	1.31	6.88	0.51	6.68	1.47
CaO	10.58	1.62	11.39	2.43	10.35	0.66	9.19	0.78
Na2O	2.36	0.64	2.17	0.83	2.61	0.31	2.93	0.62
K2O	0.47	0.21	0.26	0.16	0.95	0.41	1.55	0.49
P2O5	0.10	0.03	0.09	0.06	0.12	0.02	0.10	0.03
Sc	43.71	4.23	50.67	6.12	42.23	3.42	40.25	9.18
Ba	64.57	44.91	63.83	56.03	141.46	109.41	122.25	21.17
V	372.86	100.30	350.17	97.37	319.85	48.73	410.75	168.50
Cr	166.83	87.07	181.67	73.96	106.92	33.01	101.67	51.48
Co	53.14	7.40	49.50	3.27	57.00	10.64	61.75	3.86
Ni	100.71	24.01	77.33	16.95	87.69	17.27	108.50	49.80
Zn	81.43	20.41	98.33	36.43	74.31	30.51	55.75	32.94
Ga	19.14	2.34	17.33	2.58	19.92	1.12	20.00	2.83
Pb	28.29	4.75	17.67	6.25	28.62	3.52	27.00	4.97
Rb	27.20	18.09	9.00	9.42	66.00	40.57	81.75	41.68
Sr	134.43	41.10	154.00	62.74	146.85	27.17	162.00	13.83
Y	26.14	8.13	22.33	9.61	26.38	2.87	24.50	6.40
Zr	61.57	17.24	70.50	37.09	78.54	11.80	70.25	25.86
Nb	3.86	1.21	4.67	2.66	5.69	1.32	5.00	1.41
Se	4.78	7.34	-	-	13.25	7.16	11.85	10.80
Cd	5.57	1.84	-	-	3.03	2.75	2.23	2.63
Sn	1.23	0.52	-	-	1.33	1.07	1.95	1.53
Sb	0.86	0.49	-	-	0.46	0.26	0.73	0.36
Cs	0.54	0.74	7.00	-	0.54	0.40	1.21	1.25
La	4.33	1.12	6.80	3.03	6.87	1.61	7.38	3.06
Ce	11.03	2.77	14.33	8.41	16.06	3.74	17.09	6.23
Pr	2.78	1.45	7.00		1.79	0.97	2.62	2.57
Nd	9.77	2.37	11.00	6.44	12.32	2.26	12.92	3.29
Sm	3.11	0.98	-	-	3.56	0.98	3.98	0.78
Eu	0.99	0.06	-	-	1.30	0.35	1.44	0.43
Gd	3.99	1.39	-	-	4.46	0.74	4.52	1.03
Tb	1.07	0.60	-	-	0.54	0.29	0.73	0.64
Dy	4.87	1.38	-	-	5.02	0.80	5.36	1.35
Ho	1.46	0.87	-	-	0.69	0.41	0.94	0.89
Er	2.86	0.95	-	-	3.04	0.57	3.48	1.50
Tm	0.63	0.38	-	-	0.30	0.17	0.40	0.36
Yb	2.71	0.78	-	-	2.23	0.18	3.16	0.00
Lu	0.59	0.33	-	-	0.30	0.14	0.41	0.30
Hf	0.65	0.28	3.00	1.41	2.13	0.50	2.78	1.06
Bi	0.24	0.20	-	-	0.20	0.22	0.15	0.18
Th	0.80	0.45	2.00	2.24	1.06	0.37	1.95	1.42
U	0.30	0.22	2.50	-	0.53	0.28	0.59	0.25
Au	0.01	0.01	2.50	-	0.00	0.00	0.00	0.01
Cu	176.86	55.62	138.33	35.09	104.54	49.47	248.00	186.08
S	787.14	502.94	526.00	320.17	676.54	682.98	1262.50	541.07
Y/Nb	6.90	1.23	5.36	0.91	4.81	0.94	4.59	0.80

Zr/Nb	16.37	3.42	15.93	1.38	14.14	2.09	15.18	3.12
Ce/Y	0.43	0.03	0.54	0.14	0.61	0.12	1.10	0.65

Table 1. Averaged geochemical data, with standard deviations, for Eastern Succession mafic rock units of 1686Ma, 1660Ma (Toole Creek Volcanics) (Geoscience Australia Ozchem Database), 1600-1580Ma and 1530Ma.

Crustal Thickness

Mantle and Collins (2008) studied the Ce/Y contents of a number of basalts extruded from volcanoes globally, and proposed a relationship between the maximum Ce/Y value and the depth to Moho (where the depth was previously known from seismic data). They concluded that since the Moho is the typical level at which mafic magmas fractionate (at the base of the crust), the Ce/Y values of basalts reflects their depth (pressure) of fractionation. The maximum Ce/Y ratio for the 1686Ma generation of Eastern Succession mafic magmas studied yielded a value of 0.58. This corresponds to a depth of fractionation of approximately 3.2kbar, or ~11km. For subsequent generations of mafic magmatism at 1660Ma, 1600Ma and 1530Ma, the corresponding fractionation depths were 16km (maximum Ce/Y = 0.68), 18km (maximum Ce/Y = 0.75) and 37km (maximum Ce/Y = 2.21) respectively. These depths were then used as a basis for modeling the fractionation processes that lead to the compositions observed in the rocks. Using the thermodynamic modeling software pMelts (Ghiroso et al, 2002), and pressure set at 3.2kbar (for 1686Ma mafic compositions), hypothetical magma compositions were input into the model and iteratively refined until compositions typical of the Eastern Succession magmas was computed (Table 2). The models suggest that the geochemistry of these mafic rocks is consistent with derivation via the strong fractionation (to 58%) of a high Fe-picrite parental magma, with an initial liquidus temperature of 1377^{o}C at 3.2kb, and an initial (pre-fractionated) H_2O content of 0.5wt%. The Ce/Y ratios of 1660, 1600 and

1530Ma mafic rocks indicate they formed at pressures greater than 3.2kb, as would be expected from the effects of the post-1686 orogenic events. Modifying the pressure appropriately in the pMelts models yields similar results to the 1686 Ma model regarding Fe-rich picritic parental magmas and a high % fractionation. All the models require a contribution of H_2O in the source region in order to converge upon the real compositions.

Temp. (deg C)	P (kbars)	Fractionation (%)	SiO2 (wt%)	TiO2 (wt%)	Al2O3 (wt%)	Fe2O3 (wt%)	FeO (wt%)	MnO (wt%)
1377.15	3.2	0.01	48.28	0.51	9.25	1.34	9.07	0.15
1357.15	3.2	2.79	48.5	0.53	9.51	1.37	9.07	0.15
1337.15	3.2	5.36	48.71	0.54	9.77	1.41	9.05	0.15
1317.15	3.2	7.75	48.91	0.56	10.02	1.45	9.02	0.15
1297.15	3.2	9.97	49.12	0.57	10.27	1.48	8.97	0.15
1277.15	3.2	12.03	49.32	0.58	10.51	1.52	8.92	0.15
1257.15	3.2	13.96	49.52	0.6	10.75	1.55	8.85	0.15
1237.15	3.2	21.25	49.37	0.64	11.5	1.6	9.15	0.16
1217.15	3.2	31.92	48.93	0.72	12.76	1.64	9.81	0.18
1197.15	3.2	40.07	48.55	0.8	13.95	1.66	10.39	0.21
1177.15	3.2	46.49	48.24	0.86	15.08	1.67	10.9	0.23
1157.15	3.2	51.69	48	0.92	16.14	1.68	11.34	0.26
1137.15	3.2	58.01	47.99	1.03	16.31	1.79	12.07	0.29

Temp. (deg C)	P (kbars)	Fractionation (%)	MgO (wt%)	CaO (wt%)	Na2O (wt%)	K2O (wt%)	P2O5 (wt%)	H2O (wt%)
1377.15	3.2	0.01	16.95	12.33	1.03	0.08	0.03	0.51
1357.15	3.2	2.79	16.03	12.67	1.06	0.08	0.03	0.53
1337.15	3.2	5.36	15.13	13	1.09	0.09	0.03	0.54
1317.15	3.2	7.75	14.27	13.32	1.11	0.09	0.03	0.56
1297.15	3.2	9.97	13.44	13.64	1.14	0.09	0.03	0.57
1277.15	3.2	12.03	12.65	13.95	1.17	0.09	0.04	0.58
1257.15	3.2	13.96	11.88	14.25	1.19	0.1	0.04	0.6
1237.15	3.2	21.25	10.93	13.96	1.3	0.1	0.04	0.65
1217.15	3.2	31.92	9.81	13.06	1.48	0.12	0.05	0.75
1197.15	3.2	40.07	8.76	12.2	1.66	0.14	0.05	0.86
1177.15	3.2	46.49	7.77	11.36	1.85	0.15	0.06	0.96
1157.15	3.2	51.69	6.85	10.54	2.03	0.17	0.06	1.06
1137.15	3.2	58.01	6	9.72	2.21	0.19	0.07	1.22

Table 2. pMelts thermodynamic model results for a strongly fractionated (up to 60%) Fe-picrite parental magma composition fractionating at 3.2kbar (~12km depth), converging on the typical composition of 1686Ma Eastern Succession mafic rocks (between 1177^{o}C-1137^{o}C).

Irrespective of the age of the mafic rocks within the eastern part of the Eastern Succession (Soldiers Cap Group and parts of the Kuridala Formation), their chemistry is remarkably similar, indicating that they were all derived via similar processes from parental magmas of a common composition. On N-MORB normalised spiderdiagrams (Sun and McDonough, 1989), these mafic rocks display decoupled patterns of relatively flat heavy rare earth elements (HREEs) and high field strength elements (HFSEs), and a steeper slope for the light rare earth elements (LREEs) and lighter large ion lithophile elements (LILEs) (Fig.2a-d). A distinctive feature of the chemistry of these mafic rocks is a consistently high Pb content (25-30ppm), reflected by a greater than 80x enrichment of N-MORB on the spiderdiagram.

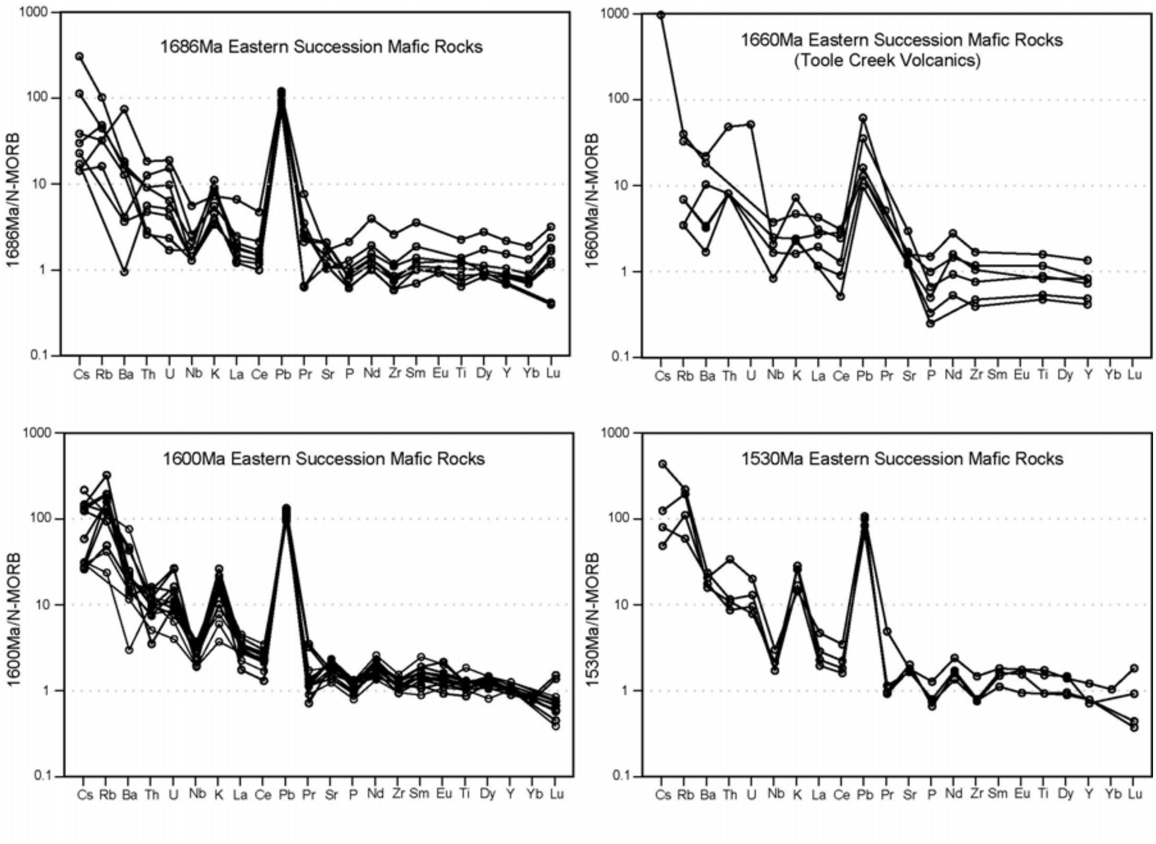

Figure 2. N-MORB Normalised spiderdiagram plots for different generations of the Mesoproterozoic mafic rocks of the Mount Isa Eastern Succession, at a) 1686Ma, b) 1660Ma (Toole Creek Volcanics), c) 1600-1580Ma (syn-metamorphic) and d) 1530Ma. All generations display a decoupled pattern of flat REE/HFSE elements, and sloped LILE elements.

The averaged data for the mafic rocks were also plotted on the tectonic discrimination diagrams of Pearce and Cann (1973), Pearce and Norry (1979) and Meschede (1986), in order to better constrain the tectonic environment into which they were emplaced (Fig. 3a-e). In all cases, the Eastern Succession mafic rocks plot in the MORB-Island Arc-Volcanic Arc fields of the diagrams. Some minor scatter in the data for the Zr-Ti-Sr plot (Fig. 3c) of Pearce and Cann (1973) can potentially be explained by the effects of metamorphic or hydrothermal overprinting on Sr and other alkali earth elements (Oliver et al, 2004; Butera et al, 2005).

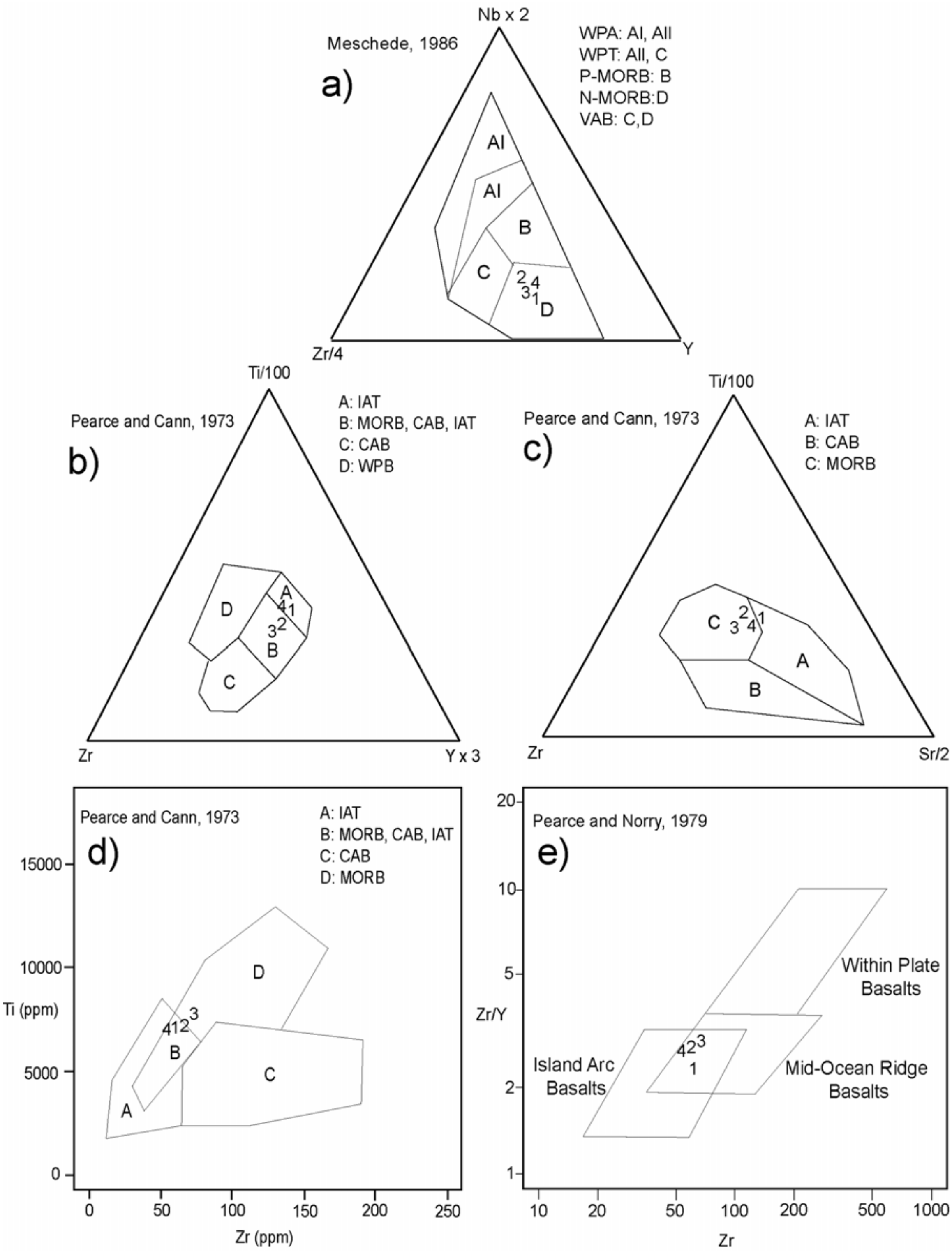

Figure 3. Averaged geochemical data for the different generations of the Mesoproterozoic mafic rocks of the Mount Isa Eastern Succession plotted on the tectonic discrimination diagrams of a) Meschede (1986), b,c,d) Pearce and Cann (1973) and e) Pearce and Norry (1979). 1 = 1686Ma, 2 = 1660Ma (TCVs), 3 = 1600-1580Ma, 4 = 1530Ma. Data for the Eastern Succession generally plot in the MORB-Island Arc-Volcanic Arc Fields. Standard deviations given in Table 1.

As previously mentioned, Myers et al (1996) defined the Archean-Proterozoic blocks of Australia as the North, South and West Australian cratons. On the eastern margin of the North Australian Craton are the Mount Isa-McArthur River and Georgetown Provinces, and on the eastern margin of the South Australian craton lies the Curnamona Province. All of these provinces share a similar tectono-stratigraphic history (Laing and Beardsmore, 1986; Whitnall et al, 1988; Laing, 1990; Laing, 1996; McDonald et al, 1997; O'Dea et al 1997; Scott et al, 2000; Giles et al, 2002; Raetz et al, 2002; Giles et al, 2004; Page et al, 2005). Mafic magmatism spans almost the entirety of the Mesoproterozoic across these provinces, and as such provides a useful means of cross-correlation.

Some of the oldest mafic rocks along the eastern margins of the North and South Australian cratons ocuur within the 1860Ma Leichhardt Volcanics that forms part of the the Kalkadoon-Leichhardt belt (KLB). The KLB is a north-south trending belt of the Mount Isa Inlier that separates the Western Succession from the Eastern Succession, and has been interpreted as the basement to the Mount Isa block (Laing and Beardsmore, 1986; Blake, 1987; McDonald et al; 1997). The ca. 1780Ma Magna Lynn Metabasalt crops out along the eastern flank of this belt. Wilson (1978) studied the felsic lavas of the Leichhardt Volcanics and the overlying mafic and felsic units of the Magna Lynn Metabasalt and Argylla Formation respectively. Wilson (1978) found that the Magna Lynn Metabaslt consisted of low-K tholeiites similar in nature to tholeiites overlaying calk-alkaline series volcanics in the southwestern United States. He also concluded that the sequence as a whole was consistent with a continental margin, similar in nature to the Andes. However other researchers concluded that these rocks were geochemically consistent with continental rifting

(Bultitude and Wyborn, 1982; Ellis and Wyborn 1984; Wyborn, 1988; Wyborn et al., 1988, 1998).

The Mount Isa Western Succession and McArthur River Basin host a number of discrete mafic intrusive suites. Scott et al (2000) used the stratigraphic associations of Jackson et al (2000) and defined a) the 1780 Ma Leichhardt Interval Association C (LIAC) which includes the extensive Eastern Creek Volcanics, b) the 1760 Ma Leichhardt Interval Association E (LIAE) (Quilalar Formation), c) the 1730 Ma Calvert Interval Association G1 (CIAG1) (Peters Creek Volcanics), and d) the 1710 Ma Calvert Association H (CIAH) (Fiery Creek Volcanics). Another event, the Slaughter Yard Creek Dolerite (SYCD) intrusions were associated with the ~1670Ma emplacement of the Sybella Batholith to the southwest of Mount Isa (Sisois-Pizanias, 2002). The 1760Ma LIAE event may correspond to the comparably aged Marraba Volcanic event on the western margin of the Eastern Succession. The Curnamona Province (Broken Hill and Olary Block) was intruded by voluminous tholeiitic sills and dykes at ~1685Ma (Nutman and Ehlers, 1998; Conor and Fanning, 2001; Raetz et al, 2002). These high Fe tholeiites share similar geochemical characteristics to those from the eastern margin of the Mount Isa Eastern Succession (Williams, 1998). 1675Ma mafic intrusives from the Georgetown Province (Black et al, 1998) may also share a common chemical affinity to those of the Eastern Succession (Withnall et al, 1988).

Averaged geochemical data for the studied mafic units are shown in Table 3. Depth to Moho (or fractionation depth) of the Curnamona Province and the Georgetown Inlier units were calculated by use of the maximum Ce/Y method (Mantle and Collins, 2008). The Curnamona Province, during the period of mafic magmatism at ~1685, had a crustal thickness of ~11km (maximum Ce/Y = 0.58), and the Georgetown Inlier at ~1675Ma had an identical crustal thickness (~11km; maximum Ce/Y = 0.58). The maximum Ce/Y ratio of 1.44 for the 1860Ma Leichhardt Volcanics represents a crustal thickness of ~28km. Minimum crustal thickness for the time of mafic magma emplacement in the 1780Ma Leichhardt Interval Association C, 1760Ma Leichhardt Interval Association E, 1730Ma Calvert Interval Association G1, 1710Ma Calvert Association H and the 1670Ma Slaughter Yard Creek Dolerite are 31km (average Ce/Y = 1.56), 29km (average Ce/Y = 1.46), 34km (average Ce/Y =1.81), 42km (average Ce/Y = 3.02) and 40km (maximum Ce/Y= 2.66), respectively (Table 3).

Age	Curnamona 1685Ma		Georgetown 1678Ma		Leichhardt 1860Ma	SYCD 1670Ma	LIAC 1780Ma	LIAE 1760Ma	CIAG1 1720Ma	CIAH 1710Ma
# samples	17		20		8	3	161	10	163	23
	Average	*st. dev.*	*Average*	*st. dev.*	*Average*	*Average*	*Average*	*Average*	*Average*	*Average*
SiO2	50.34	0.74	49.12	1.20	50.23	-	50.7	51.83	49.47	49.95
TiO2	1.24	0.28	1.30	0.46	1.42	-	1.64	1.8	2.41	2.62
Al2O3	14.07	0.99	14.68	2.26	14.34	-	14.05	14.34	13.78	14.25
Fe2O3T	14.52	2.03	13.75	2.65	12.50	-	12.85	13.54	12.63	14.2
MnO	0.34	0.17	0.20	0.04	0.23	-	0.14	0.31	0.13	0.08
MgO	6.80	0.96	6.17	0.88	6.46	-	8.09	2.89	5.41	2.49
CaO	10.50	1.03	11.02	1.56	8.86	-	3.91	2.73	3.03	2.97
Na2O	1.36	0.44	1.93	0.58	2.34	-	1.89	0.84	1.04	0.56
K2O	0.55	0.23	0.35	0.34	1.28	-	2.31	7.49	5.88	8.53
P2O5	0.11	0.03	0.11	0.04	0.15	-	0.19	0.27	0.5	1.2
Ba	204.17	56.89	103.65	82.67	272.88	-	281	160	1583	1454
V	357.50	101.12	424.55	166.34	342.63	-	296	276	274	179
Cr	187.75	73.77	121.10	45.65	112.00	-	137	76	39	35
Ni	80.62	29.09	68.25	17.20	107.75	-	82	51	25	27
Zn	90.87	38.40	102.20	24.55	112.25	-	110	128	104	45
Ga	13.60	1.67	20.00	1.53	20.33	-	19	20	21	20
Pb	10.40	13.07	6.88	4.06	6.38	-	13	37	18	13
Rb	36.00	30.04	14.22	19.64	74.50	-	78	182	109	180
Sr	146.71	46.73	167.05	60.66	155.13	-	108	82	106	85
Y	21.13	5.74	22.90	7.81	29.13	-	32	46	43	58
Zr	85.15	38.40	76.60	28.16	115.50	-	169	180	218	398
Nb	5.17	1.17	4.75	1.70	8.00	-	11	22	17	36
La	5.33	0.58	4.75	2.38	14.13	-	25	36	38	81
Ce	12.17	13.60	7.92	6.38	30.50	-	50	66	78	175
Nd	16.00	9.90	7.00	3.03	14.75	-	26	38	39	79
Hf	6.00	0.00	3.50	1.50	4.00	-	-	-	-	-
Th	2.50	0.71	3.50	1.12	3.88	-	6	9	9	9
U	1.00	0.00	1.50	0.55	2.06	-	2	4	2	3
Cu	179.62	129.16	148.45	112.85	147.63	-	162	40	63	20
Y/Nb	4.94	0.95	4.92	0.80	3.78	2.47	2.9	2.09	2.53	1.61
Zr/Nb	16.33	1.16	16.03	1.32	14.69	11.95	15.6	11.9	15.2	11.6
Ce/Y	0.46	0.16	0.41	0.14	1.08	2.22	1.56	1.43	1.81	3.02

Table 3. Averaged geochemical data, for the 1685Ma Curnamona Province, 1675Ma Georgetown Inlier and 1860Ma Leichhardt Volcanics mafic rock units (Geoscience Australia Ozchem Database), 1670Ma Slaughter Yard Creek Dolerites (SYCD) (Sisois-Pizanias), and the LAIC (Leichhardt Association Interval C), LAIE (Leichhardt Association Interval E), CIAG1 (Calvert Association Interval G1) and CIAH (Calvert Association Interval H) intervals of the Mount Isa Western Succession and McArthur River Basin (Scott et al, 2000).

Data plotted on N-MORB normalised spiderdiagrams (Sun and McDonough, 1989) reveal that the mafic magmas of the Curnamona Province and Georgetown Inlier share a decoupled pattern of flat HREEs and HFSEs and steeper LREEs and LILEs, similar to those of the Mount Isa Eastern Succession. They also display strong positive Pb and K, and moderate negative Nb anomalies (Fig. 4a,b). Normalised spiderdiagram plots for the Mount Isa Western Succession, Kalkadoon-Leichhardt Belt (Leichhardt Volcanics) and McArthur River Basin data also display K and Pb and Nb anomalies. The REEs are enriched 1.5 to 5 times N-MORB. Additionally, they do not display a decoupled trend as for the other data, but rather a steadily descending linear pattern.

On tectonic discrimination plots, data for the Curnamona Province and Georgetown Inlier plot similar to the Mount Isa Eastern Succession, predominantly in the MORB-Island Arc-Volcanic Arc fields, while data for mafics of the Western Succession and McArthur River Basin (Scott et al, 2000) typically plot in the Within Plate-Continental Arc-MORB fields(Fig. 5a-e).

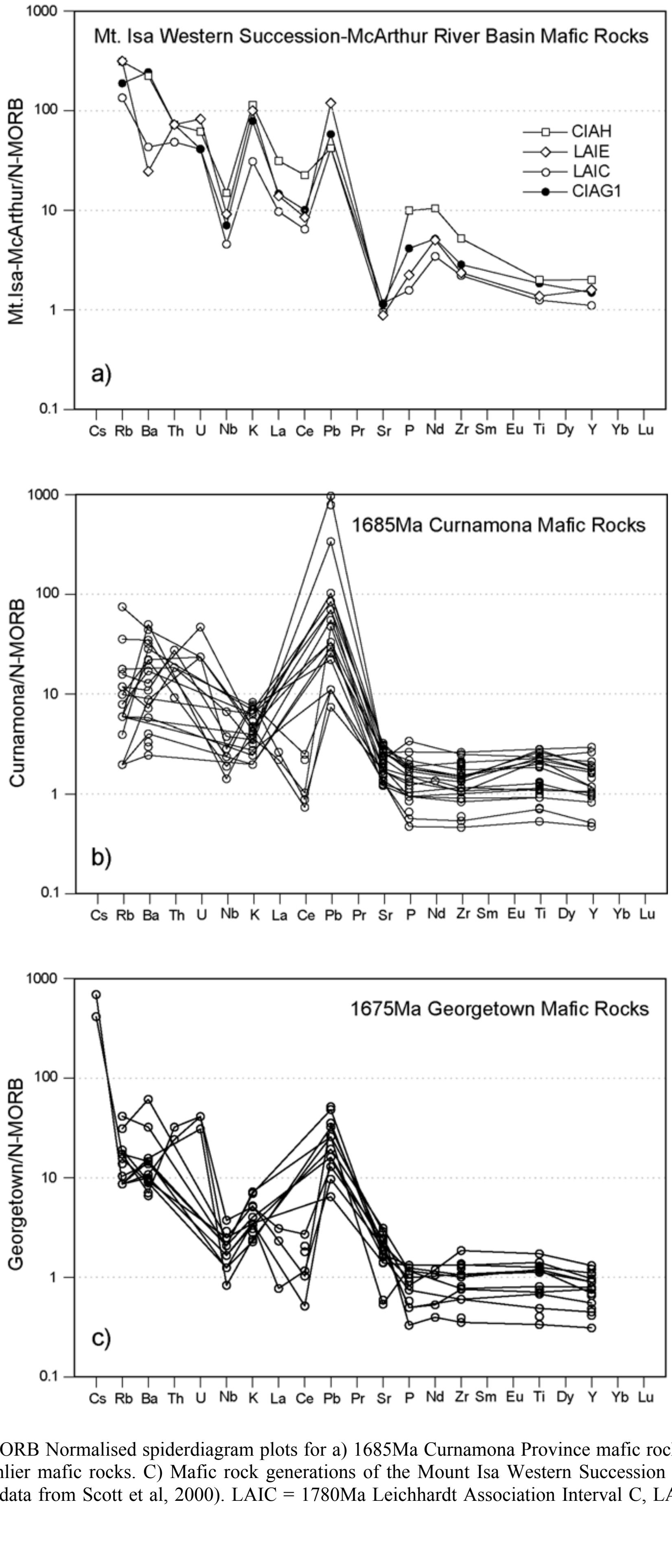

Figure 4. N-MORB Normalised spiderdiagram plots for a) 1685Ma Curnamona Province mafic rocks. b) 1675Ma Georgetown Inlier mafic rocks. C) Mafic rock generations of the Mount Isa Western Succession and McArthur River Basins (data from Scott et al, 2000). LAIC = 1780Ma Leichhardt Association Interval C, LAIE = 1760Ma

Leichhardt Association Interval E, CAIG1 = 1720Ma Calvert Association Interval G1, CAIH = 1710Ma Calvert Association Interval H. The Curnamona and Georgetown mafic rocks display similar decoupled normalised patterns to those of the Eastern Succession, while the Western Succession-McArthur River mafic rocks display a consistently sloped trend (Winter, 2001;).

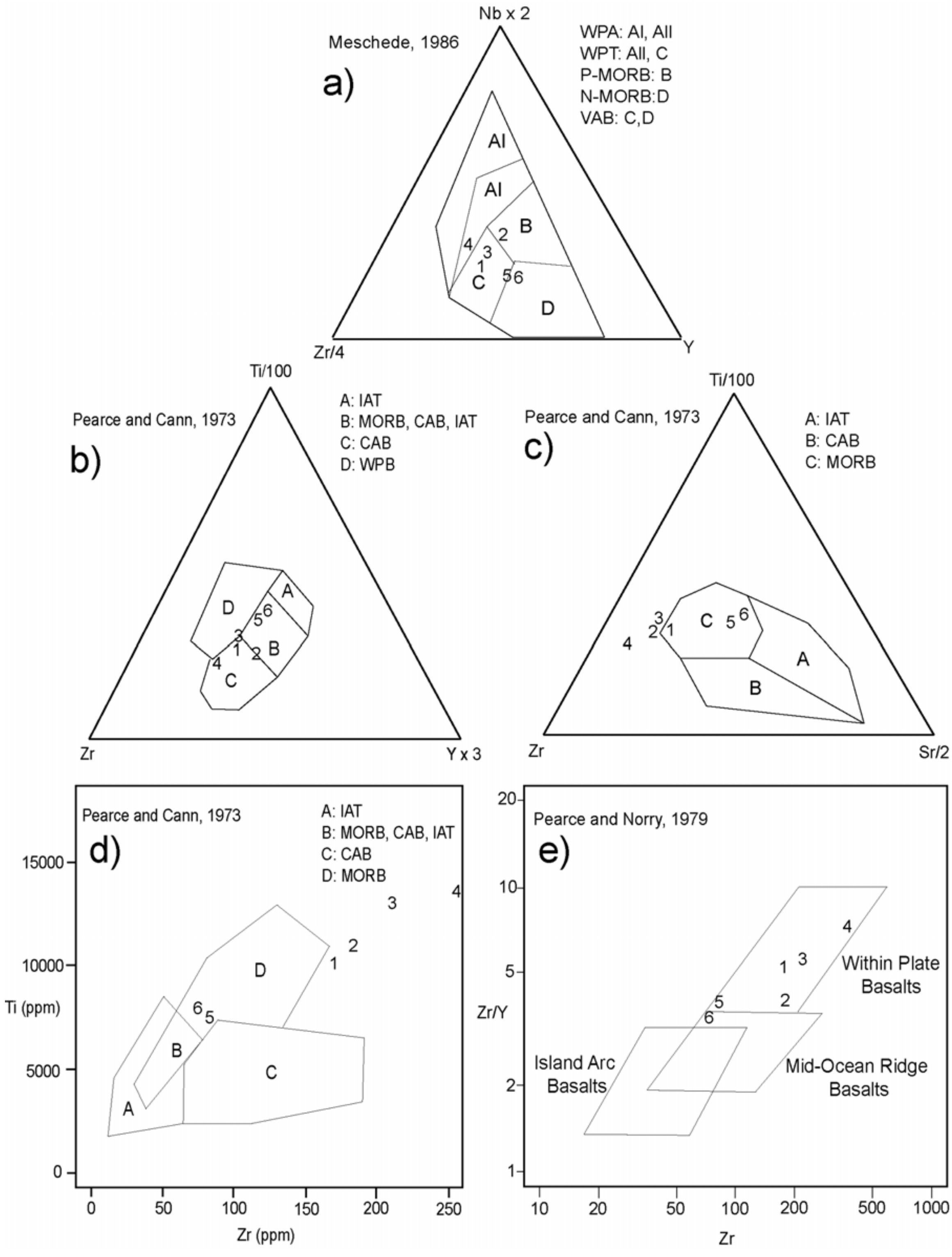

Figure 5. Averaged geochemical data for the mafic rocks of the Curnamona Province, Georgetown Inlier and Mount Isa Western Succession-McArthur River Basin (Scott et al, 2000), plotted on the tectonic discrimination diagrams of a) Meschede (1986), b,c,d) Pearce and Cann (1973) and e) Pearce and Norry (1979). 1 = LAIC, 2 = LAIE, 3 = CIAG1, 4 = CIAH, 5 = Curnamona Province, 6 = Georgetown Inlier.. Data for Curnamona and Georgetown plot similarly to the Eastern Succession (Fig. 3), while data for the Western Succession and McArthur River Basin typically plot in the MORB-Continental Arc-Within Plate Basalt fields. Standard deviations given in Table 3.

Discussion

Our analysis reveals changes within the mafic rock geochemistry of the Mount Isa block in time and space that may not be consistent with previous hypotheses for uniform tectonic and/or geodynamic evolution. The results of our study define two distinct geochemical groupings, the Western Domain (mafic magmas of the Mount Isa Western Succession, McArthur River Basin and the Kalkadoon-Leichhardt Belt) and the Eastern Domain (Mount Isa Eastern Succession, Curnamona Province and the Georgetown Inlier). The most conservative interpretation of this change is that it reflects a change in the chemistry of the mantle source region.

Eastern and Western Domain data for Zr/Nb vs Y/Nb were compared to global geochemical data for continental flood basalts (CFBs) and back-arc basalts (Fig. 6). All Western Domain data plot in the CFB field, while the Eastern Domain data plot in the back-arc field. This suggests that there was either a nearby, active subduction zone related to the back-arc signatures, or that earlier subducted crust had entered the mantle source region to be subsequently incorporated in partial melting and basalt production during rifting. Importantly, the boundary between the diverging datasets lies between the Mount Isa Western and Eastern Successions, rather than along a previously defined boundary between cratons (Myers et al., 1996). Interestingly, the Leichhardt Volcanics (KLB) also display an affinity to CFB magmas on the Zr/Nb vs Y/Nb plot, suggesting that the actual boundary lies to the east of the Kalkadoon-Leichhardt belt, in the western part of the Eastern Succession.

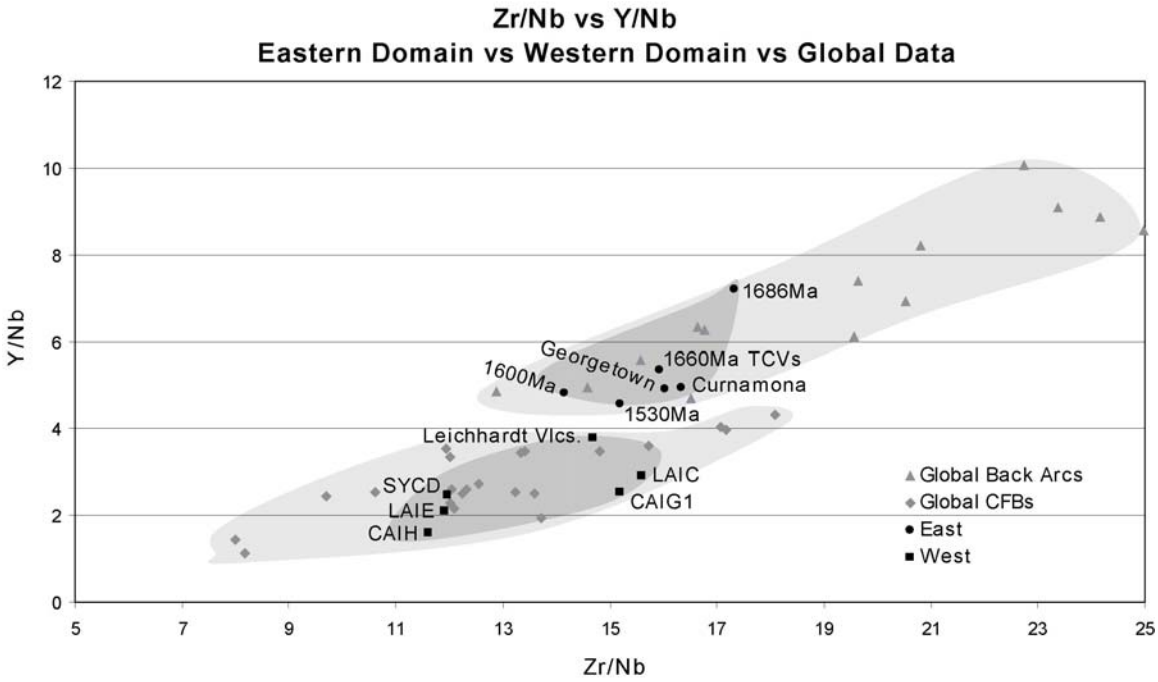

Figure 6. Zr/Nb vs Y/Nb diagram for the mafic rock units of the Eastern Succession (1686Ma, 1660Ma,1600-1580Ma, 1530Ma), Western Succession-McArthur River Basin (LIAC, LIAE, CIAG1, CIAH, SYCD), Kalkadoon-Leichhardt Belt (Leichhardt Vlcs), Curnamona Province and Georgetown Inlier. Data and fields for global continental flood basalts (CFBs) and back arc basins (BABs) are plotted for comparison. The Eastern Succession, Curnamona and Georgetown mafic rocks plot within the back arc basalt field, while the Western Succession, McArthur River Basin and Kalkadoon-Leichhardt Belt mafic rocks lie within the field for continental flood basalts. Global data drawn from GEOROC database. After Meschede (1986).

The notion that the Eastern Domain magmas were emplaced into a back arc basin between ~1690Ma and ~1660Ma is consistent with their normalised spiderdiagram patterns that share affinities with those of the Sunda Arc (Fig. 7a; Gerbe et al, 1992; Turner et al, 2001) and the Kermadec Arc (Fig. 7b; McCulloch and Gamble, 1991; Gamble et al, 1993; Regelous et al, 1997; Turner et al, 1997; Ewart et al, 1998; Smith et al, 2003). The spiderdiagram patterns of the Western Domain magmas are similar to those of the Karoo Province of South Africa (Fig. 7c; Ellis and Wyborn, 1984; Scott et al, 2000) and the Central Plains of the Midcontinental Rift System (Fig. 7d; Marshall and Lidiak, 1996). Additionally, there is a difference in both the absolute values and the temporal pattern of maximum and average Ce/Y data to the east and west of the Kalkadoon-Leighhardt Belt (Fig. 8). We thus infer that the thickness of the crust at the time of mafic magma emplacement differed between the domains, and that the evolution of this thickness also varied. The Western Domain progressively thickened, while the Eastern Domain thinned, between ~1800Ma and 1686Ma (Fig. 8). After 1686Ma, the crust of both the Eastern and Western Domains thickened (Fig. 8), synchronous with the ~1600-1580Ma Isan Orogeny. For the earlier period, a crustal thickness of ~12km at the time of mafic magma emplacement in the Eastern Domain is consistent with a strongly rifted back arc basinal tectonic environment. The apparently thicker crust (~28-42km) during the period of magmatism in the Western Domain is comparable with other within-plate continental flood basalt provinces (Wilson, 1995). The tectonic environment suggested by the crustal thickness inferred from Ce/Y ratios is also comparable with the inferred environment suggested by other trace elements on tectonic discrimination diagrams.

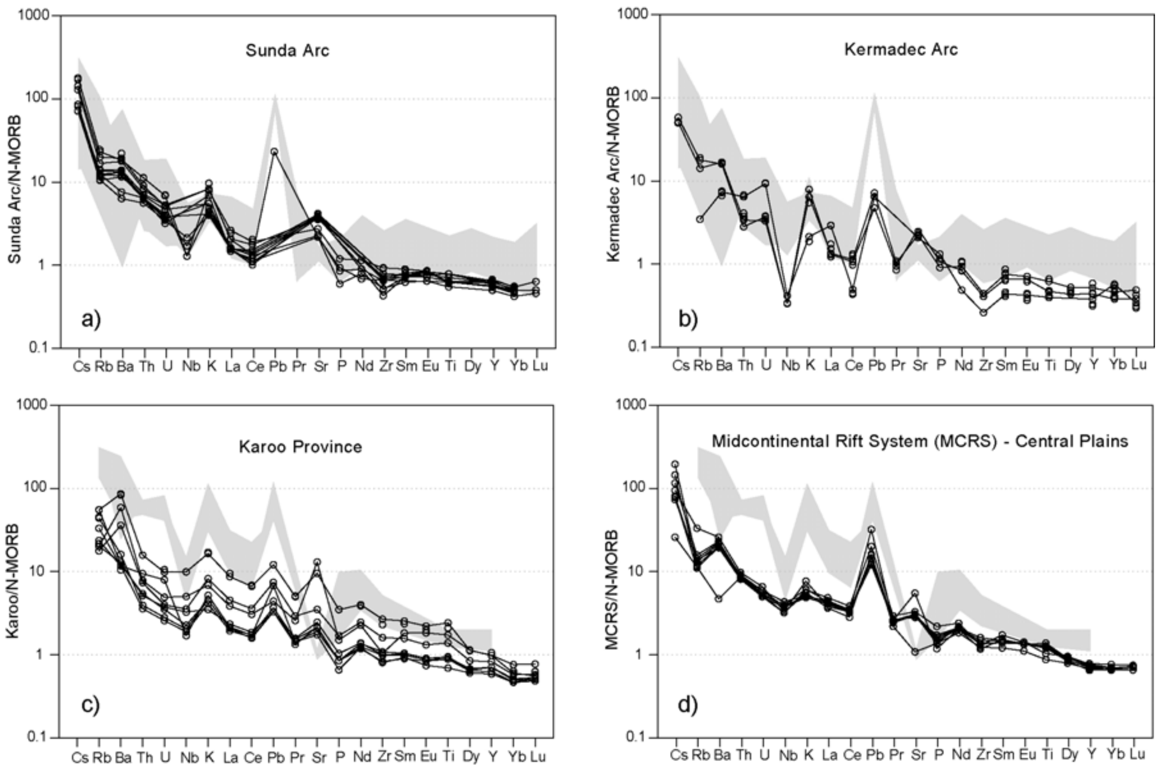

Figure 7. N-MORB normalised spiderdiagrams for geochemical data of mafic rocks in the a) Sunda and b) Kermadec Arc, with fields for the 1686Ma generation of mafic rocks from the Eastern Succession; and, c) Karoo Province and d) Midcontinental Rift Zone (Central Plains), with fields for the averages of the Western Succession-McArthur River Basin mafic units of Scott et al (2000). The de-coupled slope of the Eastern Succession (+Sunda/Kermadec Arcs) distinguish the mafic geochemistry from the gently sloping nature of the Western Succession/Macarthur River(+Karoo/MCRS), focussing on a distinction between the two datasets (not necessarily the precise tectonic environment) (Pers. Comm Bill Collins, 2006; Winter, 2001).

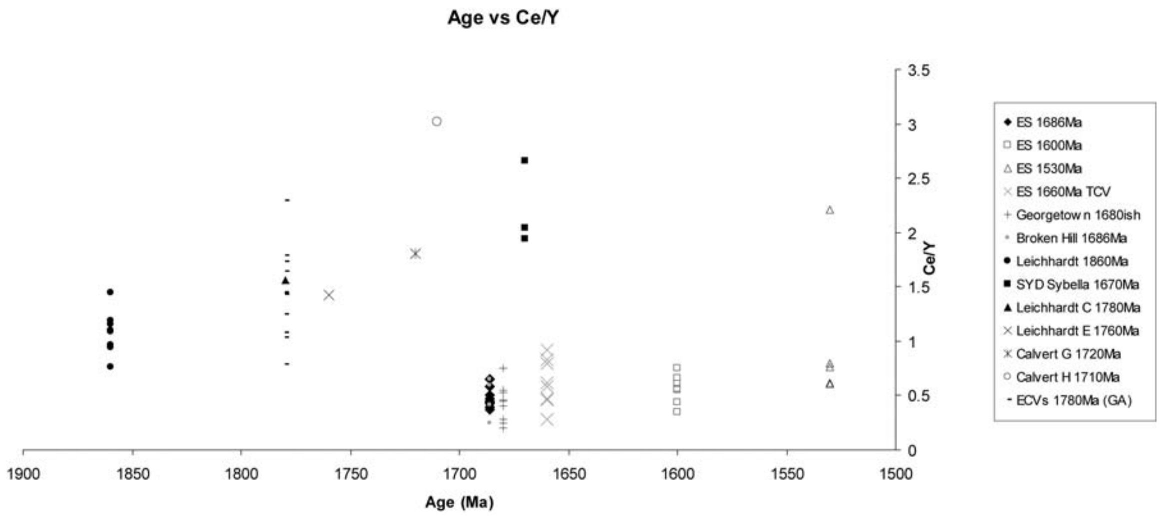

Figure 8. Age vs Ce/Y plot for mafic units of the Mount Isa Inlier, Georgetown and Broken Hill provinces. As Mantle and Collins (2008) suggest increase Ce/Y with crustal thickness, it is apparent that Western Domain (Western Succession, Kalkadoon-Leichhardt Belt and McArthur River Basin) mafics were emplaced into a thicker crust than the Eastern Domain (Eastern Succession, Curnamona and Georgetown), and that the evolution of crustal thickness was different between the two domains. Although little overlap in the age of the mafic emplacement occurs, at 1686Ma, the Eastern Succession sat on ~11km of crust, while the Western Succession at Sybella Batholith time (Slaughter Yard Creek Dolerite (~1670Ma) sat on >40km of crust.

The results presented here suggest a variation on the hypotheses of Giles et al (2002). These authors proposed that 1800Ma – 1670Ma subduction in the Arunta Block of central Australia led to magmatism in a far-field back arc basinal setting for domains of the North Australian Craton, including all of the Mount Isa block. However, because the Eastern Domain magmas show a consistent back arc affinity with very thin crust before 1600 Ma, as opposed to the magmas of the Western Domain, we suggest that subduction most probably occurred relatively close to the eastern edge of the Mount Isa Eastern Succession, Curnamona and Georgetown. Although this does not negate the model for a collisional boundary at the Arunta at the same time, the earliest onset of Australia-Laurentia plate collision (the AUSWUS model of Karlstrom et al., 1999, 2001) may have been the cause. There is a small possibility that an old plate boundary was present within the Mount Isa Block, such as along the "Pilgrim Worm" inferred from analysis of the aeromagnetic data

(Blenkinsop et al., 2005), which correlates roughly with the change in mafic magma compositions at the eastern margin of the Marraba Volcanics. However, widespread c. 1760 Ma stratigraphic units (e.g. Corella Fm) straddle this boundary (Blake, 1987; Foster and Austin, 2005), so the boundary, if it existed, was probably older than c.1780 Ma Argylla Volcanics.

The model of proximal subduction to the east of the eastern margin of the North and South Australian cratons explains concurrent back arc rifting across the eastern margin of the whole of the Australian continent, consistent with plate scale processes between Australia and the southwest United States in the AUSWUS model. This model (Fig. 9a, b) supports the conjunction of the Mount Isa Eastern Succession, Curnamona Province and Georgetown Inlier throughout much of the Mesoproterozoic, as first suggested by Laing and Beardsmore (1986), and Laing (1990). The eastern edge of the Kalkadoon-Leichhardt block in the western domain may have represented the distal, western shoulder of a north-south trending back-arc rifting zone. Significantly, it is supportive of a model that interprets the Eastern Succession, Curnamona Province and Georgetown Inlier as a separate domain or craton, formed on juvenile crust, younger and thinner than that of the Mt. Isa Inlier and North Australian craton., This shares more similar aged and natured tectono-metamorphic and lithological history and similar radiogenic isotope data for mineral deposits and rocks in the Eastern Domain and the western margin of Laurentia than the Western Domain (Western Succession, Kalkadoon-Leichhardt Belt and McArthur River Basin (Wilson, 1978; Wooden and DeWitt, 1991; Wooden et al, 1994; Zhao and McCulloch, 1995; Hawkins et al, 1996; McDonald et al, 1997; Ramo and Calzia, 1998; Karlstrom and Williams, 1998; Karlstrom et al, 2001; Mark et al, 2005a; Foster and Austin, 2005).

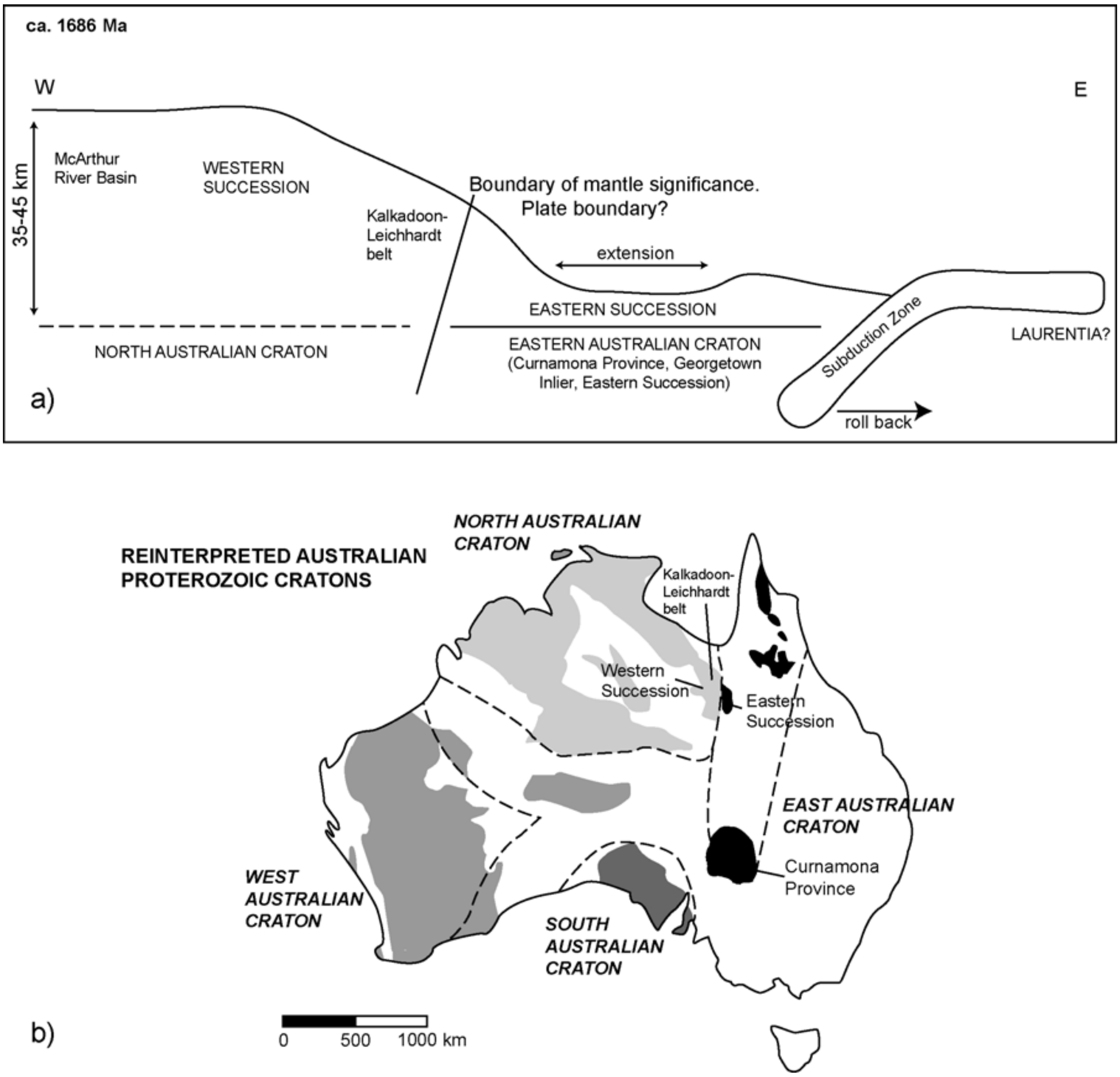

Figure 9. a) Tectonic regime of the eastern margin of the Austalian continent at ca. 1686Ma, showing the development of a back arc basin in response to slab roll back from a subducting slab to the east. b) Reinterpreted Proterozoic Cratons of Australia, including the newly defined East Australian Craton (Mount Isa Eastern Succession, Curnamona Province, Georgetown Inlier).

The mafic magmatic and tectonic distinction between the Eastern and Western Domains of Mesoproterozoic Australia is accurately reflected by their metallogenic nature. Importantly, it implies that the distribution of Cu-Au-(Fe), IOCG and BHT-type mineralisation in the Eastern Domain, and Mount Isa style and stratiform Pb-Zn-Ag mineralisation in the Western Domain may be related to the geochemistry of mafic rocks (or nature of the underlying mantle), the thickness of the crust, or the influence of these factors on the tectonostratigraphic and tectonothermal evolution.

Further, the metallogenic nature of the Eastern Domain is much more analogous in style to southwest Laurentia than the Western Domain (Condie, 1987; DeWitt, 1987; Wooden and DeWitt, 1991; Wooden et al, 1994; Karlstrom, 1991; Williams, 1998b; Skirrow and Ashley, 1999; Skirrow et al, 1999; Williams and Pollard, 2003; Williams et al, submitted).

Conclusions

Based on the distinct evolutionary trends for mafic magmas of the domains of Mesoproterozoic Australia, we suggest that the Mount Isa Western Succession and Macarthur River Domains continue to be recognised as part of the North Australian Craton, while the Mount Isa Eastern Succession, Curnamona Province and the Georgetown Inlier be referred to as the East Australian Craton, in agreement with the earlier-termed 'Diamantina Orogen' of Laing and Beardsmore (1986) and Laing (1990). Furthermore, during the period of 1860Ma to 1500Ma, the divergence of the geochemical evolution of mafic source regions was focussed around the western margin of the Mount Isa Eastern Succession, and we henceforth consider this area to be a major boundary of either crustal or mantle significance across which the nature of the controlling processes of mineralization are distinct. The variance of the geochemistry of mafic magmatism between the North and Eastern Australian Cratons reflects complex influences on the chemical and physical processes that enact upon the mantle source regions for the mafic melts. It is the disparity in mantle chemistry between terranes, perhaps the influence of new or old subducted material, and the nature of the crustal thickness, that we postulate controls the potential to host significant IOCG and BHT-type deposits (East Australian Craton) versus Mt. Isa style

Cu-Pb-Zn and stratiform Pb-Zn-Ag mineralisation (North Australian Craton). In this context, McDonald et al (1997) speculated that a high velocity crustal slab sitting underneath the Mt Isa Eastern Succession reflected part of an Archean to Paleoproterozoic continental assembly process. Similarly, a slab of subducted oceanic crust sitting in the mantle lithosphere to the east of the eastern margin of the East Australian Craton may have provided the appropriate mantle chemistry to contribute to subsequent generation, in an extended continent, of magmas and volcano-sedimentary input that led to the formation of Palaeo-Mesoproterozoic IOCG and BHT deposits.

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CHAPTER 2

The role of mafic rocks in the genesis of Iron oxide-Copper-Gold deposits, Mount Isa Eastern Succession, Northwest Queensland.

The role of mafic rocks in the genesis of Iron oxide-Copper-Gold deposits, Mount Isa Eastern Succession, Northwest Queensland.

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Abstract

In the Mesoproterozoic Mount Isa Eastern Succession, mafic rocks and magmas contributed sulphur and metals to IOCG ore deposition over a protracted (~170My) period. Between 1686 Ma and 1660Ma, S and metals (Cu, Au, Zn, Fe, Ni, Co) were exsolved from crystallising strongly fractioned back-arc tholeiitic magmas into active extensional faults, and surrounding country rocks. During Isan peak-metamorphism, at ~!600Ma-1580Ma, significant amounts of S, Cu, Au, Zn, Ni, Co and Cr were leached from mafic rocksand crustal accumulations, and led to the deposition of early IOCG and base metal deposits. Subsequent albitic alteration associated with the hydrothermal fluids of the ~1550Ma-1490Ma Williams-Naraku Batholith may also have sequestered sulphide material from mafic rocks. This study highlights the possibility that the previously held consensus that the Williams-Naraku Batholith of felsic-intermediate magmas contributed the bulk of the metals to the Eastern Succession mineral deposits, may not necessarily be the case, but rather, fluids

derived from these magmas remobilised previously existing mafic derived metal accumulations.

Keywords: IOCG deposits, Mafics, Sulphur, Metals, Exsolution, Metmorphism

Introduction

The Eastern Succession of the Mount Isa Inlier hosts numerous Fe-oxide Cu-Au (IOCG), Cu-Au, Cu-only, Au-only, Broken Hill-type Pb-Zn-Ag (BHT) and other precious metal deposits. Some of the more prominent of these (Fig. 1) include Ernest Henry (IOCG), Osborne (IOCG), Selwyn-Starra (IOCG), Eloise (IOCG), and Cannington (BHT) (Pollard et al, 1998; Williams, 1998; Williams and Pollard, 2003; Williams et al, 2005). Although numerous genetic models for IOCG and BHT-type mineralisation have been constructed in the last decade, many gaps still remain in the understanding of the critical ingredients and processes for ore deposition.

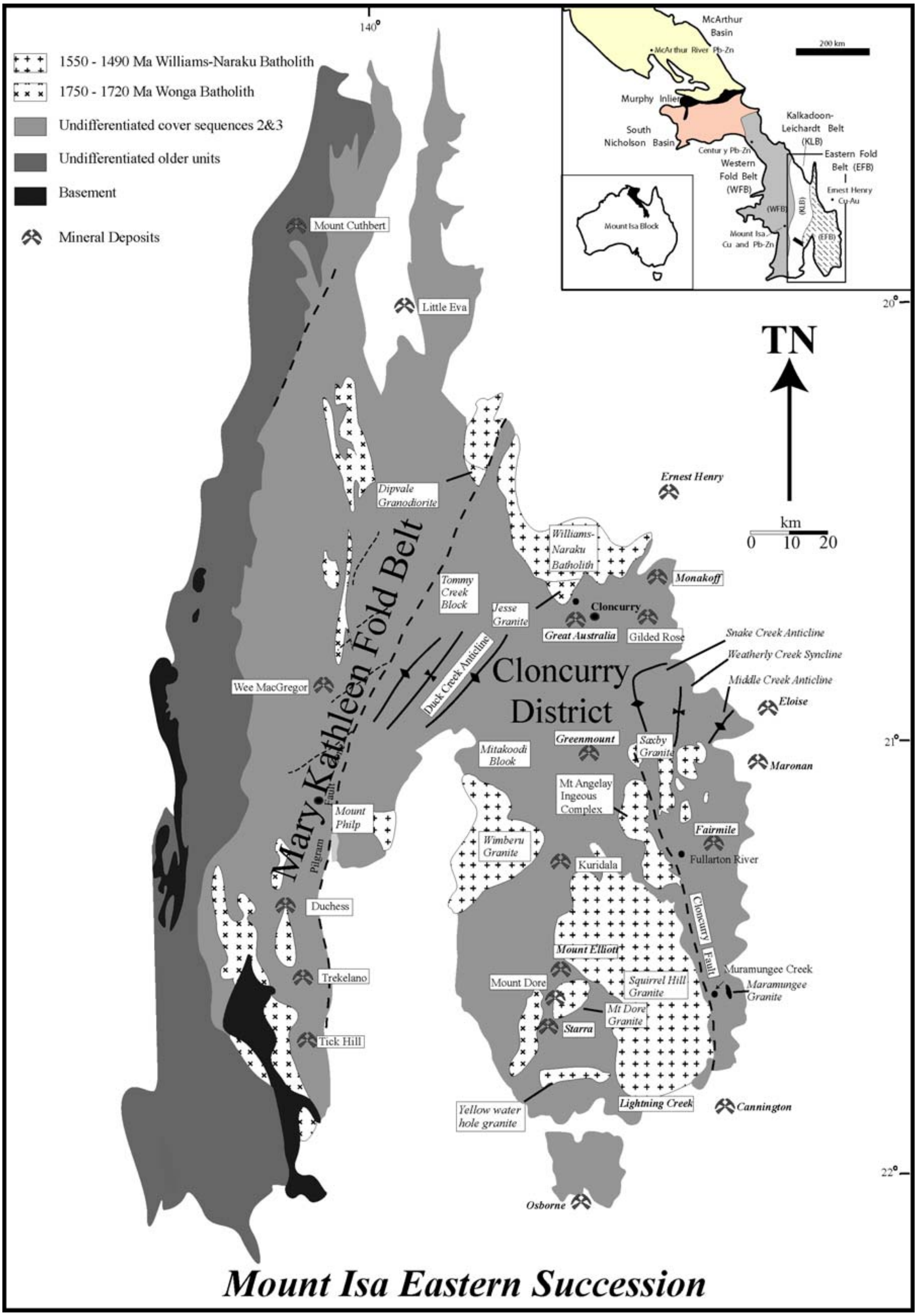


Figure 1. Mineral deposit and tectono-stratigraphic map of the Eastern Succession. (after Williams (1998).

Many previous workers have concluded that the sources of metal, sulphur, and fluids for IOCG mineralisation in this district were predominantly derived from the ~1550-1490Ma Williams-Naraku Batholith of felsic to intermediate intrusive rocks (Rotherham, 1997; Wyborn, 1998; Perring et al 2000; Williams and Pollard, 2003; Mark et al, 2005. Williams (1993) and Oliver et al. (2004), while favouring magmatic fluid sources, also note that these fluids may have leached substantial mass from the surrounding country rocks prior to ore deposition. However, a number of key observations of the ore-forming systems highlight significant problems with a unified model for ore genesis in which the Williams-Naraku Batholith was instrumental. Firstly, molybdenite sampled from the ore association at the Osborne deposit has a Re-Os age of 1595 ± 6Ma (Gauthier et al., 2001), and albitization surrounding syn- to post-ore pegmatites has associated titanite with a U-Pb age of 1595Ma (Rubenach et al, 2001). These ages for mineralisation and cooling pre-date the Williams Batholith by ~60 My. There are no felsic batholiths known in the Osborne area of this age - the pegmatites appear to be derived by local partial melting of metasediments (Rubenach, 2005).

Secondly, Perring et al. (2000) examined fluid inclusions from the Lightning Creek ironstone prospect, a large tonnage (> 1 billion tonnes) magnetite body inferred to be generated by magmatic-hydrothermal processes late during the fractionation of a body of the Williams Batholith. They found abundant barium and copper in the fluid inclusions, yet there are no barite- or copper-bearing sulphides in the prospect. They concluded that hydrothermal fluids derived from the Williams batholith were sulphur-poor or absent, or the fluids were too hot. Given the low solubility of barite over most geological conditions, their model did not explain the source of sulphur for the ~1530Ma IOCG deposits. To make the matter more complicated, sulphur isotopic studies for ore systems in the Eastern Succession revealed a dominantly magmatic origin for sulphur (Davidson and Dixon, 1992; Rotherham et al, 1998).

Finally, at the Osborne, Selwyn and Eloise deposits, observations have been made of primary sulphide and magnetite mineralisation folded or deformed by the ~1600-1580Ma peak-metamorphic shortening event, suggesting that at least some ore components were present at these deposits before or during metamorphism. In the nearby Mary Kathleen Fold Belt (Fig. 1), there is an apparent absence of Williams-Naraku Batholith age intrusions. This belt displays comparable styles of albite and Na-Ca alteration to the Cloncurry area (Oliver, 1995), and includes alteration dated at 1550 to 1527 Ma (Oliver et al., 2004), raising the possibility that not all fluids of Williams-Naraku age were directly derived from them. The Mary Kathleen Fold Belt also contains a significant IOCG resource (Trekelano) and the Tick Hill Au deposit, suggesting either non-Williams ore components were contributed to these deposits, or the deposits were not formed at Williams time.

Thus, despite a proliferation of Ar-Ar ages in the range 1540 to 1490 Ma for Eastern Succession IOCGs (Perkins & Wyborn, 1998), dating of pre-ore albitization titanites at 1550 to 1525 Ma (Oliver et al., 2004), and abundant evidence for post-metamorphic sulphides and related alteration, observations of deformed ores and older U-Pb and Re-Os ages of many of these deposits point to inherited components. The original understanding of the age of peak metamorphism at the time of many earlier studies was focussed around the 1550 Ma age inferred from the Western Succession and Mary Kathleen orebody (Page, 1983), such that the 1550 to 1490 Ma Williams Batholith was regarded as immediately post-peak metamorphic. Evolving metamorphic-magmatic fluid systems were thus seen as viable (e.g. Baker et al., 2001). More recent recognition of earlier metamorphism, peaking at 1600-1580 Ma with D_2 deformation (Giles and Nutman, 2002; Hand and Rubatto, 2002), requires a reinterpretation of earlier workers' paragenetic stages.

Mafic rocks and magmas have recently been implicated in the genesis of IOCG and other mineralisation types, globally. In a study of the mineralising fluids for the giant Olympic Dam deposit in South Australia, Johnson and McCulloch (1995) concluded that mafic/ultramafic rocks were crucial to the genesis of the deposit. Based on a ≥13% contribution of rare earth elements from mantle derived material to the ore, the model inferred a minimum contribution of 50% of the Cu in the deposit from mafic material, either via leaching of pre-existing mafic rock, or through direct exsolution from the magma. Contrasting stable isotopic signatures of magnetite and hematite suggested that ore deposition involved two distinct fluids. However, the isotopic data did not allow the distinction between a model involving ore deposition by fluid mixing (e.g. Oreskes and Einaudi, 1992), or a model involving temporally discrete overprinting of magnetite by hematite + Cu-sulphides (Gow et al., 1994).

The 1686/1660Ma magmatic event(s) of voluminous intrusive and extrusive mafic magmatism, within the Eastern Succeession, was in response to extension caused by back arc basinal rifting (Chapter 1), a low pressure environment in which it may have been possible for direct exsolution of mafic derived metal and sulphur bearing fluids to be exsolved, in a similar fashion to mineralising processes found in other back arc settings, the East Manus Basin for example (Yang and Scott, 2002; Sun et al, 2004), or the Miocene-Pliocene Cu deposits of central Chile (Stern and Skewes, 2002). The next event considered here was the 1600Ma-1580Ma peak-metamorphic event in which there may have been potential for metamorphic fluids to sequester sulphide material from pre-emplaced mafic rocks, in a similar way to that suggested for the giant Mount Isa deposit in the Mount Isa Western Succession (Hannan et al, 1993; Heinrich et al, 1995) and for mineral deposits within the McArthur Basin, Northern Territory (Cooke et al, 1998). Finally, consideration is given to the ability of mafic magmas to contribute sulphur and metals, either directly or indirectly, in the widespread 1530Ma Williams-Naraku felsic-intermediate magmatic event in which exchange of sulphur and metals between intermingled mafic and felsic magmas may have resulted in the hydrothermal expulsion of those components, as suggested for the Bingham Canyon Cu-Au deposit (Hattori and Keith, 2001; Maughan et al, 2002).

In consideration of these observations, where the Williams-Naraku batholith hydrothermal fluids do not fully explain the sources of metals, sulphur and mineralising fluids, it is necessary to search for other sources of metals and sulphur for Eastern Succession deposits.

In light of these recent findings and the spatial relationship of mafic rocks and high density sub-surface material to IOCG mineralisation (Butera and Blenkinsop, 2004; Butera, 2004; Mustard et al 2005; see Chapter 4), we aim to test the following hypotheses of contribution of S and metals from mafic material to the overall IOCG sulphide accumulations within the Eastern Succession:

1) Were metals and sulphur bearing fluids exsolved from mafic magmas at different times?
2) Did metamorphic leaching of earlier mafic rocks contribute to the ores?
3) Did hydrothermal leaching of metamorphic rocks by Williams-aged fluids contribute to the ores? and
4) Did mingling and mixing of c. 1530 Ma mafic and felsic magmas promote metal and sulphur transfer into the ~1530Ma hydrothermal system.

Mafic Rocks of the Eastern Succession

The Eastern Succession refers to the eastern most portion of the Mount Isa Inlier, and is subdivided into the Mary Kathleen Fold Belt, including the Wonga Belt, in the west, and the Cloncurry district in the east. Major stratigraphic and magmatic sequences of the Eastern Succession include the calc-silicate and pelitic rocks, marbles and volcanic rocks of the 1760Ma-1730Ma Mary Kathleen Group (which includes the Corella Formation), and the 1690Ma-1620Ma Soldiers Cap Group of siliciclastic metasedimentary and mafic to intermediate extrusive rocks. Intrusive rocks include the early Wonga Granite and associated mafic rocks (1760Ma – 1730Ma), gabbros and dolerites emplaced early in the history of the Soldiers Cap Group deposition, and the Williams-Naraku batholith of felsic-mafic rocks emplaced ~1550-1490Ma.

The oldest mafic rocks exposed in the Eastern Succession are those of the ~1760Ma Marraba Volcanics (~1760Ma – 1740Ma), and the 1740Ma Lunch Creek Gabbro. These magmas may have been related to the ~1780Ma-1740Ma Wonga extensional event, in which voluminous bimodal magmatism occurred in and above the Wonga Belt within the Mary Kathleen Fold Belt (Holcombe et al, 1991; Oliver et al, 1991). The next major mafic magmatic event is constrained by a U-Pb SHRIMP age of 1686±8 Ma for tonalite intruding the Llewellyn Creek Formation of the Soldiers Cap Group in the Snake Creek Anticline, toward the eastern margin of the Eastern Succession (Rubenach, 2005). Tonalite sheets, lenses and small bodies are abundant within the sill-like intrusive complex. The tonalites generally preserve igneous textures, whereas the related mafic rocks, which include gabbro, layered gabbro and dolerite, have been largely converted to foliated hornblende-plagioclase amphibolites, only locally preserving igneous textures. Mingling/mixing relationships between tonalite and gabbro indicate coeval emplacement, so that the above age is inferred to be the age of intrusion of the mafic rocks.

SHRIMP zircon ages of 1658±8 and 1654±4 Ma have been determined for the Toole Creek Volcanics and Mt Norna Quartzite respectively, of the Soldiers Cap Formation (Page & Sun, 1998). Both these units overlie the Llewellyn Creek Formation which is intruded by the 1686 Ma tonalites, implying that there is a significant depositional hiatus between them. Similar ages for the nearby Ernest Henry Diorite (1660 ±13Ma, 1658 ±10Ma, 1657±7Ma; Pollard and McNaughton, 1997; Page and Sun, 1998), and an albitized granite near Cloncurry (1679±7; Pollard & McNaughton, 1997), all indicate significant igneous activity during deposition of the Soldiers Cap Formation. Currently available geochronological data precludes us from determining whether the ~1686Ma magmas and those of the ~1660Ma Toole Creek Volcanics were discrete events, or part of a single ~30my protracted igneous event. The bulk of the remaining mafic units in the south and central parts of the Eastern Succession also appear to be related to either the 1686Ma or 1660Ma magmatic events, based on similarities in geochemistry, magnetic response and stratigraphic position. The intrusion of these mafic dykes into the upper Mount Norna Quartzite is shown by Hatton and Davidson (2004) to be contemporaneous with the diagenesis of the sediments.

Other mafic magmatic episodes within the Eastern Succession have been interpreted to have occurred at ~1600-1580Ma and ~1530Ma. The 1600-1580Ma generation of mafic rocks are constrained to the axial plane of the Snake Creek Anticline, and are present as thin doleritic dykes, generally less than 100m in width.

Their syn- peak metamorphic (D_2) age are constrained by their cross-cutting nature of earlier mafics folded at this time. They are axial planar to these folds.

The final Mid-Proterozoic mafic magmatic event evident in the exposed portions of the Eastern Succession occurred at ~1530Ma. These are unfolitated gabbroic bodies that are intimately associated (mixed and mingled) with the ~1530-1500Ma Williams-Naraku Batholith of intermediate to felsic magmatic rocks (Page and Sun, 1998; Wyborn et al, 1998; Perring et al., 2000; Pollard et al., 1998; Mark et al, 2005; Rubenach, 2005).

IOCG Mineralisation, Eastern Succession

In order to better understand the subtle differences in Cu-Au mineralization styles, and to evaluate ore genesis processes and models, the IOCG mineralisation in the Eastern Succession has previously been catergorised into four broad groups, based on their general physio-chemical characteristics and associations with Fe-oxide rich rocks (Carew, 2004): 1) Fe oxide-rich rocks where sulphides are minor to absent; 2) Cu-Au mineralisation overprints earlier Fe oxide-rich rocks; 3) Cu-Au mineralisation and Fe oxide formation are synchronous; and 4) Cu-Au mineralisation is not spatially or temporally associated with significant Fe oxide.

Fe oxide-rich rocks (Category 1) with little or no Cu-Au mineralisation are common throughout the Eastern Succession. Examples of sedimentary Fe oxide-rich rocks occur (e.g. Monakoff and Fairmile; Davidson and Davis, 1997; Davidson, 1998), although some examples that have been proposed are controversial (Starra; Rotherham, 1997). Many Fe oxide-rich rocks in the EFB are interpreted to be metasomatic (Hitzman et al., 1992; Williams, 1994; Rotherham et al., 1998; Oliver et al., 2004). They typically occur as lenticular or vertical bodies associated with dilation within, or at intersections between, fault or shear zones (Hitzman et al., 1992; Baker & Laing, 1998; Laing, 1998; Marshall & Oliver, 2001).

The second category refers to pre-existing Fe oxide-rich rocks that are apparently overprinted by a later, not necessarily related, Cu-Au mineralising event. Deposits in this category potentially include Starra (Rotherham, 1997) and Osborne (Adshead, 1995). Olympic Dam and Emmie Bluff deposits in the Gawler Craton appear to show similar relationships (Oreskes and Einaudi, 1992; Gow et al., 1994). One of the most significant reported examples of this style of mineralisation in the Eastern Succession is the Starra deposit, which is unique in in that it has significantly higher Au:Cu ratios than the other deposits (Williams and Pollard, 2003). Fe oxide-rich rocks at Starra form two prominent ridges that are situated in a major N-S striking and steeply dipping shear active late in the deformational history of the region (Adshead-Bell, 1998). Economic Cu-Au mineralisation is confined to only one of these ridges and is referred to as the Western Ironstone. However, Au-only and Cu-only equivalents also exist and in some cases are not associated with Fe-oxides (Rotherham, 1997). Two paragenetic stages pre-dating Cu-Au mineralisation are recognised and include early widespread Na-Ca alteration (albite, quartz, scapolite, actinolite), and localised K-Fe alteration (biotite, magnetite, hematite, quartz, pyrite), with the latter responsible for the formation of the Western Ironstones. Typical mineral assemblages associated with Au-Cu mineralisation include pyrite, gold, chalcopyrite, barite, hematite, calcite, anhydrite and magnetite (Rotherham, 1997). The Au-Cu mineralisation has previously been interpreted to have formed via the brecciation and subsequent hematisation of previous magnetite-rich rocks by their interaction with oxidised fluids (Rotherham et al, 1998). The source of Cu, Au and S remains uncertain, although Williams et al (2001) identified highly complex fluid inclusions associated with mineralisation at Starra and speculated that fluid mixing may have contributed to ore genesis, rather than fluid-rock interaction alone. The Osborne deposit most likely represents the other major deposit of this type in the Eastern Succession. The deposit is hosted by Proterozoic metamorphic and igneous rocks. The host rocks are dominated by Na-rich feldspathic psammites and amphibolites, and early Fe oxide-rich rocks. Regional-scale faults are thought to have acted as conduits for the fluids responsible for economic Cu-Au mineralisation, while reverse movement on biotite shears are believed to have provided structural traps for the ore-bearing fluids (Harris, 1997). Mineralisation at Osborne is divided into two discrete domains: the western domain containing two substantial Fe oxide-rich units, and the eastern domain, which is largely devoid of Fe oxide-rich rocks (Adshead, 1995). The ore mineral assemblage at Osborne comprises of massive silica flooding, chalcopyrite, hematite, magnetite and pyrrhotite as well as quartz, apatite, chlorite, talc, magnetite, chalcopyrite and pyrite within magnetite-rich breccia. The assemblages differ between domains and highlight the possible role played by previous Fe oxide-rich rocks in the precipitation of the Cu-Au mineralisation. In particular, Cu-Au mineralisation in the eastern domain contains more reduced associations of pyrrhotite-magnetite ± pyrite compared to the more oxidized hematite-magnetite-pyrite altered Fe oxide-rich rocks of the western domain (Adshead,1995).

Category 3-type IOCG mineralization includes deposits in which Cu-Au and Fe-oxides appear to have precipitated contemporaneously. Deposits of this type include Ernest Henry, the largest Cu-Au deposit in the Mount Isa Block (Ryan, 1998; Mark et al., 2000), and the Mt Elliott deposit (Little, 1997; Drabsch, 1998). The Ernest Henry ore body is predominantly hosted in felsic to intermediate metavolcanic rocks originally composed of fine- to medium-grained plagioclase phenocrysts in a finegrained plagioclase-rich groundmass (Mark et al., 2000). Other rock types found within and adjacent to the Ernest Henry deposit include metasedimentary rocks (calc-silicate rocks and pelitic schists) and metadiorite. The latter occur to the northwest and south of the deposit and have U-Pb titanite crystallisation ages of 1660-1650 Ma (Pollard and McNaughton, 1997). They were metamorphosed to amphibolite facies and contain hornblende, plagioclase, magnetite, quartz and rare K-feldspar (Mark et al., 2000).

Cu-Au mineralization at Ernest Henry was associated with two distinct events. The first, and major, ore-forming event was associated with brecciation, with the matrix largely composed of magnetite, calcite, pyrite, biotite, chalcopyrite, K-feldspar, titanite and quartz. The second event is similar in mineralogy, but is contained in a network of veins that cut the earlier mineralised breccias (Mark et al., 2000).

Cu-Au mineralisation at Mount Elliott is hosted within multiply deformed and extensively skarn-altered metasedimentary rocks and amphibolite of Paleoproterozoic age (Little, 1997, Wang and Williams, 2001). The development of skarn and Cu-Au mineralisation occurred synchronously with movement along NE-dipping brittle reverse faults (Little, 1997, Wang and Williams, 2001). Magnetite is associated with pyrrhotite and chalcopyrite within the amphibolites in the lower zone. In contrast, Cu-Au mineralisation hosted in metasedimentary rocks is typically magnetite poor (Little, 1997; Wang and Williams, 2001).

Category 4-type IOCG mineralization refers to deposits where Cu-Au mineralisation is not closely spatially associated with significant Fe-oxides. These deposits are more typically associated with dominant sulphides (pyrite and pyrrhotite). This style of deposit includes Eloise (Baker, 1998), Mount Dore and Greenmount IOCG deposits (Krcamrov and Stewart, 1998; Laing, 1998). The Eloise Cu-Au deposit is hosted in meta-arkoses, quartz-biotite schist and amphibolite within a dilational structural that has been interpreted as the major conduit for Cu-Au-bearing fluids, in which alteration and mineralisation was synchronous with ductile-brittle deformation. Baker and Laing (1998) suggested that Cu-Au mineralisation was synchronous with the waning stages of the Isan orogeny and emplacement of the Williams and Naraku Batholith (note however these two events have more recently been dated as being ~ 60 m.y. apart). The mineralization is associated with highly strained and altered rocks that form part of the Eloise Shear Zone and are largely composed of chalcopyrite, pyrrhotite, minor magnetite and pyrite (Baker, 1998). Baker (1998) and Carew (2004) postulated that the deposition of pyrrhotite at Eloise instead of iron oxide observed at many of the other IOCG deposits in the district may be a reflection of the composition and redox state of the host rock - carbonaceous shales and other metasedimentary rocks at Eloise may have inhibited the deposition of iron oxides.

Although there is a variation in the association of Cu-Au mineralisation with Fe-oxides, most IOCGs in the Eastern Succession share some common characteristics. They most often occur in dilational sites within shear zones (Adshead, 1995; Rotherham, 1997; Adshead-Bell, 1998; Baker and Laing, 1998; Baker, 1998; Mark et al., 1999; Marshall, 2003). Most deposits record an earlier period of Na-Ca alteration followed by later potassic-iron alteration (Adshead-Bell, 1998; Baker,1998; Mark et al, 1999; Oliver et al, 2004). All deposits are associated with both CO2 and hypersaline fluid inclusions which has been interpreted to represent unmixing of a H2O-CO2-salts fluid (Pollard, 2000) or fluid mixing (Mark et al, 2000; Williams et al., 2001; Oliver et al., 2004). The Cu-Au systems exhibit overlapping calculated $\delta^{18}O$ (+7 to +11 ‰), $\delta^{34}S$ (-3 to +3 ‰) and $\delta^{13}C$ (-10 to -3 ‰) fluid compositions, suggesting a dominant magmatic component diluted by external fluid input and/or variable host rock interaction (Davidson and Dixon, 1992; Adshead, 1995; Twyerould, 1997; Rotherham et al., 1998; Mark and Crookes, 1999; Mark et al., 2000; Baker et al., 2001; Oliver et al., 2004; Marshall et al., 2006). On the other hand, some of the variations in the physico-chemical properties in the deposits have been attributed to change in the composition or oxidation state of source intrusions, changes in the conditions of ore formation (T, P, fO_2, fS_2, fluid salinity, and pH), varying degrees of fluid mixing (Adshead, 1995; Little, 1997; Baker, 1998; Rotherham et al., 1998; Mark et al., 2000; Williams et al., 2001; Oliver et al., 2004) and influence of wall/host rock geochemistry (Williams and Pollard, 2003; Oliver et al, 2004; Williams et al, 2005). The differences in these properties may reflect polyphase ore genesis, and perhaps the involvement of fluids other than those derived from the Williams Batholith. Hence, the study of the potential for mafic rocks and magmas to influence IOCG genesis is warranted.

Geochemistry-petrography

Data

Geochemical data on mafic rocks was gathered in order to attempt to constrain the possible role of the mafic rocks in IOCG genesis. Wholerock XRF and ICP-MS major and trace element data for the 1686Ma, ~1600Ma and ~1530Ma generations of mafic magmas were obtained for this study, analysed at the Advanced Analytical Centre

(James Cook University). S, Cu and Au were analysed on high precision instrumentation at SGS Analabs Townsville (50g Fire-Assay and ICP-OES; S detection limit 50ppm, Cu detection limit 5ppm, Au detection limit 1ppb). These results were combined with complementary data for the 1686Ma and 1660Ma (Toole Creek Volcanics) events from the Geoscience Australia Ozchem Database (www.ga.gov.au), and deposit related amphibolite data from Baker (1996) and Oliver et al (2004). Most pre- 1530 Ma samples were affected by at least partial amphibolitisation during peak metamorphism, and some have been weakly altered by the ~1530Ma hydrothermal event.

1686 Ma mafic rocks of the Snake Creek anticline and Hampden syncline were metamorphosed to low-mid amphibolite facies, and typically contain secondary amphiboles, plagioclase, minor remnant clinopyroxene, rare orthopyroxene and primary hornblende, and minor interstitial quartz, magnetite, ilmenite-titanomagnetite and both primary (chalcopyrite, pyrite, nickeliferous pyrite and rare pyrrhotite)and secondary sulphides (pyrite, chalcopyrite) (Fig.2 a). The syn-metamorphic 1600Ma mafic rocks share the same petrologic characteristics as the earlier generation, but they are more variably metamorphosed and more commonly tend to preserve their igneous textures (Fig. 2b). In rare cases, primary igneous amphiboles are observed (Pers. Comm. M. Rubenach, 2004). The 1530Ma (Fig. 2c) mafic rock samples studied by electron microprobe (Advanced Analytical Center, James Cook University) have undergone high degrees of alteration, and are typically scapolitised, amphibole is Cl-rich, and plagioclase has been mostly sericitised. Minor epidote veining accompanies some secondary magnetite-sulphide precipitation. Unaltered mafic rock samples of the 1660Ma Toole Creek Volcanics in the Weatherly Creek syncline, have been described by Davidson (1998) as containing actinolite, plagioclase and titanite with minor chalcopyrite, pyrite, pyrrhotite and chlorite.

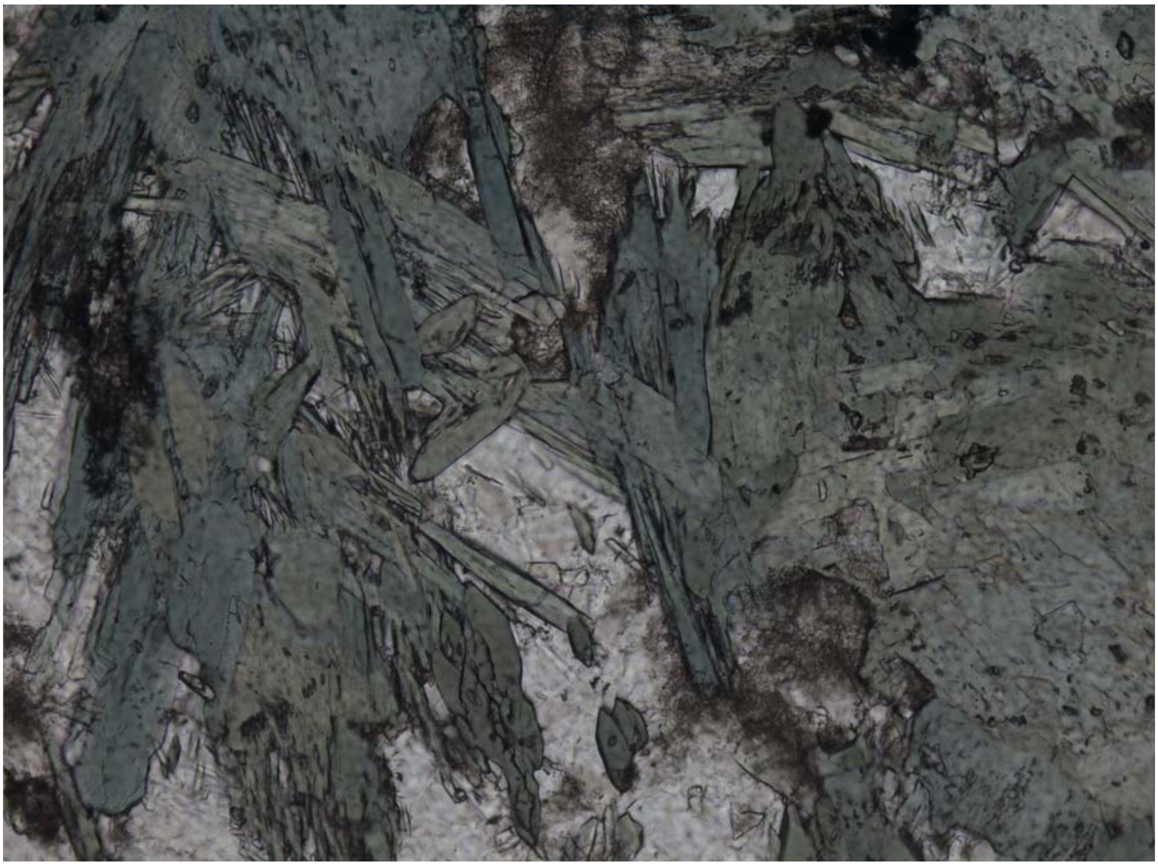


Figure 2a). Typical 1686Ma dolerite (amphibolitised during peak metamorphism at ~1600-1590Ma), Snake Creek Anticline. Actinolite (dark green) and other Cl-amphiboles replacing primary clinopyroxene and overprinting sericitised feldspar, primary magnetite and sulphides (black globules interstitial to minor quartz). Mildly metamorphically recystallised. 10x Leica - Plane Polarised Light. 1.4 x 1.1mm view. Sample M12.

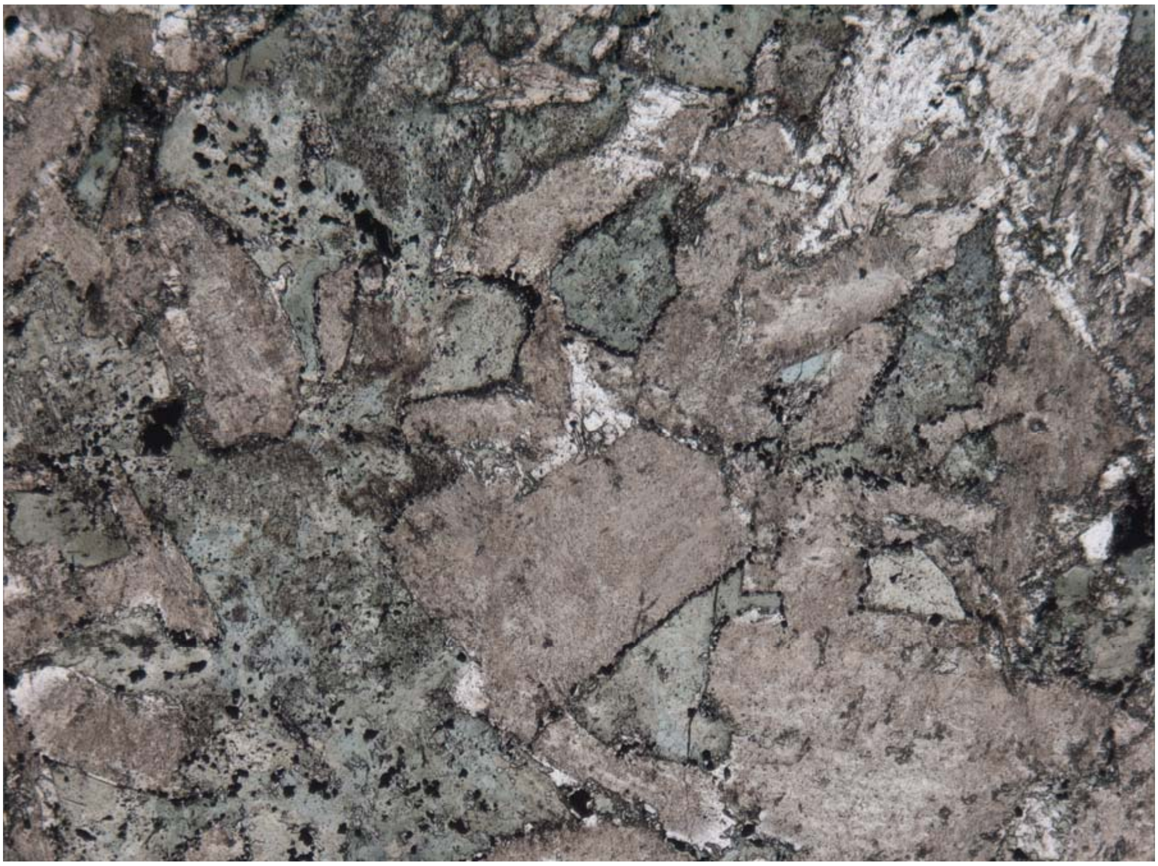


Figure 2b). Typical ~1600Ma dolerite retaining primary igneous texture, Snake Creek Anticline. Mildly sericitied feldspar, minor clinopyroxene partly replaced by amphibole, primary magnetite and sulphides (black globules interstitial to minor quartz and clinopyroxene). 5x Leica - Plane Polarised Light. 2.8 x 2.1mm view. Sample T11.

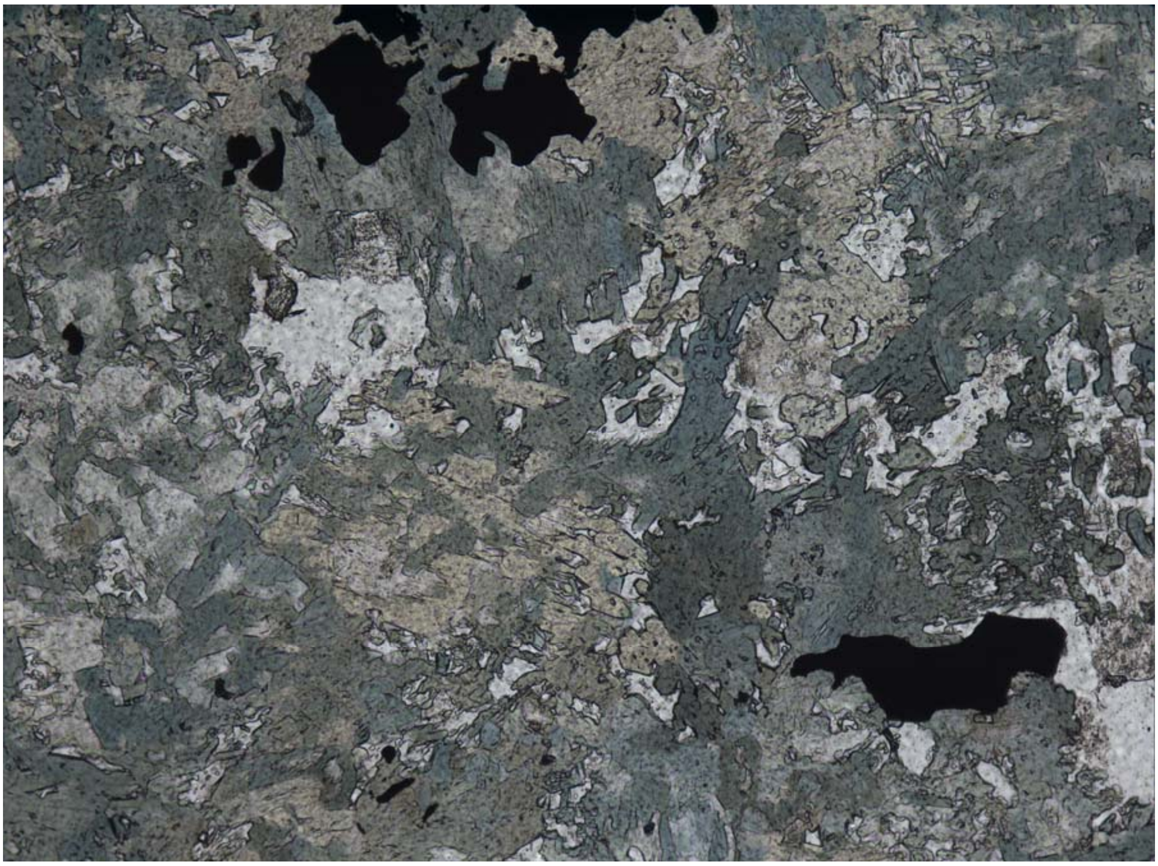


Figure 2c). Typical ~1530Ma gabbro, altered. Cloncurry Fault, west of Snake Creek Anticline. Extensively altered to amphibole-sericited feldspar, minor scapolite, quartz and chlorite, secondary magnetite and pyrite. 5x Leica - Plane Polarised Light. 2.8 x 2.1mm view. Sample T19.

Geochemically, the mafic rocks of different ages are very similar (Chapter 1). They all exhibit a typically strong fractionation, with high total Fe in the range of 11-20wt%, and this has been interpreted as a primary igneous feature (Chapter 1; Williams, 1998b). Alteration is commonly, but not always, indicated by Na_2O > 3.5wt%, and K_2O > 2wt%, and these elements have been used to filter the data in order to minimise erroneous data.

Secondary S and Metal Trends – Metamorphism

Most pre- to syn-metamorphic mafic rocks in the Eastern Succession have undergone textural changes from primary igneous texture, through to partly and fully metamorphically recrystallised textures. The dolerite dykes of the ~1600Ma generation of mafic magmatism present an excellent means of testing the ability of metamorphism of pre- or syn- intrusive mafic rocks to modify their composition, particularly their S and metal contents. In some areas of Snake Creek, the same dyke has both preserved igneous and strongly recrystallised textures. Figure 3 is an isocon plot (Grant, 1986) of an average of five igneous textured and five metamorphically textured samples from the same set of dykes, showing how the geochemistry of these rocks changes during amphibolitisation.

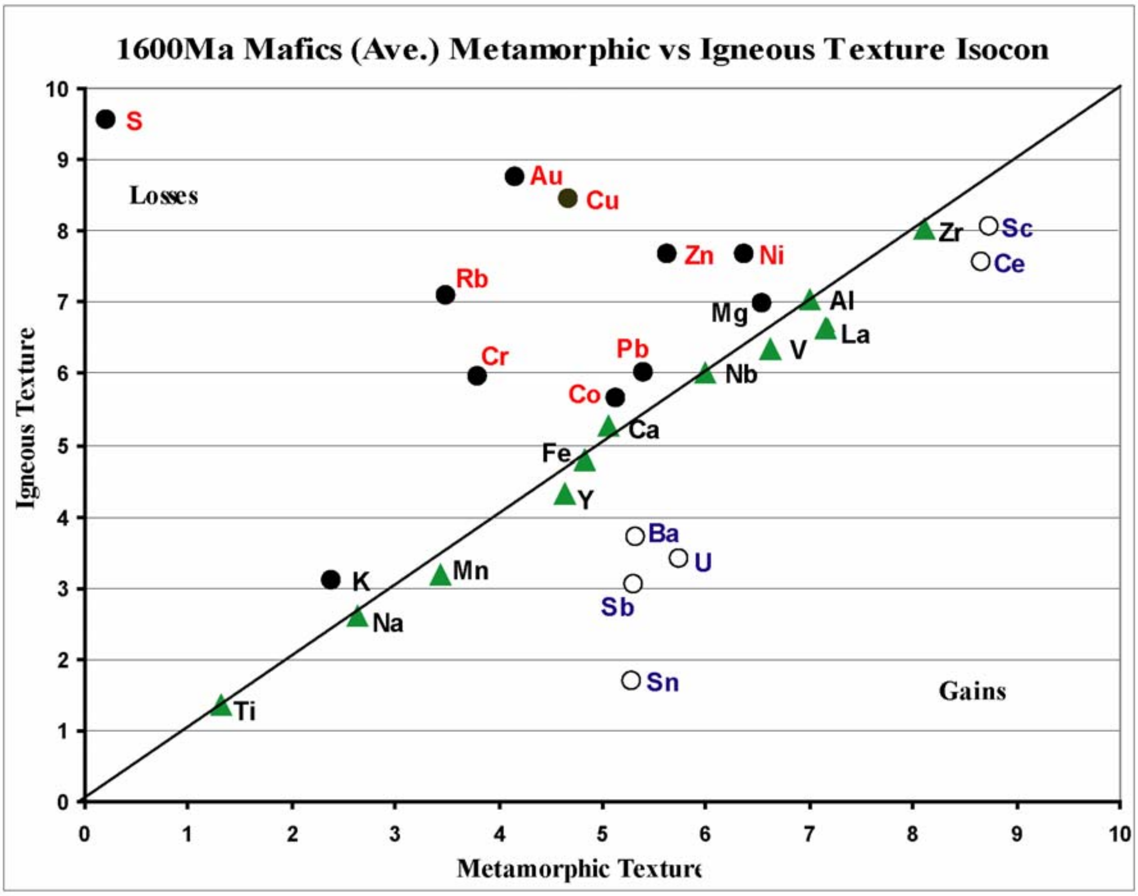


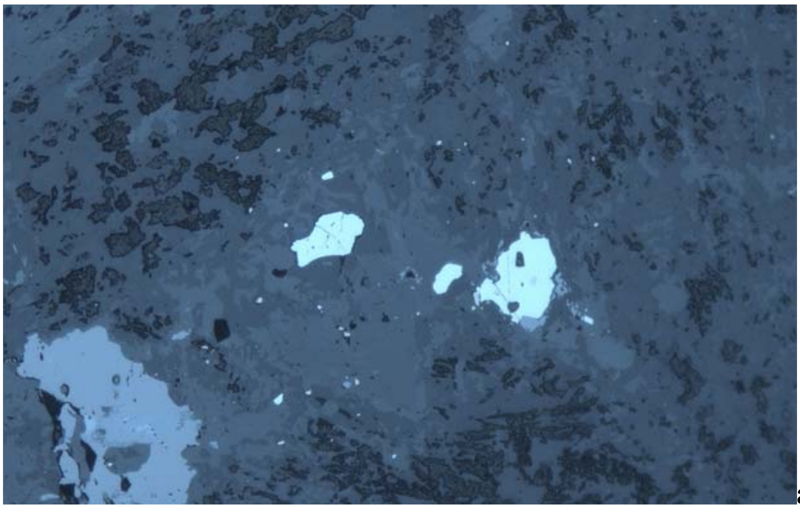
Figure 3. Isocon plot, after Grant (1986), (with individual elements multiplied by factors which distribute them from 0 to 10) of average geochemical analysis for elements of igneous textured vs metamorphic textured dolerites from the Snake Creek Anticline. Dykes inferred to be emplaced near the peak of the Isan Orogeny at ~ 1590 Ma from the Snake Creek Anticline. Average data with 2□ standard deviation compares 6 igneous-textured mafic rocks from the core of the dykes with 7 amphibolitic equivalents from the dyke margins (author's data, Appendix I,II), showing the leaching of S, Cu, Au, Zn, Ni, Cr, Rb and addition of Sn, Sb, U, Ba with the infiltration of metamorphic fluids. Note also the immobility of Fe during metamorphism. The multiplication factors for the various elements are: Ti, Al/2, Fe/3, Mg, Ca/2, Na, 3K, Sc/5, Ba/30, V/50, Cr/20, Mn/500, Co/10, Ni/12, Zn/12, Pb/5, Rb/12, Sr/20, Y/6, Zr/10, Nb, 3Sn, 10Sb, La, Ce/2, 10U, 2500Au, Cu/15, S/150. Standard deviations given in Table 1.

The results demonstrate that Zr, Y, Ti and Fe are immobile, while S, Cu and Au are dramatically reduced in the metamorphosed samples, implying that infiltrating metamorphic fluids were extremely effective in leaching these components from mafic rocks in the Eastern Succession at ~1600Ma-1580Ma. Zn, Ni, Co and Cr were also depleted by this process, while Ba, U, Sn and Sb were added to the mafic rocks.

In a more detailed look at the petrochemistry of the mafic rocks, the S and metal contents of individual samples were compared with their texture (Table 1). The samples were broken down into the following groups: A) those that retained their primary igneous texture, or have not undergone any metamorphic recrystallisation, B) metamorphosed and partly recrystallised, and C) completely metamorphically recrystallised. The results show a consistent decrease in S, Cu and Au with increasing degrees of metamorphic recrystallisation, with an average of 1074 ppm S, 162ppm Cu and 10ppm Au in igneous textured samples, and 12ppm S, 47ppm Cu and 1ppb Au in the metamorphically recrystallised samples. The change in sulphide content of dolerites and their amphibolites are highlighted by photomicrographs in Fig 4 (a,b).

Texture	Sample	S	Cu	Au
	(detection)	50ppm	5ppm	0.001ppm
Igneous	T15	1420	128	b.d
	T14A	1420	137	0.007
	T12B	1530	101	b.d
	M9	1480	166	0.013
	T12A	1370	141	0.007
	M8	430	121	0.008
	T1	945	138	0.017
	T2	1540	201	0.027
	M13	1320	234	0.011
	M1	390	211	0.010
	M2	321	132	0.009
	M14	720	230	0.009
	Average	**1074**	**162**	**0.010**
	s.d.	**483.3**	**45.6**	**0.007**
Metamorphic partly recrystallised	M12	440	101	0.011
	M7	285	92	0.008
	T14B	85	103	b.d.
	T10	110	84	0.007
	T8	950	145	b.d.
	Average	**374**	**105**	**0.007**
	s.d.	**35.6**	**23.6**	**0.005**
Metamorphic recrystallised	T3	60	b.d.	b.d.
	T17	b.d.	152	0.003
	T9	b.d.	31	b.d
	T16	b.d.	24	b.d
	T11	b.d.	26	b.d
	Average	**60**	**47**	**0.001**
		26.8	**60.1**	**0.001**

Table 1. Geochemistry versus petrography: concentration of S, Cu and Au as a function of the degree of metamorphic recystallisation of Mount Isa Eastern Succession mafic rocks. Igneous textured mafic rocks that preserve some primary pyroxene typically contain substantially more S, Cu and Au than their amphibolitised equivalents. Full dataset supplied in Appendix I and Appendix II. In calculations, b.d. levels are treated as 0.0. Visual QA/QC checks were made on data, and a review of internal lab checks were made.


a)

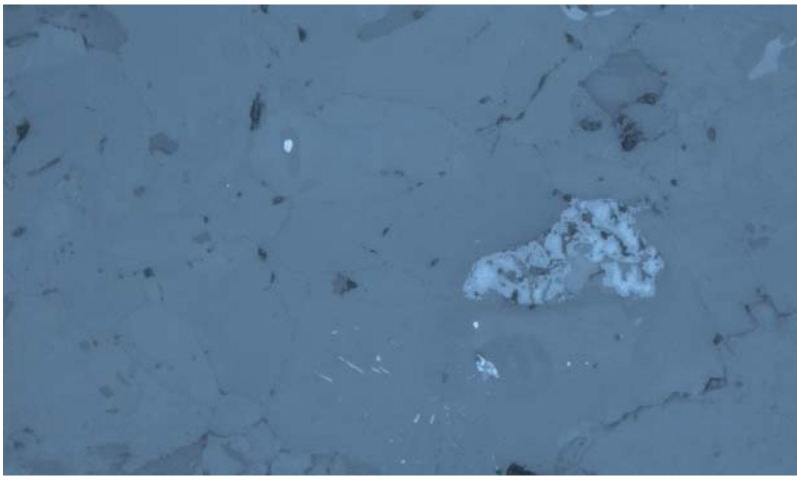

b)

Fig 4 a and b) Reflected light photomicrograph of a dolerite (a) vs amphibolitised equivalent (b) from Snake Creek Anticline showing the presence of abundant Fe-oxides, pyrite and chalcopyrite in the dolerite, and absence of those phases in the amphibolite, suggesting the destruction and leaching of sulphide components during metamorphism. Scale 2.8 x 2.1mm.

Secondary S and Metal Trends – Syn-Williams Batholith (~1530Ma) Alteration

After examination of the geochemistry of Syn-Williams hydrothermal fluid altered mafics, it appears that this alteration episode did not result in clear enrichments or depletions of key metals and sulphur. Scapolite altered samples typically contain both primary (interstitial to primary minerals) and secondary Fe- and Cu- sulphides (associated with Cl-amphiboles, reprecipitated magnetite, and minor hematite), but the petrography does not allow for the determination of whether new sulphide material was introduced, or whether pre-existing sulphides or metals held in primary magnetites and pyroxenes was remobilised locally. Geochemically, there are no significant chemical differences between altered and unaltered samples, suggesting that within the mafic rocks, either the conditions were not suitable for sulphide precipitation contemporaneous with Williams-Naraku batholith hydrothermal fluid flow, or more likely, metals and sulphur were neither introduced, nor depleted by these fluids, but rather the fluids remobilised pre-existing sulphides on a micro to local scale. Amphibolite data from Baker (1996) for a dolerite and a strongly albitised equivalent proximal to the Eloise Cu-Au deposit, however shows no major loss of Cu, but moderate losses of Co, Ni, Zn, Fe and V (Oliver et al, 2004). However, it must be noted that these samples come from within the near mine environment, and the data should not be considered to necessarily reflect typical regional values. Nevertheless, a 7.3wt% reduction of Fe_2O_3T from amphibolites at Eloise, and similar depletions in mafic rocks in other Eastern Succession immediate ore environments may be a significant contributor of Fe to the IOCGs systems (Adshead, 1995; Syna, 2000; Carew, 2004; Oliver et al, 2004).

Primary S and Metal Trends

In the endeavour of trying to relate S and metal contributions to the crust and mafic magmatism, primary fractionation trends for S and metals (Cu, Au) in the 1686Ma and 1660Ma mafic rocks were determined by plotting them against total Fe as Fe_2O_3T (Fig. 5a-c), as total Fe has been established as a primary igneous feature, as mentioned above, immobile during metamorphism and (but not during late alteration) in the Eastern Succession (Williams, 1998b; Foster, 2004, Oliver et al, 2004). Plots for S, Cu and Au versus Fe_2O_3T were compared to Fe_2O_3T versus immobile elements

Y, Zr, TiO_2 (Fig 5d-f) from the 1600Ma generation of mafic rocks. The immobile elements show a consistent increase with fractionation, as would be expected for incompatible elements within a fractionating melt. Pb is variable, reflecting the strong mobility of the element, and shows no systematic trend with respect to fractionation. S, Cu, and Au however, typically show a trend of initial increase in concentration, followed by a subsequent semi-linear decrease, in a manner contrary to the hydrothermally immobile elements. This trend is defined by the general uppermost data points, and does not coincide with the degree of metamorphism or alteration, but it is a primary igneous trend. The effects of metamorphism are interpreted here to decrease the S and metal values at constant Fe_2O_3T, and alteration may also affect the data (minor increase or decrease) with respect to S and metal, but not Fe. Zn, Cr, Co and Ni share similar trends to the metals and sulphur in these samples.

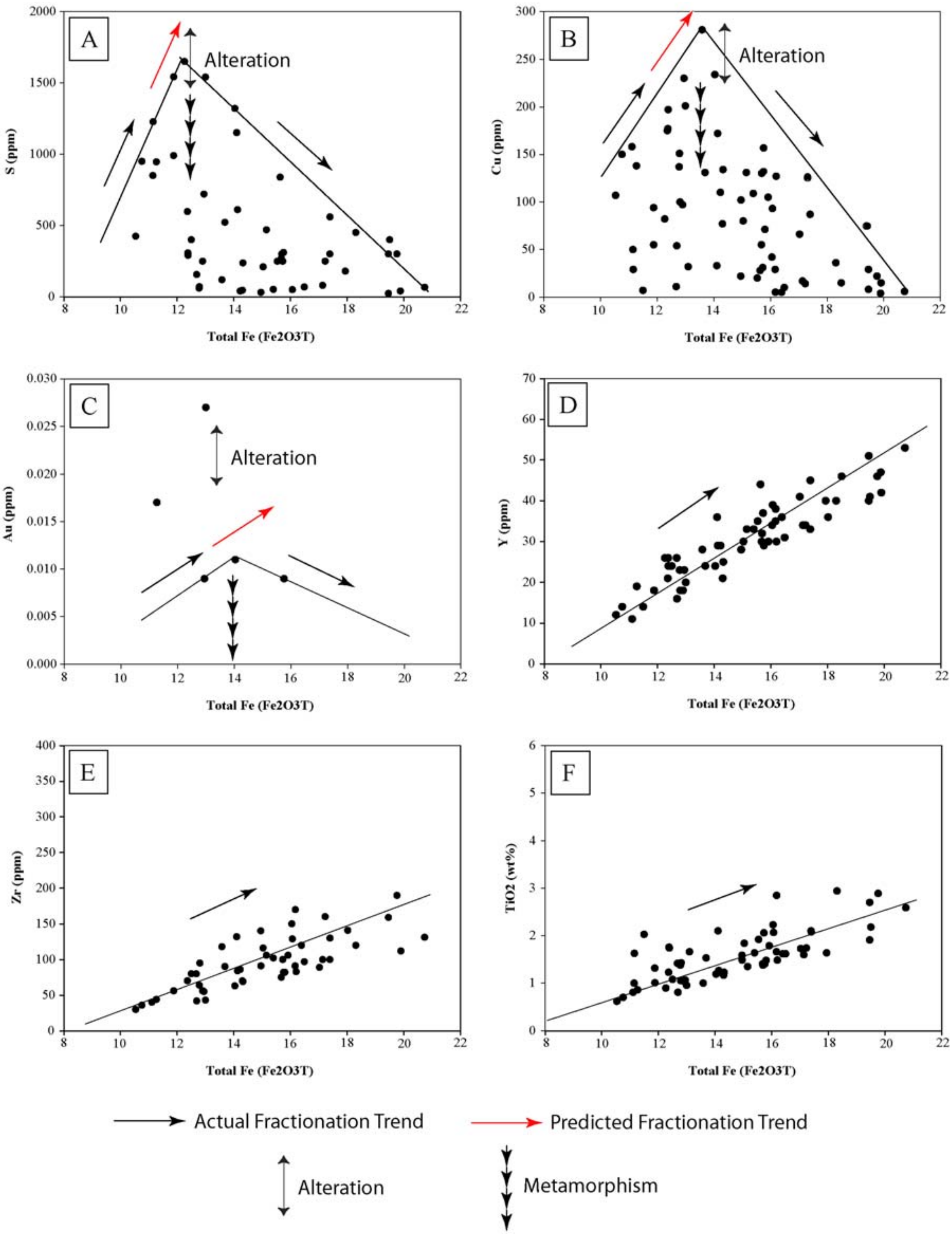


Figure 5a-f. Primary fractionation trends (visually estimated; black lines) for S, Cu, Au, Y, Zr, TiO2 versus total Fe (Fe_2O_3T) for 1686Ma-1660Ma mafic rocks of the Eastern Succession. Black arrows indicate observed fractionation trend, while red arrows indicate predicted trends for the elements in a fractionating tholeiitic melt. Alteration and metamorphic vectors are also shown. S, Cu and Au tend to decrease in abundance after an initial increase, while immobile elements increase throughout the fractionation process. Data collected by author, and also drawn from the Geoscience Australia Ozchem database. Samples for Au from author are igneous textured, non-altered (based on K, Na) samples only.

On the assumption that IOCG deposit related amphibolites and those studied here for the 1686Ma and 1660Ma generation of mafic rocks in the Soldiers Cap Group, are chemically and genetically similar (Chapter 1), it is interesting to note that the average total Fe (Fe2O3T) content for the non-deposit related mafics is approximately 14wt%, while the deposit related amphibolites are typically 15-16wt% Fe_2O_3T (more fractionated) (Baker, 1996; Adshead, 1995; Syna 2000; Wang and Williams, 2001).

Discussion

The initial increase followed by decreases in the concentration of S and metals in the progressively fractionated mafic melt presents an interesting scenario. Decreasing elements in a fractionating tholeiitic melt can be interpreted in a number of ways. Firstly, it may represent leaching of elements with alteration processes that add Fe to the rock, discounted here because we know that Fe is immobile in these rocks. Secondly, orthomagmatic crystallisation of primary sulphides or metal- and sulphur-rich phases dropping out of the fractionating melt into the basal parts of the magma chamber (i.e. cumulates) could account for the observed trends in the upper, cumulate depleted parts of the intrusions. Finally, the expulsion of a S and metal rich fluid phase from the magmatic system could also explain the trends. More clearly, that fractionation towards a S-metal rich fluid might lead to accumulation of these in a fluid phase, that when released upon crystallization would reduce the S and metal content of the residual melt.

The geochemical nature of the 1686Ma and 1660Ma mafic magmas has been used by Butera et al (in prep; Chapter 1) as evidence for fractionation in a back arc basinal environment at pressures between 3 and 5kbar (11-18km depth). Both the thermodynamic modelling of primary hydrous and CO_2 rich Fe-picrite in pMelts Software (Ghiroso, 2002), and the presence of primary igneous amphiboles in the mafic rocks, suggests these mafic rocks were H_2O bearing, providing a means for separation of an H_2O and CO_2 bearing phase. If cumulate sulphides and oxides had descended into the basal parts of the mafic magma chambers in the amount necessary to explain the loss of the elements as observed in remaining mafic rocks, large portions of the mafic magma chambers in the Eastern Succession should contain sulphide or Fe-oxide cumulates. Despite ~200My of repeated thrusting and folding in the region, exposing many structural levels, sulphide cumulates are not observed in any mafic plutons, even in the exposed layered plutons of Snake Creek. Further, experimental work on sulphur content at sulphide saturation in basic magmas by Mavrogenes and O'Neil (1999), would suggest that it would be relatively improbable for such high level crystallising mafic melts (3-5kbar) to ever reach sulphur saturation, and hence precipitation of orthomagmatic sulphides is unlikely at these pressure conditions. Observations of primary magnetite and Fe-, Cu- and Ni-sulphides in the mafic rocks is always interstitial to other minerals, as the latest phase of crystallisation, and we interpret these primary Fe-oxides and sulphides as reflecting the composition of an Fe-S-metal (Cu, Au, Zn, Co, Ni)-H_2O-CO_2 volatile phase that separates from the residual melt at the final stages of mafic rock crystallisation. The more fractionated the magma, and the higher the total Fe content, the more H_2O is available to transport the S and metals out of the system, reflecting the decrease in the elements after an initial consolidation of metals and sulphur in the less fractionated melt. Similar interpretations for S and metal (Ni, Cu, Zn and Fe) exsolution from mafic magmas have been made for the East Manus back-arc basin (Yang and Scott, 2000), and for mafic-intermediate magmas also at East Manus (Sun et al, 2004). Stern and Skewes (2002) discuss the mafic derived fluids contributing to the Cu deposits of Central Chile, and propose a strong association with these fluids and the contribution of metals the deposits. Thus, during the fractionation and crystallisation of mafic magmas in the Eastern Succession, high levels of S, Cu, Au, Zn, Ni and Co were exsolved out of mafic magmas, during the 1686Ma-1660Ma (and perhaps the ~1600Ma event), either into the local roof zones of the magma chambers, or along active extensional faults, such as the strongly mineralised Mount Dore Fault, noted for its abundance of IOCG, Cu and Au mineralisation and proximal mafic rocks.

Later, peak-metamorphic (~1600Ma) fluid infiltration and scavenging of sulphur and metals from mafic rocks has been demonstrated to be of great significance. In the progressive metamorphosis of amphibolitisation of a primary mafic rock (mid-upper greenschist facies) to a completely metamorphically recystallised equivalent (upper amphibolite facies), (presumably from the moderately Fe-enriched magmas that retained the bulk of their S, Cu and Au during fractionation) over 90% of the sulphur is leached along with ~65% of initial copper and 90% of the gold. Because the IOCGs sit in zones of variable metamorphic grade and irregular amphibolitization of mafic rocks across the Eastern Succession, it is difficult to quantify the amount of S, Cu and Au leached from mafic rocks and subsequently contributed to ore systems. However, most deposit related mafic rocks have undergone metamorphism to at least lower amphibolite grade (Adshead, 1995; Baker, 1996; Foster, 2004) and up to upper amphibolite facies at Osborne (Sayab, 2005), and as such it is reasonable to assume that these rocks were leached of significant amounts of ore components. It is not possible to directly measure elemental losses in the near mine environment due to the overprinting and remobilising effects of alteration. In a similar fashion, peak-metamorphic scavenging of metals from the Eastern Creek Volcanics in the Mount Isa Western Succession has been interpreted to have supplied copper to the massive Mount Isa deposit (Hannan et al, 1993; Henrich et al, 1995).

Our favored interpretation, based on a number of critical pieces of evidence and supported by experimental S and metal solubility studies in basalts, favors the exsolution of a S and metal rich volatile phase from crystallising mafic bodies at 3-5kb. The possibility also remains that mafic intrusives (gabbroic bodies), contemporaneous with the Williams-Naraku magmatic event exsolved S and metals in a similar process to that of the 1686Ma/1660Ma events, however further data is needed in order to test this. Figures 6a-c summarizes how mafic magmatism may have been involved in the contribution of S and metals to IOCG deposits.

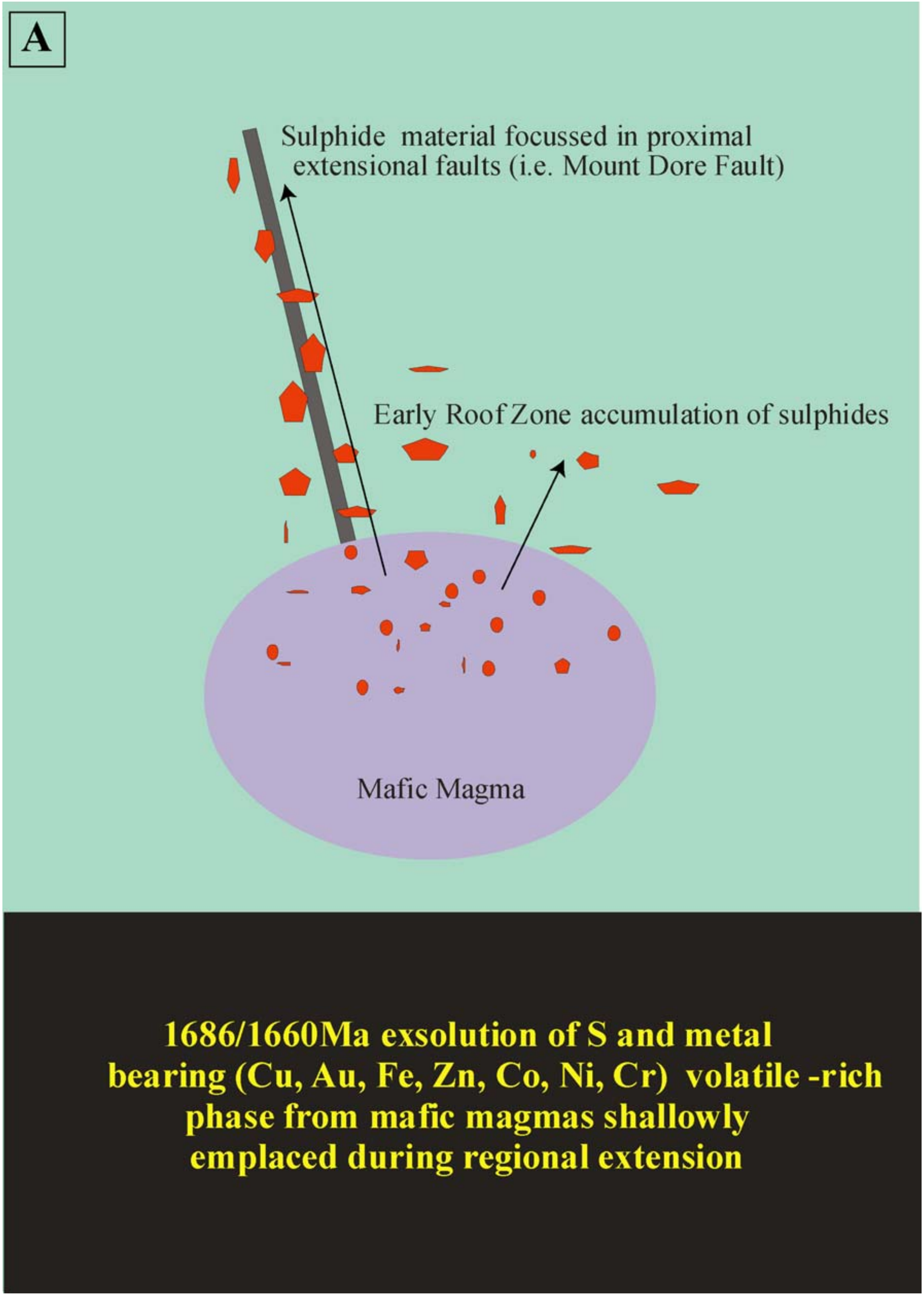


Figure 6a. Schematic interpretation of the process of S and metal exsolution from crystallizing mafic magmas at 1686Ma – 1660Ma, focused into active extensional faults and overlying roof zones.

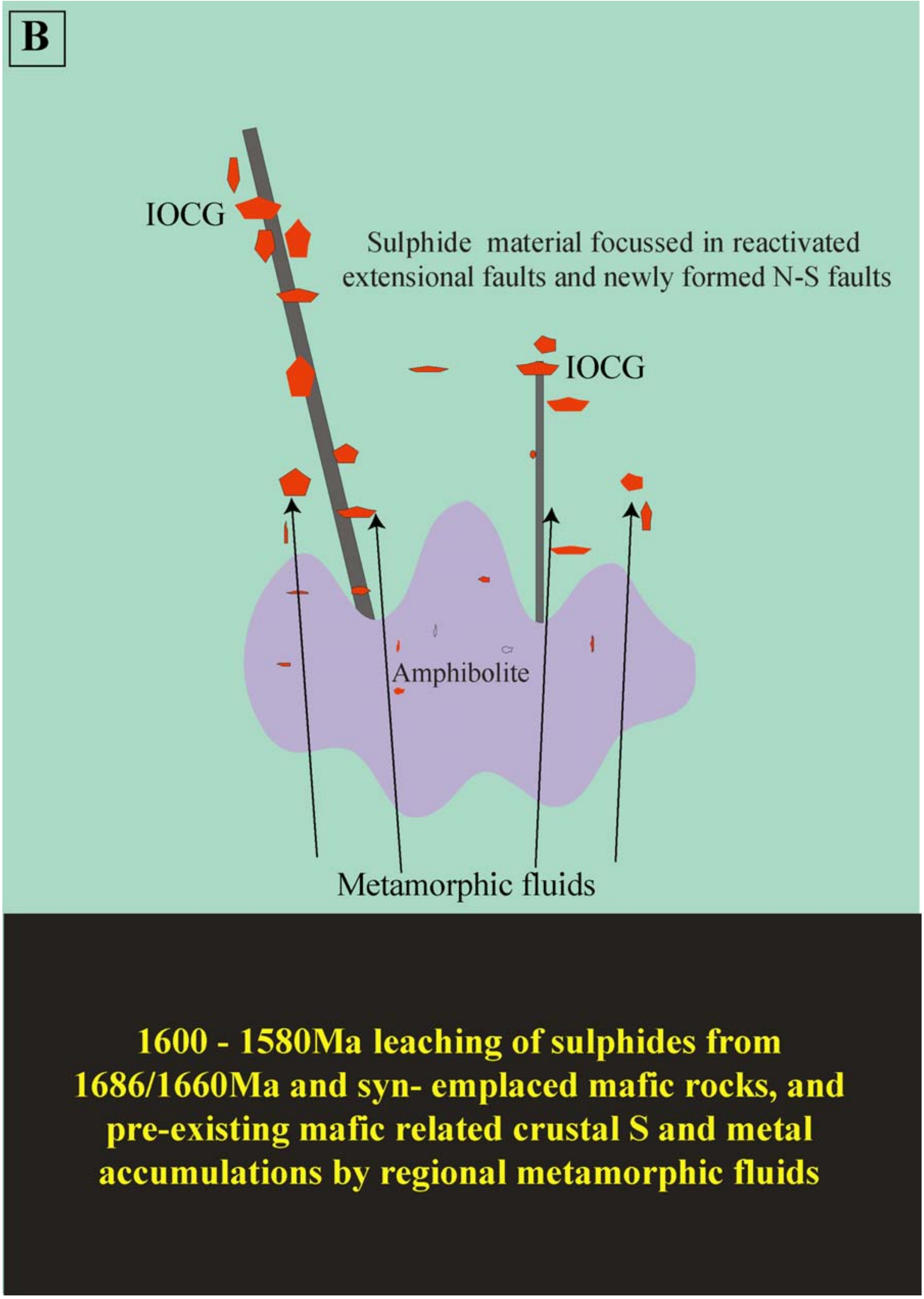


Figure 6b. Schematic interpretation of the process of S and metal leaching pre-emplaced mafic rocks and mafic derived crustal sulphide accumulations during Isan peak-metamorphism at 1600-1580Ma.

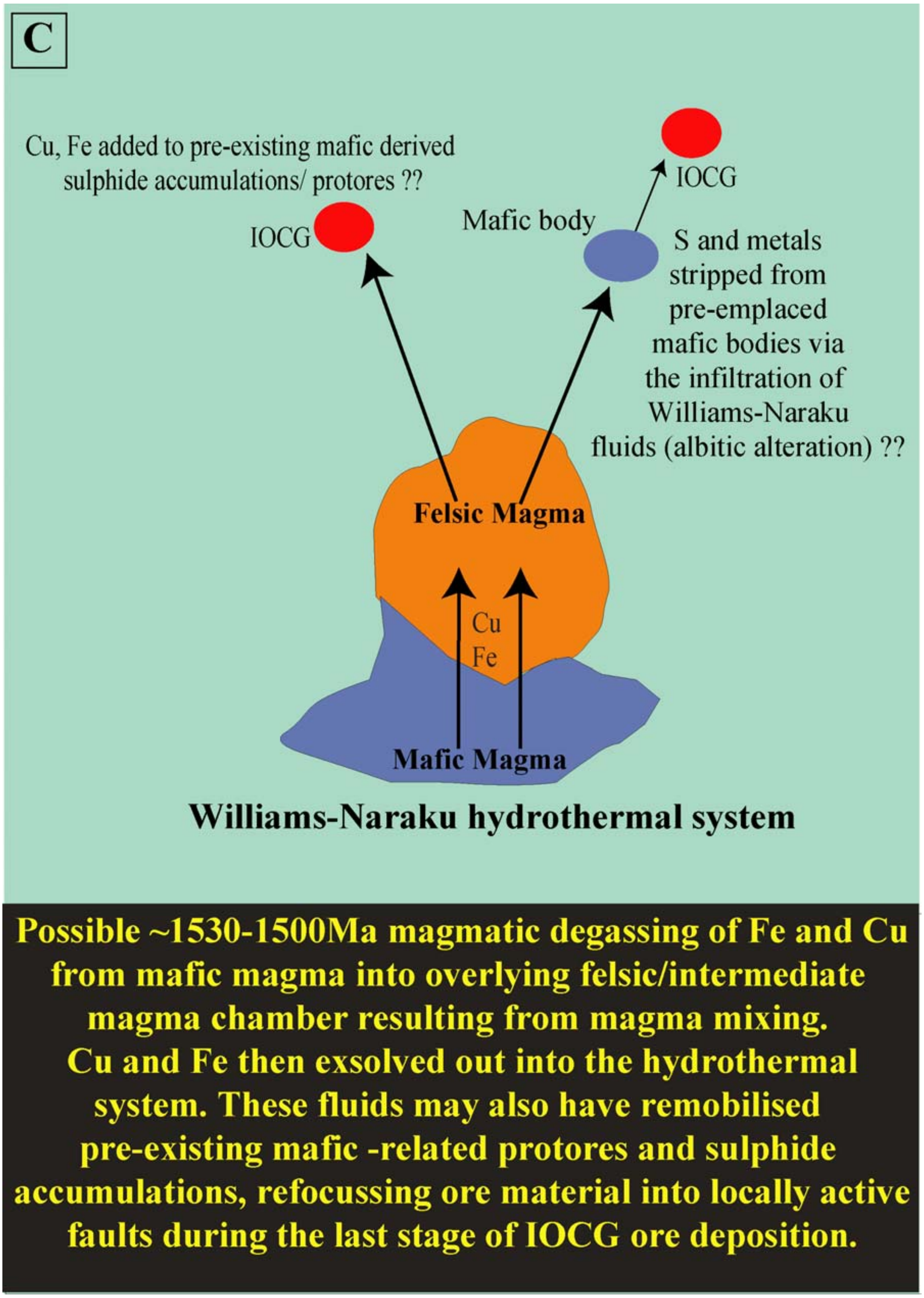


Figure 6c. Schematic interpretation of the process of Cu and Fe transfer between mixed mafic-felsic melts, and subsequent addition to pre-existing crustal sulphide accumulations, and potential albitic alteration of pre-emplaced mafic bodies as a source S and metal for IOCG ore.

Conclusions

After detailed petrographic and geochemical work on the mafic rocks of the Mount Isa Eastern Succession, it is evident that they could have played a critical role in supplying sulphur and metals to IOCG. At 1686Ma/1660Ma, metal and sulphur accumulations in the upper crust may have been deposited via the exsolution of a metal-volatile rich phase directly from crystallizing mafic magmas. These concentrations were potentially focussed proximal to the mafic rocks, possibly in large, early extensional fault systems such as the Mt. Dore Fault Zone, or in disseminations above 1686 magma chambers. 1600Ma to 1580Ma peak-metamorphism (upper greenschist to upper amphibolite grade) played a key role in scavenging sulphur and metals both from pre-(1686/1660Ma) and syn-(1600-1580Ma) emplaced mafic rocks, and may also have remobilised pre-existing crustal accumulations from the earlier 1686/1660Ma mafic rocks, leading to the formation of early ore deposits. Oxidised hydrothermal brines and albitic fluids associated with the 1530Ma felsic-mafic mixed and mingled Williams-Naraku Batholith may have leached further metals, and potentially added more copper to the system directly, but probably did not directly contribute sulphur. These fluids and the associated structural regime at 1530-1500Ma provided the final spatial controls, locally, on ore genesis.

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CHAPTER 3

A protracted multi-staged model for Fe oxide-Cu-Au mineralisation, Mount Isa Eastern Succession, NW Queensland.

(A reworked version of this Chapter with significant contributions by Nick Oliver was published in Precambrian Research – That paper is included as Appendix III of this thesis.

Chapter 3: Butera 80%, Oliver 15%, Nortje 5%; Precambrian Reseach Paper: Oliver 50%, Butera 45%, Others 5%)

A protracted multi-staged model for Fe oxide-Cu-Au mineralisation, Mount Isa Eastern Succession, NW Queensland.

Butera, K.M., Oliver, N.H.S. and Nortje, G.S.

Abstract

Protracted metal and sulphur contributions to the Mount Isa Eastern Succession Iron oxide-Cu-Au (IOCG) province occurred primarily as a consequence of long-lived fluid and melt fluxes from the base of the crust, stimulated by initial back-arc emplacement of voluminous mafic magmas. The concentration of sulphur, iron, copper and gold into the presently observed mineral deposits involved a significant component of remobilisation and reworking of early initial enrichments (pre- to syn-Isan Orogeny) by later fluids (syn- to post-Isan and syn-Williams/Naraku Batholith). Osborne (eastern domain) and Eloise-type ores formed or were strongly remobilized at c. 1600 Ma by reduced, mafic-derived fluids, whereas oxidised brines released by the Williams/Naraku granitoids overprinted magnetite ± sulphides at Osborne (western domain) and Starra to produce younger (c. 1530 Ma) hematite-chalcopyrite associations. CO_2-rich, potentially mantle-derived fluids may have periodically pulsed through the system, manifest now as pyrrhotite-stable carbonate veins and pods. Exploration for Ernest Henry and Starra style deposits should focus on recognition of oxidised corridors in relation to mafic- proximal and structurally- defined targets, However, the possibility remains that large, early mafic rock related Cu-Au ± (Fe, Co, Ni, Zn) deposits are preserved distal to the oxidising effects of the Williams-Naraku hydrothermal system, and may also present exploration opportunities.

Keywords: Cloncurry, iron-oxide-Cu-Au, mafics, alteration, mineralization

Introduction

Genetic models developed in recent years for IOCG deposits of the Eastern Succession have focussed attention mostly on the role of volatile phase separation from the Williams-Naraku Batholiths as the most likely source of metals (Rotherham et al, 1998; Perring et al, 2000; Pollard et al, 2001). This concept has not particularly helped explorers because of the apparent distal relationship between the intrusions and known ore deposits. Recent work (Chapter 2) has identified a more protracted history of contribution of metals and sulphur, and a spatial distribution implicating, in particular, faults and mafic rocks (Butera et al, 2005; Mustard et al., 2005; Ford et al, 2005; McLellan & Oliver, 2005). These new ideas are developed here, including also consideration of the tectonic evolution that hosted to the protracted metals contribution. An attempt is also made to develop a more complete model that incorporates previous work on the Williams-Naraku batholith as well as the new concepts.

Several observations raise questions about models that focus on syn-1530 Ma and Williams Batholith-dominated IOCG development:

1. The Mary Kathleen Fold Belt (MKFB) lacks Williams-age intrusions, despite comparable styles, if not extent, of albite alteration to the Cloncurry District, supposedly mostly related to the Williams-Naraku batholiths (Williams, 1998; Oliver et al., 2004). The MKFB also contains a significant IOCG resource (Trekelano).

2. There is a notable convergence of stable isotopic signatures of alteration systems of all ages (from 1740 to 1500 Ma) upon mantle-like values, with outliers clearly related to admixture with Corella marine carbonates, or Soldiers Cap black shales (Oliver et al., 1993; Oliver et al., 1994; deJong &Williams, 1995; Oliver, 1995; Rotherham et al., 1998; Mark et al., 2000; Baker et al., 2001; Marshall, 2003; Oliver et al., 2004; Marshall and Oliver, 2006). The convergence cannot be related only to the influence of Williams-age magmatic fluids because it includes abundant pre-1530 Ma veins and alteration (Figure 1).
3. There is metallogenic similarity of IOCG deposits apparently formed at different times, i.e. Osborne at pre- or syn-1600-1590 Ma and Ernest Henry and Mt Elliott at 1530 Ma, with the latter being coeval with Williams-Naraku Batholiths (Williams, 1998; Rubenach et al., 2001; Mark et al., 2006b)
4. Fluid inclusions from the deposits and regional vein systems show high salinity and variable Br/Cl ratios of fluid inclusion populations throughout the protracted hydrothermal history, implying that the Williams-Naraku system was not the only contributor to the unusual salinities, and that recycling of evaporite (Corella Fm) salt may have occurred several times.
5. Williams (1998) noted a strong mafic minor element association for many of the deposits, including enriched Ni, Co, V and Mn. Mingling and mixing of mafic magmas with the Williams-Naraku suite prior to or synchronous with fluid exsolution at 1530 Ma may explain the contribution of some of these elements to the IOCGs, but the same enrichments are apparent at deposits which have a pre-Williams age (i.e. Osborne).

6. The sulphur-undersaturated fluids of the Williams-Naraku batholith (Perring et al, 2000) presents a most perplexing question as to the source of sulphur and some metals for the deposits. Other fluid sources, or pre-Williams age sulphide accumulations or protores are needed to explain ore deposition (Chapter 3).
7. There is a need to explain the predominantly magmatic (or mantle) S isotopic signatures of both the early (Osborne) and late (Ernest Henry) IOCG ore (Mark et al., 2006b), even though only the latter are thought to have formed at the same time as the Williams Batholith.

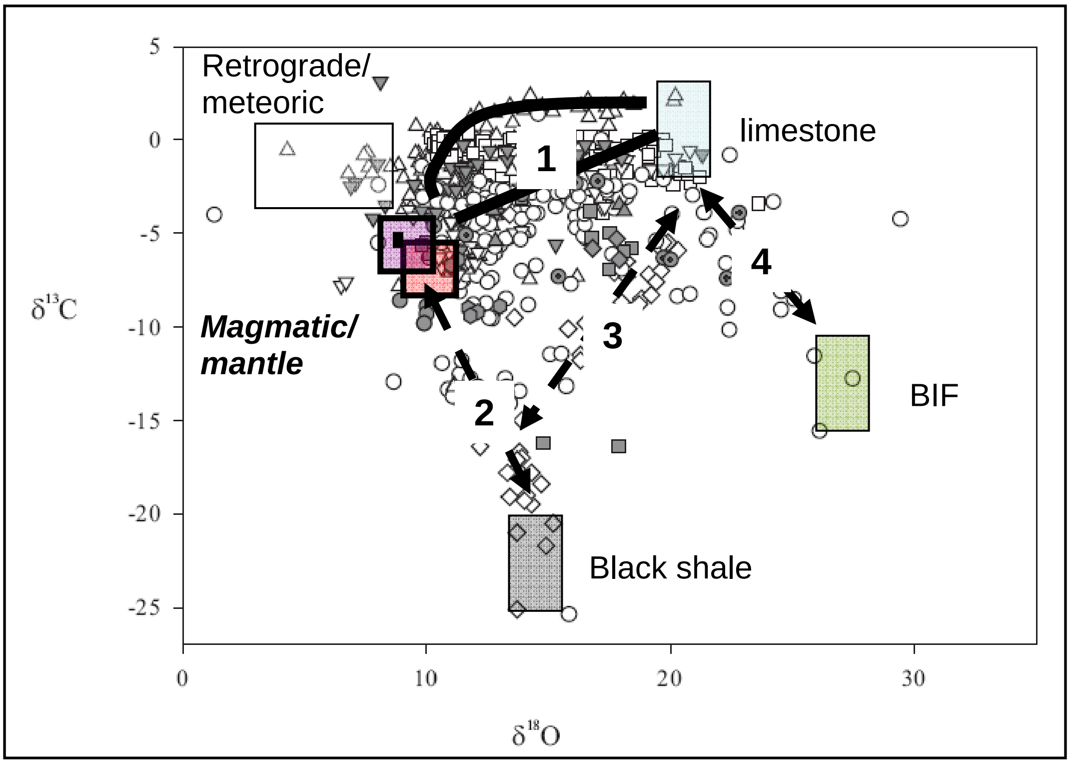


Figure 1. C and O isotope data for calcite and dolomite from IOCG deposits, veins and alteration systems in the Eastern Succession, from (Oliver et al., 1993; Marshall, 2003) and Marshall and Oliver (2006). The red box shows the inferred magmatic or mantle derived signal, the adjacent purple box to the left is the calculated fluid composition for fluid with modest CO_2 content at 450 to 500°C. This box has values intermediate between mafic or mantle fluids, and felsic-derived magmatic-hydrothermal fluids. The other boxes are the end-member isotope reservoirs (as carbonates) as indicated, trends 1and 2 represent admixture of Corella marine carbonates and Soldiers Cap black shales (respectively) with the mantle-like fluid, trend 3 is observed only at Dugald River(Zn-Pb-Mn) prospect and reflects an absence of the mantle signal and admixture of carbonate and black shale signals, and trend 4 is found only at Starra and Osborne in carbonates associated with the earliest iron oxides, which we therefore infer are true BIFs rather than metasomatic products. Data between trends 1 and 3 reflect likely passage of mantle or magmatic fluids through Corella carbonates before interacting with Soldiers Cap schists (Marshall, 2003; Marshasl and Oliver, 2006).

In this paper, we review models for the genesis of IOCGs in the Eastern Succession, and in light of recent work pertaining to the involvement of mafic rocks and magmas in ore genesis (Chapter 2), construct a more stringent set of IOCG genetic model parameters.

Protracted evolution of IOCG ore genesis, Eastern Succession

1750 to 1730 Ma

Prior to Soldiers Cap deposition, the end of the rifting and sag cycle that produced the Corella Fm and equivalents culminated in extensional deformation and the development of upper-crustal hydrothermal systems in which granite-gabbro bodies triggered circulation of basinal and magmatic-hydrothermal fluids (Holcombe et al., 1991; Pearson et al., 1992; Oliver et al., 1994; Oliver, 1995). U-REE and probably gold (Tick Hill) were added in subhorizontal shear zones and skarns (Oliver, 1995). Widespread dolerites and gabbros were emplaced into the Corella Formation and possibly reflect the first major injection of Cu into the Eastern Succession. However, it cannot be determined whether Cu was concentrated to ore grades at this time, even though Au and U-REE possibly reached ore grades. Constraints on the oxidation state and sulphur and metal content of fluids responsible for the U-REE and gold enrichments are limited due to uncertainty of solubility of U-REE and gold at very high salinities and temperatures (Oliver et al., 1999); however, widespread scapolitization of dolerites at this time, and some granites, points to the circulation of high salinity, CO_2-bearing basinal brines probably derived by evaporate dissolution (Oliver et al., 1994).

1690 to 1620 Ma

Early extension

The 1690 to 1650 Ma portion of this time period involved extension, widespread mafic volcanism, intrusion, and sedimentation in the Eastern Succession, and inferred contribution of significant copper via exsolution of a CO_2-H_2O-S fluid late during fractional crystallisation of mafic magmas (Chapter 2; Butera et al., 2005). In the Mt Isa area, Rubenach et al. (unpubl. report) have recently identified a major extensional hydrothermal system associated with the emplacement of the Sybella Batholith at c. 1672 Ma. Similar to the earlier Wonga-Mary Kathleen system, the Sybella was emplaced into an extensional shear zone, causing widespread circulation of basinal fluids. This system may have been responsible for localisation of heat flow associated with syn-sedimentary and diagenetic Pb-Zn, and possibly Cu enrichments in the c. 1650 Ma Mt Isa Group. A major mantle or mafic connection to the bulk IOCG metal budget at this time is implied from recent work (Chapter 2; Butera et al., 2005), who postulate both a primary fractionation exsolution of S and metals, and a secondary leaching of S and metals during ~1600Ma metamorphism.

Onset of orogeny

Later in this time period, shortening and a possible phase of metamorphism commenced at c. 1640 Ma (Rubenach, 2005), probably shutting down the prior extension-related events, but also developing the first of a long history of sodic alteration systems in Soldiers Cap Group rocks (e.g. Snake Creek, Osborne). This prepeak Isan metamorphic activity may have involved circulation of evaporate-derived fluids from overthrust Corella Fm, into the Soldiers Cap Group, driven by deformation and/or topography into the core of the newly developing orogenic belt (Oliver et al, 2005). The impact of this system on Cu-Au distribution is uncertain, but was probably similar, although more localised, than the effects of the main phase of the Isan Orogeny. It may have leached a large volume of pre-existing copper.

Isan Orogeny 1600 – 1580 Ma peak metamorphism

The main phase of the Isan Orogeny liberated metamorphic H_2O and CO_2 from the Corella Fm and equivalents, and H_2O from the Soldiers Cap Group, as well as significant quantities of salt (Marshall and Oliver, 2006).

Mafic dykes emplaced into the core of the Snake Creek Anticline at this time share characteristics with earlier mafic rocks emplaced during rifting, implying that although the depth of mafic magma generation had shifted, subduction was still active (Chapter 1; Butera et al., 2005). In situ or proximal partial melting of near-granulite facies metasediments produced localised pegmatites at Osborne at 1590 Ma (Rubenach, 2005), probably triggered by fluid fluxing. The abundance of pyrrhotite preserved in the eastern domain at Osborne suggest that metamorphic or other fluids at this time were relatively reduced, as reflected in the local presence of methane and nitrogen in the fluid inclusions there (Fu et al., 2003). Osborne methane-bearing brines contain elevated Cu concentrations, and this may reflect the capacity of reduced S-poor fluids to carry Cu as species other than sulphate, i.e. various Cu chlorides (Mustard et al., 2004; Davidson et al., 1989). CO_2-rich fluids at Osborne display elevated arsenic contents and relatively low chloride – if As acted as a proxy for Au, this may indicate that Au in these systems is carried in an HCOS vapour. This vapour may have exsolved from mafic rocks or come directly from the mantle, although it may have been derived by unmixing (Mustard et al., 2004) of a complex metamorphic fluid.

Most significantly, metamorphic fluids remobilised sulphides from mafic rocks (Chapter 2; Butera et al., 2005), and earlier sulphide accumulations, as indicated by petrography and mass balance calculations. If we accept that 1600 to 1590 Ma Re-Os and U-Pb ages at Osborne represent the major time for metal accumulation, then a cycle of leaching by and reprecipitation from metamorphic fluids may explain this deposit (and potentially other enrichments elsewhere such as Selwyn, Eloise and pre-ore shear zones at Ernest Henry). Alternately, if Osborne was formed earlier, during or soon after sedimentation and volcanism (e.g. similar in timing to metal introduction at Cannington), then the metamorphic fluids both imparted the radiogenic isotope signal and redistributed sulphides (both chemically and mechanically) into favourable D_2 and/or late structures. In any case, mafic and/or mantle derived fluids most likely provided the bulk of the metal and sulphur for this deposit, and similar ore types (e.g. Eloise, early magnetite-chalcopyrite at Starra, see below). The key characteristic of fluids at this time was their reduced nature, unlike at least some fluids exsolved off the later Williams Batholith (Perring, 2000).

Williams thermal event, 1550 – 1490 Ma

Oxidised brines

Examination of alteration systems in close proximity to the Williams-Naraku Batholith gives the best idea of how these intrusions may have contributed to the

IOCG deposits. Mark (1998) first documented the complexity of alteration around the top of intrusions at Mt Angelay, speculating on the exsolution of hypersaline, CO_2-bearing brines as a cause of albite alteration that affected the granite carapace and surrounds. Perring et al. (2000) and Pollard (2001) documented the co-occurrence of sodic alteration and voluminous magnetite at Lightning Creek, inferring an origin for this alteration by unmixing of complex brines upon release from the crystallizing granite-gabbro sill complex. Oliver et al. (2004) built on this work to propose that granite-derived fluids moving through metasedimentary rocks attained elevated Fe- and K-contents by wallrock interaction, prior to their potential involvement in Ernest Henry-type IOCG genesis, and Cleverley and Oliver (2005) have modelled the effect of oxidized, modified magmatic brines in the production of alteration proximal to Ernest Henry. Oliver et al. (2006) have also documented the occurrence of pipe- and sheet-like breccias emanating from contact aureoles of the Williams Batholith, which they inferred may have been driven by CO2 expelled from mingled mafic-felsic intrusions.

Fluid inclusions at Lightning Creek are distinctive for their highly elevated Fe, Ba and Cu contents, implying at least one of the fluids present was sulphur-deficient (Perring et al., 2000). The apparent absence of sulphur in these granite-proximal systems, but the presence of sulphur with distinctive mantle- or magmatic $\delta^{34}S$ values in the deposits (e.g. Mark et al. 2006b), most likely requires derivation of deposit sulphur from sources other than the c. 1530 Williams Batholith, such as mafic rocks and magmas (Chapter 2).

Fluid inclusion data reveal some connections between granites and aspects of the orebodies, although the interpretation is complex. Figure 3, for example, shows an apparent clear connection between Ernest Henry and fluid inclusions from the top of the Mt Angelay pluton (Mustard et al., 2004), separate from the other (inferred older) deposits. However, Fe and Cu are constituents of chalcopyrite, so the data can also be inferred to be a consequence of depletion of ore fluids in these components as they are precipitated from the original fluids. Lightning Creek, with the highest Fe and Cu contents in fluid inclusions, has no chalcopyrite (although a huge volume of magnetite); and Ernest Henry, with modest Fe and Cu in the fluid, is the biggest orebody. The trend is further confused by regional fluids associated with albitization. Overall, the fluid inclusion data probably reflect a close association between granitoids and the inferred oxidised, S-poor fluids at Ernest Henry and Lightning Creek, with the latter in particular lacking sulphur and/or at too high temperatures for ore formation.

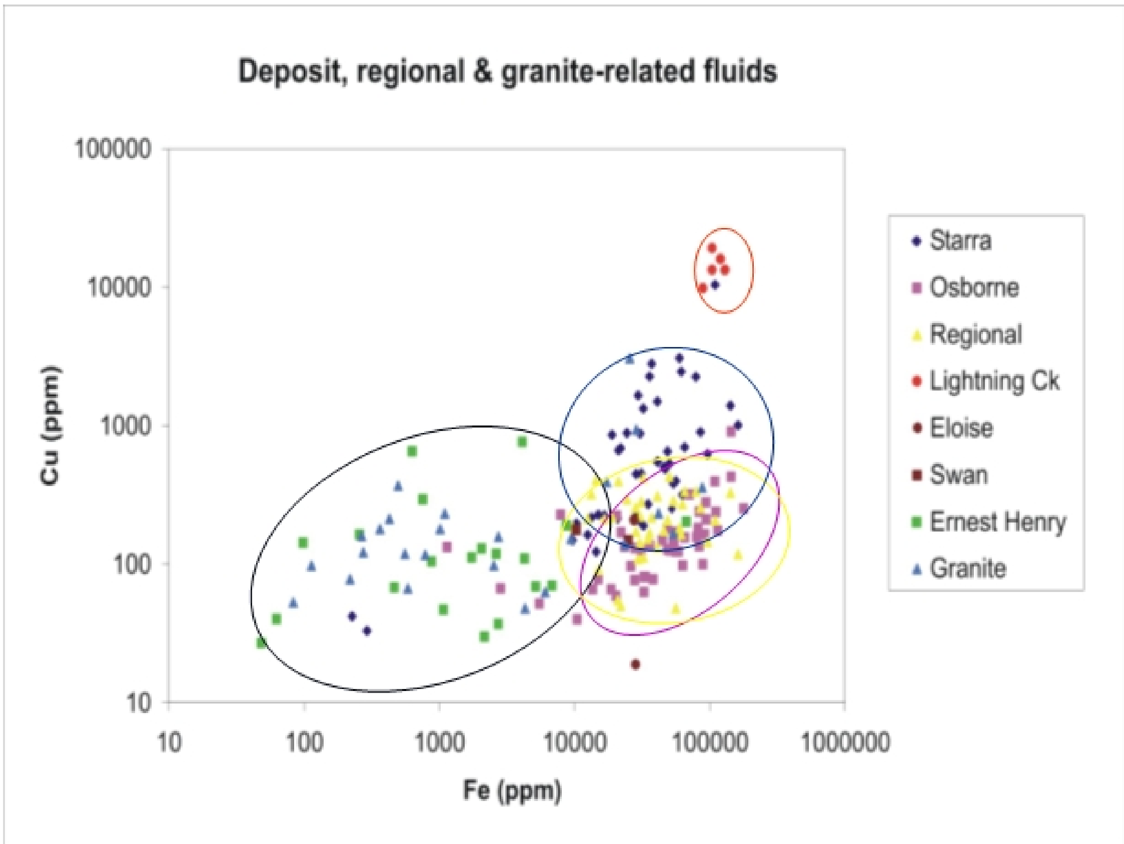


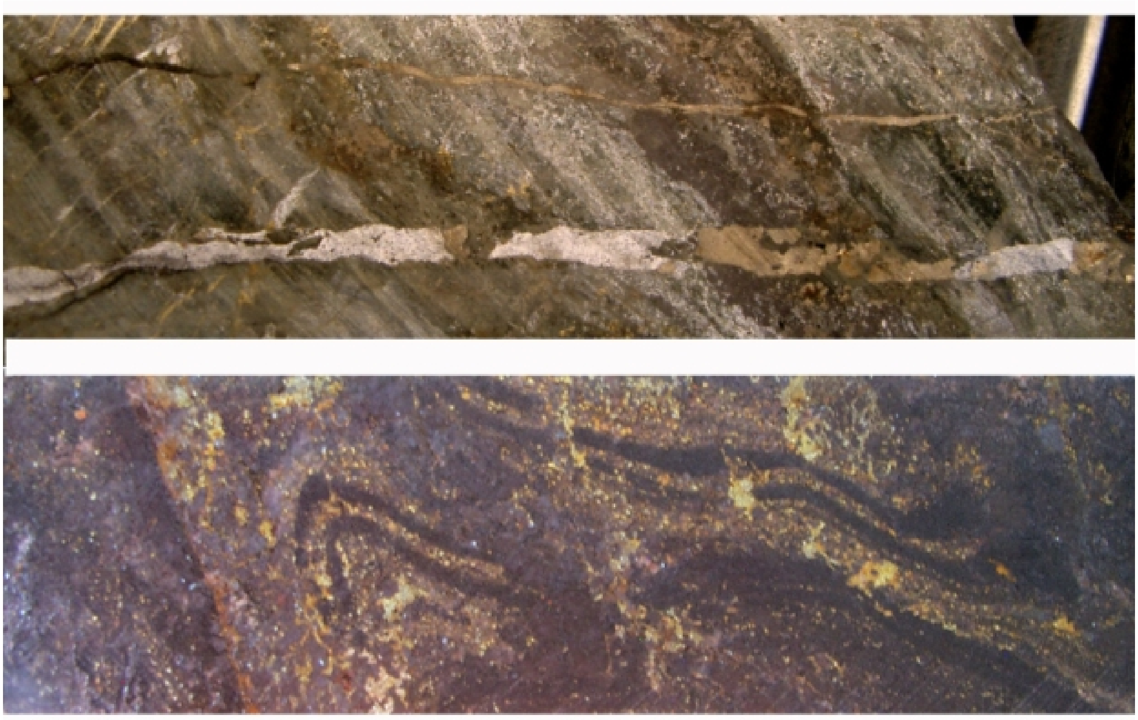
Figure 3. PIXE fluid inclusion data from Eastern Succession deposits, prospects, Mt Angelay Granite, and regional alteration. From Perring et al. (2001), Williams et al. (2001), Mustard et al. (2004) and Fu et al. (2004).

In the Snake Creek area, breccia pipes emanating from contact aureoles of 1530 Ma granitoids (Oliver et al., 2006) are dominated by magnetite, hematite, and albite (Cleverley & Oliver, 2005). Sulphides are found only in these pipes either within relict gabbro bodies (that themselves were probably emplaced syn-granite) or in distal locations where wallrocks or other fluids may have provided the sulphur. The implication of all of these lines of evidence is that the Williams Batholith released large volumes of oxidised, sulphur-poor fluids that locally carried copper and iron, and may have released some of this fluid via violent brecciation processes. This fluid may have been involved in oxidation of earlier reduced iron oxide ± sulphide assemblages at Osborne and Starra.

Textural and geochronological evidence for protracted cycling of metals in and around mineral deposits of the eastern succession.

Despite a proliferation of Ar-Ar ages in the range 1540 to 1490 Ma for Eastern Succession IOCGs and abundant evidence for late sulphides and related alteration, U-Pb and Re-Os ages of many of these deposits point to inherited components. The original understanding of the age of peak metamorphism at the time of these studies was focussed around the 1550 Ma age inferred from the Western Succession and Mary Kathleen orebody, such that the Williams Batholith was regarded as immediately post-peak metamorphic and evolving metamorphic-magmatic fluid systems were seen as viable (e.g. Rotherham et al., 1998; Baker et al., 2001). More recent recognition of earlier metamorphism, peaking at 1600-1590 Ma with D_2 deformation (Gauthier et al., 2001; Rubenach et al., 2001; Giles & Nutman 2002), and a possible earlier event at ~1640 Ma (Rubenach, 2005), requires a reinterpretation of earlier workers' paragenetic stages.

The protracted history of mineralisation and remobilisation is well displayed by the Mary Kathleen uranium orebody, which has a clear history of initial U-REE enrichment at km-scales associated with emplacement of the c. 1740 Ma Wonga-Burstall granites (providing a notable prospector's target at 1:100 000 scales), and yet the orebody in its present appearance was assembled at 1550 to 1500 Ma (Page, 1983a; Maas et al., 1988; Oliver et al., 1999). The timing of these events implies initial enrichment followed by repeated recycling and remobilization, leaving behind the ultimate question as to whether the 1550-1500 Ma event involved regional leaching of disseminated U-REE, or remobilization of an already formed orebody or protore. Similar issues are now quite pertinent to the IOCG deposits. Silica alteration forming the envelope to Osborne is locally marked by a banded, gneissic foliation (M. Rubenach, pers. comm.) and this foliation is folded by folds which are correlated with regional D_2 – i.e. this silica alteration is pre- or syn-D_2 in timing. The earliest iron oxides in this deposit have a distinctive BIF-like stable isotope chemistry (Marshall et al., 2006; Fig. 1 herein), and are clearly pre-D_2 (Figure 4b), being overprinted by coarse magnetite and chalcopyrite that was apparently introduced (or remobilized) during and after D_2. These observations at Osborne are confirmed by the bimodal distribution of geochronological data (See Table 1, Chapter 2), with both 1600-1590 Ma and 1540 – 1520 Ma results being prominent. Similar geological observations can be made at Eloise, where at least one of the orebodies contains abundant folded and foliated sulphides (Figure 4a) and *durchbewegung* texture (Figure 4c), although there has been insufficient geochronological work with U-Pb or Re-Os to determine an age for this likely older mineralisation style. Baker (1998) originally inferred a progression from metamorphism to ore genesis at Eloise, with significant alteration and mineralization occurring during the metamorphic stage. By this reasoning, with the recent geochronology, these stages would now be separated by 70 m.y. or more.



Figures 4 a) top and b) bottom: evidence for pre- to syn-D2 sulphides at Osborne and Eloise.
Figure 4a: Foliated pyrrhotite-calcite-amphibole ore at Eloise –the presence of deformed ore suggests syn- to pre-1600 Ma timing. This is cut by a later vein that demonstrates a close match between wallrock mineralogy and vein mineralogy, suggesting diffusional control of infill i.e. later diffusional remobilization (e.g. Oliver and Bons, 2001).
Figure 4b: Osborne ore with folded (pre-D2) magnetite and disseminated chalcopyrite, overprinted by magnetite seams containing patchy sulphides and zones of sulpide depletion; the latter appear to be syn-D2 (axial planar) structures.

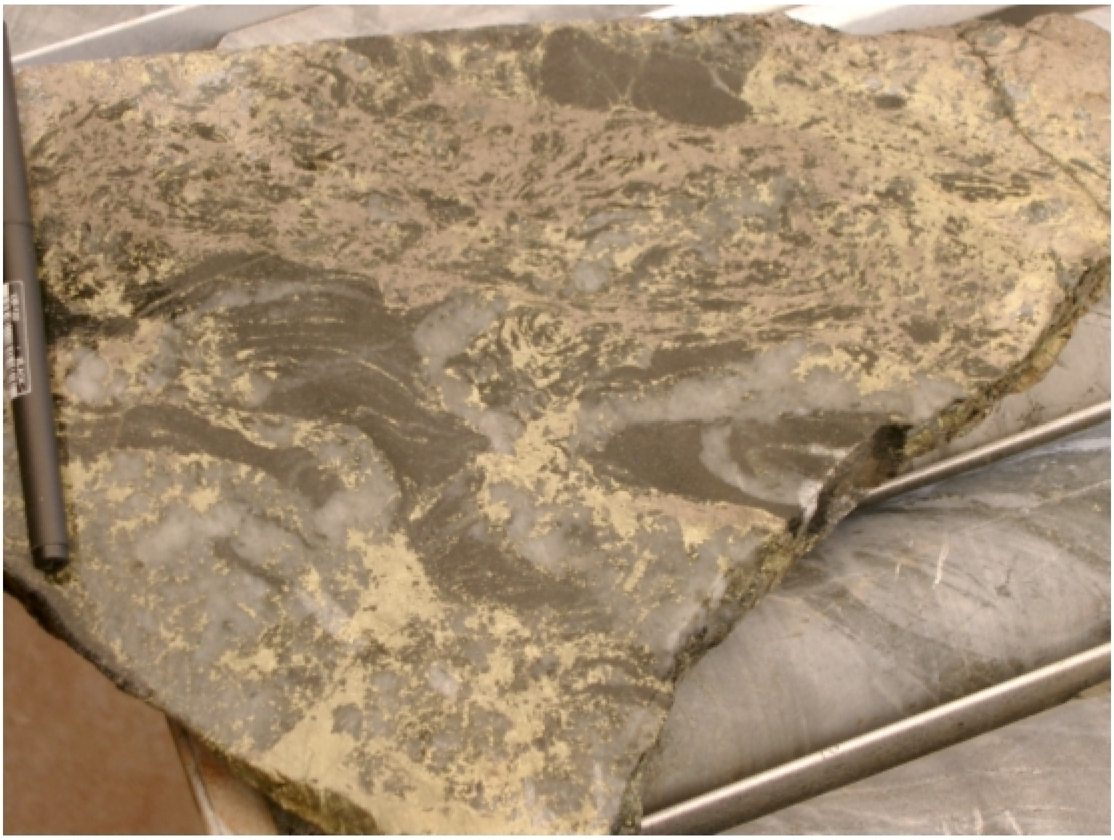


Figure 4c. Classic *durchbewegung* texture developed in pyrrhotite-rich ore at Eloise Cu-Au deposit: note the transposed fold remnants in the silicified alteration zone (bottom), texturally younger sulphides remobilized into boudin necks (pale pyrrhotite), and the shredded appearance of most of the pyrrhotite at the top. If the regional deformation peak accompanied peak metamorphism at c. 1600 Ma, these sulphides must be pre- to syn-1600 Ma, younger than the Ar-Ar ages (c. 1520 Ma, Baker et al., 2001.

Despite the bulk of the ore at Starra being dominated by coarse chalcopyrite and hematite which transgresses foliations, we have observed rocks in the open cuts containing magnetite and chalcopyrite in which the chalcopyrite forms irregularly spaced bands that look like bedding, and all are folded by D_2 folds. Some or even all of the later paragenesis of hematite-chalcopyrite may have overprinted or remobilized earlier magnetite that already contained chalcopyrite. The original premise of Davidson & Large (1994) concluding that some ironstones and possibly some sulphides pre-date peak metamorphism is also supported by stable isotope data (Marshall et al., 2006) which support a clear, non-Williams origin for early magnetite at both Osborne and Starra (Figure 1).

Although old ages persist in some of the recent geochronological data for Ernest Henry (Mark et al., unpubl. data; Butera et al., 2005), Ernest Henry shows little if any apparent physical or paragenetic inheritance within the orebody. The ore is defined by a fairly sharp-edged breccia in which magnetite-chalcopyrite-pyrite-calcite ore is clearly related to the brecciation, and titanite and molybdenite within ore have precise 1527 Ma ages (Mark et al., 2006b), similar to the nearby 1530 Ma Mt. Margaret Granite. The orebody is also notable for significant enrichment in fluorine (in biotite and fluorite), and F is also enriched in breccias emanating directly off the Mt Angelay intrusion (Rubenach, unpubl. data; Cleverley & Oliver, 2005), and in the skarn-like Mt Elliott deposit (Wang & Williams, 2001). In addition, the Ernest Henry breccia has very similar internal characteristics (clast spacing, roundness, roughness and particle size distribution) to the unmineralised but magnetite-enriched breccias near the Mt Angelay Granite (Figure 5), and may share a common physical origin (comminution, chemical corrosion and abrasion in a fluidised breccia pipe or chamber) (Oliver et al., 2006).

Figure 5. a) Top – typical Ernest Henry ore breccia with hematite-K-feldspar altered clasts in a magnetite-chalcopyrite-pyrite-Kfeldspar-calcite±barite-titanite matrix.
b) Bottom – typical breccia from a breccia pipe emanating from the Mt Angelay Granite and crosscutting Soldiers Cap Group schists, from the western edge of the Snake Ck anticline, with albite-actinolite-magnetite±Kfeldspar-chlorite clasts set in a albite-magnetite-hematite-actinolite matrix. Scale is similar in both photographs.

Ernest Henry fluid sources

Unlike Osborne or Cannington, the Ernest Henry orebody shows few physical attributes that can clearly be related to pre-Williams-Naraku hydrothermal events (Mark et al., 2005). Although inherited source components are present at 1650 to 1600 Ma (Re-Os wholerock and Pb-Pb chalcopyrite (pers. comm. K. Bassano), we remain uncertain as to the extent to which local (≤ 1km scales) pre-1530 Ma concentrations of Cu-Au ore, sulphides, or ironstones provided mass for the present orebody. The distinctive K-feldspar-hematite alteration of the host volcanic rocks associated with ore deposition (Mark et al., 2006b) was probably caused by reaction of initially granite-derived fluids, modified by albitization, with the host metavolcanic rock, as suggested by geochemical models (Oliver et al., 2004; Cleverley & Oliver, 2005). Barian K-feldspar associated with this ore-related alteration reflects likely absence of sulphur in one of the fluids, whereas the presence of barite late in the ore paragenesis suggests the possibility of fluid mixing (Mark et al. 2006b).

The key ore-forming fluid ingredients at Ernest Henry are thus considered to be:

1) Oxidised Fe- and K-rich fluid derived by brine release from the Williams Batholith during brecciation events, modified by wallrock reaction along the transport paths and deposition sites, and potentially carrying copper derived from magma mingling with mafic bodies at 1530 Ma.
2) Reduced HCOS fluid derived either directly from the mantle, by leaching of pre-existing mafic rocks or protores, or by release of fluids from crystallising Williams-age gabbros
3) 3) A possible contribution from surface derived fluids is implied by the Br/Cl fluid inclusion data (Mark et al., 2005); however these fluid inclusion results may have been influenced by precipitation of Cl-bearing silicates in Ernest Henry alteration (e.g. biotite, scapolite).

It must also be noted, however, that recent wholerock Re-Os dating of Ernest Henry ore, treated as a Re-Os molybdenum age, yielded an age of 1687Ma, within error of the proposed 1686Ma mafic exsolution event (pers. comm.. B. Schaffer, 2005). This suggests the possibility that at least some component of the ore in the Ernest Henry deposit was derived from either mafic material, or an early protore formed in response to 1686Ma mafic magmatism.

A protracted history of interaction between mantle-derived mafic melts, possible mantle-derived fluids, and the lower crust which produced the Williams Batholith (Mark et al., 2005) can explain the diversity of ages and associations in the district, but also the commonalities. Highly abundant CO_2-rich fluid inclusions in the district are not primarily a consequence of devolatilisation of the Corella Fm carbonates, because the CO_2 is found in inclusions of most ages, and associated carbonates have C- and O-isotope signatures indicative of mantle or magmatic sources (Marshall et al., 2006). This implies that mantle or magmatic CO_2 was available at almost every stage of the evolution of the belt, a situation most likely to evolve during protracted crystallisation of bimodal magmas. The interactions between mantle-derived melts, mantle fluids and generation and emplacement of felsic magmas involved:

1) Prior to 1550 Ma, significant concentrations of IOCGs had already occurred, by release of fluids directly off the top of crystallising mafic intrusions, potentially even by exhalation in mixed sedimentary-mafic rock packages, and probably by leaching and reprecipitation during regional metamorphism (Butera et al., 2005, Chapter 2).
2) At c. 1550 Ma, a phase of extension or possibly volatile fluxes from deep in the mantle lithosphere triggered renewed generation of basaltic melt just below the Moho, and triggered anatexis of lower crustal felsic melts with a distinctive mantle radiogenic isotope signature (Mark et al, 2005).

3) Some felsic intrusions, e.g. Lightning Creek, may have been contaminated with voluminous mafic melts at a relatively early stage of crystallisation, leading to widespread mingling, mixing, and transfer of metals in the melts.
4) Other felsic intrusions evolved to a much greater extent by protracted crystallisation (e.g. Mt Angelay, Mt Margaret), such that the remaining felsic liquid was near saturated with large volumes of oxidized, hematite-stable brine. Emplacement of CO_2- and possibly Cu-bearing mafic magmas into these rocks may have triggered release of Cu and CO_2 during quenching of the mafic rocks, which in turn forced exsolution of the brine from the granitoids (e.g. Oliver et al., 2006).
5) Consequently, explosive release of mixed volatiles at the granitoid carapaces produced discordant breccia pipes which carried Fe, Mn, K, Na, Ca and possibly Cu to sites above the intrusions, potentially to make orebodies. The same fluid, where it interacted with pre-existing ironstones and/or IOCGs, oxidised these rocks and either redistributed or added some copper as sulphide via redox reactions (e.g. Starra, Osborne western domain).
6) Direct release of reduced CO_2- and S-bearing fluids from crystallising mantle or lower crustal mafic melts may have produced carbonate-dominated vein systems in rocks away from the Williams Batholith.
7) Where the primitive mantle- or gabbro-derived HCOS fluids met with the brine-laden fluids evolved off highly fractionated Williams Batholith, Ernest Henry may have formed. Alternately, the S was derived from older, remobilised sources proximal to Ernest Henry. It is possible that orebodies such as Starra formed where oxidised Williams-derived fluids interacted with pre-existing sulphides until a point where the fluid became sufficiently reduced that sulphide

saturation was imminent, with final ore precipitation occurring due to pressure changes and phase separation. However, this "single fluid" model does not explain the fluid inclusion complexity at Starra nor the presence of barite (Williams et al. 2001).

Tectonic Setting and IOCG Metallogenesis

On the basis of the major early phase of mapping by the Geological Survey of Queensland and the Bureau of Mineral Resources in the Mt Isa Block, Wilson (1978) proposed, on the basis of the overall asymmetry of the sedimentary-volcanic packages, that the eastern edge of the Mt Isa Inlier was close to a plate boundary. Part of the evidence included an appreciation of the Soldiers Cap Group as relatively deep water, high energy turbidites in comparison to possible time equivalents in the centre and west of the Inlier. Subsequently, a continent-scale model for intra-cratonic rifting and limited thickening was developed (Etheridge et al., 1987), supported by concepts of bimodal igneous geochemistry, lack of andesites and blueschists, and recognition of apparent temporal similarity between packages of rocks in the Western and Eastern Successions. Both these models have some validity in recent reinterpretations, because the mafic magma chemistry, and indeed the asymmetry of the metal endowments, can be interpreted in the context of a back-arc continental environment (Chapter 1; Butera et al, 2005) in which a plate boundary was somewhat closer to the Eastern Succession than suggested by the 'far-field back-arc' model of Giles et al. (2002).

Modern continental back-arcs are characterised by high heat flow and bimodal igneous activity and any possible blueschists typically lie closer to the trench, such as the relationship between the Basin-and-Range and the Franciscan blueschists in western USA (Krueger and Jone, 1989). The global distribution of IOCGs is also certainly not restricted to rifted continental interiors, with several examples lying in arcs or back-arcs in the Cainozoic tectonic context, particularly in the Andes (Williams et al., 2005). Hypotheses of plate boundaries sitting within 200km of the eastern boundary of the exposed Mt Isa Block have recently been considered (Chapter 1; Butera et al, 2005).

Another feature of arc-related hydrothermal systems worldwide is the capacity of dewatering subducted oceanic slabs to act over a protracted period, to liberate fluids and incompatible elements directly by devolatilization, and to trigger mantle metasomatism, upper mantle partial melting and lower crustal dehydration and melting, all of which subsequently can lead to further volatile release via emplacement of crustal magmas (e.g. Peacock, 1993; Peacock et al., 1994).

The Eastern Succession is marked by c. 250 m.y. of metasomatic activity, not just by two major phases related to metamorphic devolatilization and granite emplacement. In modern convergent systems, porphyry copper deposits and island-arc related epithermal systems are a product of this type of process in fore-arcs, and such deposits are not apparently found at Mt Isa. However, back-arc extension systems can produce both Besshi-style (magnetite-chalcopyrite-dominant) and Kuroko-type (Cu-Pb-Zn) VHMS deposits, IOCGs, and a range of sediment-hosted deposits, right from the initial volcanism and rift-related sedimentation, through to basin reactivation and local shortening triggered by subduction of oceanic plateaus or continent scale shift in plate vectors. This particular environment, in which early basin metal contributions may be rapidly overprinted by the effects of convergent metamorphism, may be the specific reason for the distinction between BHT Ag-Pb-Zn and the "SEDEX" shale-hosted orebodies in northern Australia, the latter having formed in the distal flanks of the rifting system whereas BHTs may have formed and been reworked in a more arc-proximal setting (Chapter 1).

Conclusions: Synthesis of IOCG ore forming processes, Eastern Succession

In light of the new understanding of the critical processes involving mafic rocks in the contribution of significant concentrations of sulphur and metals, it is no longer apparent that the Williams age granites were the key source of metals for IOCG mineralisation. Spatial, temporal and geochemical evidence now supports a much more important role for mafic magmas and rocks than previously recognised. Complications in the attempt to directly link mafic rocks to IOCG mineralisation arise due to the nature of multiple periods of metamorphic and hydrothermal remobilisation. These hydrothermal, albitisation and metamorphic events at 1640Ma, 1600-1580Ma and 1530-1500Ma were all capable of remobilising pre-existing sulphide concentrations, from deposits, proto-ores or disseminated country rock metal accumulations, at scales comparable to the degree of mafic-deposit correlations in detailed prospectivity analysis (Butera et al, 2005; Chapter 4).

At 1686Ma metal and sulphur accumulations in the upper crust were deposited via the exsolution of a metal-volatile rich fluid from mafic magmas (Figure 7). These concentrations were potentially focussed proximal to the mafic rocks, possibly in large, early extensional fault systems such as the Mt. Dore Fault Zone, or in disseminations at the top of, or in the roof zones of, the 1686Ma-1660Ma magma chambers. A localised metamorphic event with a possible association with albitisation at 1640Ma (Rubenach, 2005) may have had a minor remobilising effect on the metals and sulphur in the Snake Ck area. 1600Ma to 1580Ma metamorphism played a key role in scavenging sulphur and metals both from pre-(1686/1660Ma) and syn-(1600Ma) mafic rocks, in addition to pre-existing accumulations from the earlier 1686Ma mafic rocks, leading to the formation of Osborne, and possibly Eloise. Oxidised hydrothermal brines and albitic fluids associated with the 1530Ma felsic-mafic mixed Williams-Naraku Batholith may have leached further metals, and potentially added more copper to the system directly, but probably did not directly contribute sulphur. These fluids and the associated structural regime at 1530-1500Ma provided the final spatial controls on ore genesis. Fluids derived from both the Williams Batholith (Mark et al., 2006b) and a direct or indirect primitive mafic source are implicated in the genesis of the Ernest Henry deposit (Cleverley & Oliver, 2005; Oliver & Cleverley, 2004).

A protracted history of uranium and REE remobilisation at 100m to km-scales was inferred at Mary Kathleen by Maas et al. (1988) and Oliver et al. (1999), with primary enrichment at 1740 Ma culminating in eventual ore accumulation by remobilisation at c. 1530 Ma. A similar process is inferred here for copper in the Eastern Succession. This may explain the presence of mineralisation in c. 1590 Ma D_2 folds in the Selwyn-Starra area, and at Eloise, older than the apparent 1550-1500Ma Ar-Ar age dates for mineralisation. These data suggest that sulphur at least may have been derived from local mafic rock, or even pre- to syn-1600 Ma proto-ores, during a 1530Ma magmatic-hydrothermal brecciation and magnetite precipitation event. A revised event chronology for the Eastern Succession is shown in Figure 6, and a summary diagram of the processes leading to IOCG ore deposition is given in Figure 7.

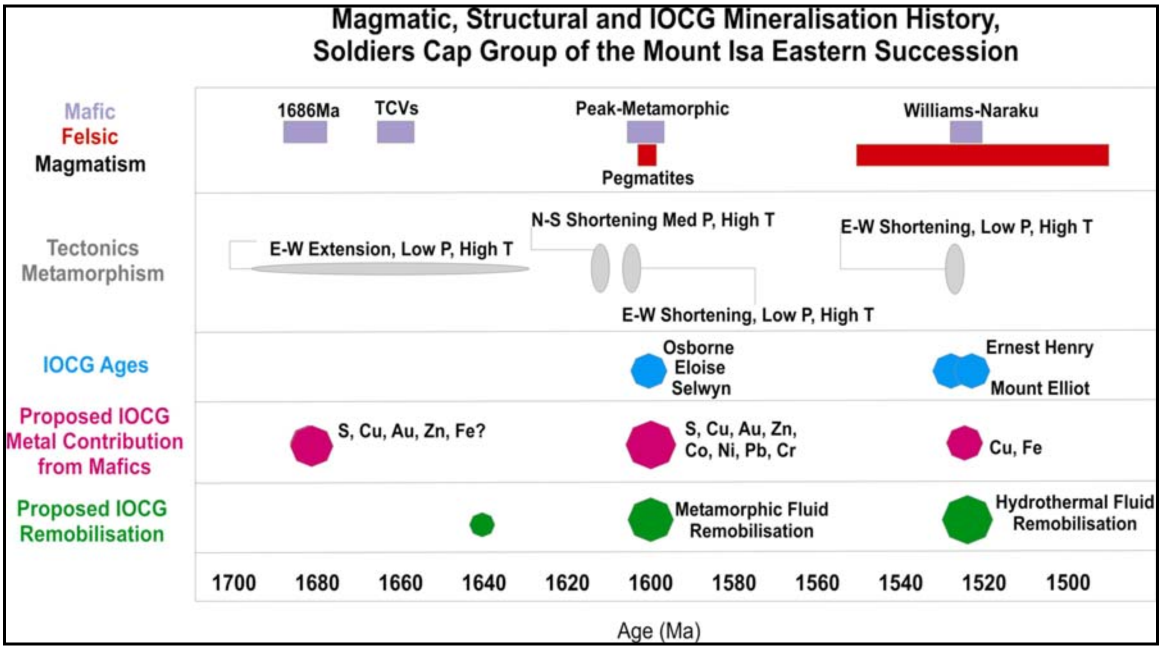


Figure 6. Summary of the magmatic, structural and IOCG mineralisation history of the Soldiers Cap Group, with proposed timing of metal and sulphur contributions from mafic rocks, and proposed IOCG remobilisation events. TCV = Toole Creek Volcanics.

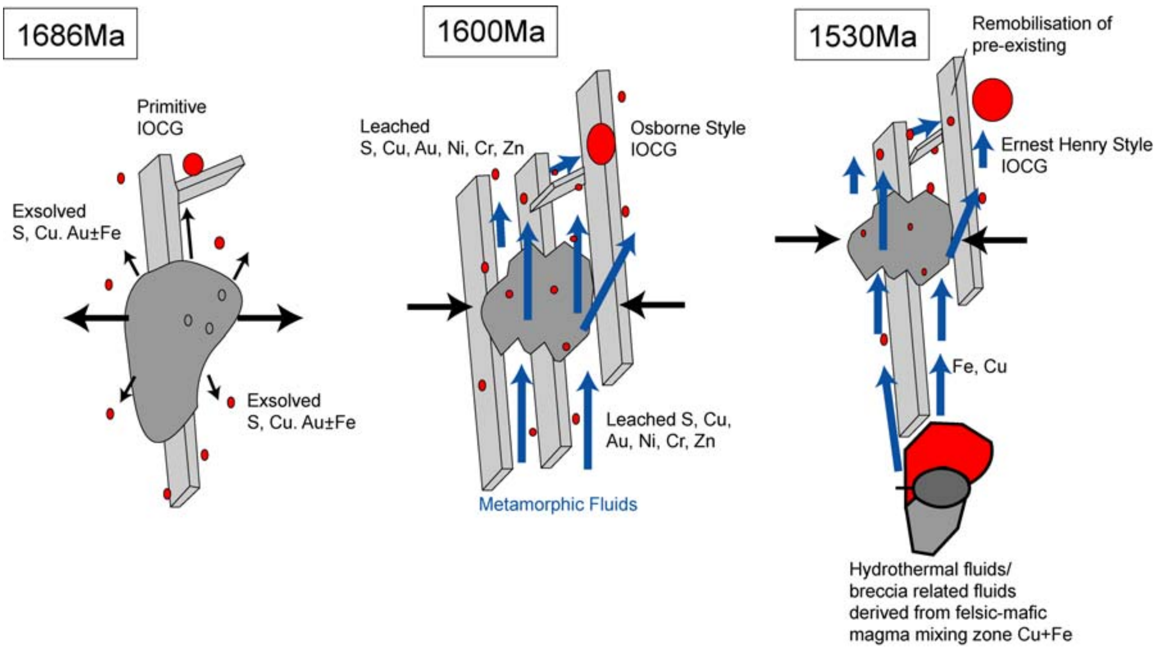


Figure 7 Evolutionary model of the contribution of S and metals via direct exsolution from mafic magmas at 1686Ma, metamorphic leaching at 1600Ma, and hydrothermal remobilisation with addition of Cu and Fe from mixed felsic-mafic magmatic fluids at 1530Ma. Large grey blobs are mafic bodies, small red blobs are Cu-Au (IOCG) protore, and large red blob at bottom of 1530Ma diagram is granitic melt mingling/mixing with coeval mafic melt.

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CHAPTER 4

Spatial Associations of mafic rocks and Fe-oxide Cu-Au deposits, southern Mount Isa Eastern Succession: implications for exploration

Spatial Associations of mafic rocks and Fe-oxide Cu-Au deposits, southern Mount Isa Eastern Succession: implications for exploration

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Abstract

Within the southern portion of the Mount Isa Eastern Succession, mafic rocks, and faults that intersect areas of mafic rocks, exhibit a stronger spatial relationship to IOCG mineralisation than any other geological parameter. In contrast, felsic rocks, of which both genetic and exploration models have relied heavily upon in the past in order to explain the final localisation controls on IOCG deposits, do not display a significant relationship to mineralisation. The results attained call for an immediate review of exploration practices in the Eastern Succession, and call upon more mafic-related models in order to achieve further IOCG mineral discoveries.

Introduction

Strategies for exploring mineral systems in the Mount Isa Eastern Succession have been impaired in recent years by a lack of adequate ore genesis models, and further, recent work has demonstrated that previously unrecognised processes may play a critical role in these genetic models. Fe-oxide Cu-Au (IOCG) and Broken Hill-type Pb-Zn-Ag (BHT) deposits constitute the most economically significant of these mineral systems (Williams, 1998; Williams and Pollard, 2003)., and mineral explorers have focussed a considerable amount of their effort into identifying these mineralisation types in both exposed and undercover portions of the Eastern Succession. Until recently, exploration strategies for IOCG deposits relied primarily on geophysical techniques, and specifically, because of the relationship of Fe-oxides to Cu-Au mineralisation, magnetic anomalies proximal (often) to roof zones of the ~1550Ma-1490Ma Williams-Narakau Batholith felsic-intermediate intrusive rocks (Brescianini. 1992; Craske, 1995; QLD DME, 2000; Tullemans et al, 2001). Since the discovery of the world class Ernest Henry deposit in 1991, however, no significant IOCG deposits have been found.

Genetic models for IOCGs have generally relied on source components being derived via Cu- and Fe-rich phase separation from the crystallising Williams-Naraku Batholith (Rotherham et al, 1998; Perring et al, 2000; Pollard, 2001) often accompanied by Sodic-Calcic alteration (Mark, 1998; Williams and Polard, 2003; Oliver et al, 2004).

In order to overcome ever-depleting reserves, it is imperative to the future success of the Cloncurry mining district that an immediate refocused approach to mineral exploration is instigated. This study deals with the exploration implications of recent work regarding the role of mafics in IOCG genesis.

Spatial Analysis

Weights of Evidence: introduction

Weights of Evidence has been used by researchers (Mustard et al, 2005; Ford, 2005) recently to measure the spatial relationships of geological units to mineralisation, and to evaluate and rank the most significant geological units in order to help build process models for the genesis of a number of deposit types. Weights of Evidence measures the strength of a spatial relationship of a set of 'training data points' i.e. mineral deposits, with lithological or structural units. The basis for the calculation is the measured "chance of a mineral deposit falling within an area surrounding the studied unit (i.e. within a buffer of a certain radius around that unit), over the chance that it does not sit within that area." The resulting parameter of the strength of spatial relationship of a deposit to the studied area is termed the Contrast Value, while the statistical strength of the contrast value is referred to as the Confidence. Typically, a contrast value > 0.5 is considered a good spatial association, while this study considers a contrast value > 1 significant (more stringent). This study has applied the Weights of Evidence test to Iron-Oxide Cu-Au deposits (as described by the NWQMP dataset), Cu Deposits, All (metalliferous) deposits, Large Deposits (>500t metal), and Au-only deposits in the Mount Angelay and Selwyn 1:100K Geological Sheet Areas, a total of 240 individual deposits. Conditional independence tests, to measure the effects of stray data, or smaller sets of data, were performed in order to check the statistical viability of the results. The results were obtained by performing the Weights of Evidence test on the Mapinfo Software add-inn MI-SDM. Buffers were created at various scales (0-5km) around mafic rocks, granites and different fault types in order to evaluate the spatial strength between these units and the different mineral deposit types. This is calculated by calculating the chance of the number of a particular type of mineral deposits sitting in the area of a particular buffer ring around the geological feature, versus the chance that it lays outside that area. The resultant data is presented as the Contrast Value, along with the statistical strength of that data present as the Confidence Value.

Results

Provided here is a summary of the results of the Weights of Evidence spatial analysis study (Table 1). Detailed results are given below. Results were obtained for Mafic Rocks, Major Faults, Medium Faults, Minor Faults, Faults that intersect mafic rocks, Wimberu Granite, Mount Dore Granite, Gin Creek Granite, Mount Cobalt Granite, Mount Angelay Granite, Squirrel Hills Granite, Yellow Waterhole Granite, Saxby Granite, Cowie Granite, Marumungee Granite and Corella Breccia.

All Granites	All Deposits	Larger Deposits	Ironoxide Cu Au	Cu Deposits	Au Deposits
Distance	3.25-3.5km	INSIGNIFICANT	INSIGNIFICANT	1.25-1.5km	1.25-1.5
Contrast	1.41	INSIGNIFICANT	INSIGNIFICANT	1.19	2.29
Confidence	5.28	INSIGNIFICANT	INSIGNIFICANT	3.45	5.07
Deposits	15	INSIGNIFICANT	INSIGNIFICANT	9	6
Mafic Dykes	**All Deposits**	**Larger Deposits**	**Ironoxide Cu Au**	**Cu Deposits**	**Au Deposits**
Distance	0-250m	0-250m	250-500m	0-250m	0-250m
Contrast	1.99	1.77	1.71	1.7	1.2
Confidence	14.2	4.09	3.48	8.2	2.5
Deposits	71	7	5	30	5
Major Faults	**All Deposits**	**Larger Deposits**	**Ironoxide Cu Au**	**Cu Deposits**	**Au Deposits**
Distance	0-100m	0-100m	0-100m	0-100m	0-100m
Contrast	1.23	3.03	2.18	1.23	2.21
Confidence	5.62	7.92	4.76	4.06	5.2
Deposits	23	11	6	12	7

KEY	INSIGNIFICANT	SIGNIFICANT	HIGH	VERY HIGH

Table 1 Summary of the results of the Weights of Evidence spatial study.

Mafic Rocks vs Mineralisation:

- IOCG Deposits are optimally spaced from mafic rocks between 0km and 0.5km. Greatest optimisation was at 200-300m (4 dep, Contrast= 2.24, Confidence = 4.46), and at 1 – 1.25km (4 dep, Contrast = 1.41, Confidence =2.62)

- Cu Deposits are optimally spaced from mafic rocks between 0km (within mafic body) to 1km, particularly 0-250m (30 dep, Contrast = 1.7, Confidence = 8.20_. Greatest optimisations at 0-10m (13dep, Contrast = 1.87, Confidence = 6.39), 750m-1000m (24 dep, Contrast = 1.78, Confidence = 7.89)

- Au Deposits are optimally spaced from mafic rocks between 750m and 1km (15 dep, Contrast = 3.09, Confidence = 8.85), and 0-250m (5 dep, Contrast = 1.19, Confidence = 2.46). Of the deposits proximal to the mafic bodies, optimisation occurs between 100m and 200m (4dep, Contrast = 2.26, Confidence = 4.25)

- All Deposits (NWQMP) are optimally distanced 0km – 0.75km from mafic rocks, peaking at 0-50m (26 dep, Contrast = 1.92, Confidence 9.26) and 50-100m (14dep. Contrast = 2.1, Confidence = 7.6)

- Larger Deposits (NWQMP) are optimally distanced 0-250m (7 dep, Contrast = 1.77, Confidence = 4.09), peaking at 0-10m (3dep, Contrast = 1.91, Confidence = 3.14), 750m – 1.25km, and again at 2.25km-2.5km (3 dep, Contrast = 1.22, Confidence = 2.01). Larger deposits occur both proximal and distal to the mafic bodies.

Faults vs Mineralisation

- **Major Faults:**
    - All Deposits (i.e. large and small, all types) (NWQMP) are optimally spaced within 100m of major faults (23 deposits, Contrast = 1.23, Confidence = 5.63)

    - Larger Deposits are also optimally distanced from major faults within 100m (11 deposits, Contrast = 3.03, confidence = 7.92)
    - Large deposits have a stronger correlation with major faults than smaller deposits

    - Ironoxide Cu Au deposits are optimally distanced 0-100m (6 deposits, Contrast = 2.18, Confidence = 4.75), and again at 1.3km – 1.4km (5 deposits, Contrast = 2.2, Confidence = 4.47)

    - Cu deposits are optimally spaced 500-600m (18dep, Contrast = 1.73, Confidence = 6.82), and also at 0-200m, peaking at 0-100m (12 deposits, Contrast = 1.23, Confidence = 4.06)

    - Au deposits are optimally spaced 500-600m (16 deposits, Contrast = 3.51, Confidence = 10.07) and 0-100m (7 deposits, Contrast = 2.21, Confidence = 5.19. related to either syn-D2, D3 or 1675 Detatchment Fault in Mount Dore/Selwyn Area

- **Medium Faults:**
  - All Deposits (NWQMP) optimally spaced 0-100m (13 deposits, Contrast = 1.24, Confidence = 4.34) and at 300-400m (12 deposits, Contrast = 1.12, Confidence = 3.8)

  - Larger Deposits (NWQMP) show no significant correlation

  - Ironoxide Cu-Au deposits are optimally spaced 0-100m (2 dep, Contrast = 1.53, Confidence = 2.10) and again at 1.3-2.5km, peaking at 2 - 2.25km (3 dep, Contrast = 1.17, Confidence = 1.92)

  - Cu deposits optimally 1.5km from Medium faults (16 dep, Contrast = 2.24, Confidence = 8.42), but also at 0-500m (Contrast 0.91 – 0.37)

  - Au deposits optimally 1.4km to 1.5km (17 dep, Contrast = 4.28, Confidence = 12.287) – Gold deposits closely spatially related to each other – along. They are more closely related to major faults (Mt Dore area).

- **Minor Faults:**
  - Minor faults show no significant trends in relation to mineralisation

Faults that intersect mafic rocks

- Faults that intersect areas of mafic rocks (1km buffers) show the strongest spatial relationship of any geological feature to any deposit type. (8 deposits, Contrast = 7.78, Confidence = 18.73 at 0-250m).

  This is the most significant result of this study, and suggests the possibility that the most important features necessary for IOCG deposition are faults and mafic rocks.

Granites vs Mineralisation

- Granites show no significant correlation with IOCG, Cu, Large or All Deposits. However the Mount Dore granite was found have a significant relationship with Au-only deposits (6 deposits, Contrast = 2.29, Confidence = 5.07 at 1.25–1.5km). However, these 6 deposits are those of the Sewlyn group of deposits, which for the purpose and scale of this study should be considered a single deposit. That being said, there is then no significant relationship between the Au deposits or any of granites studied.

In the context of IOCGs, mafic rocks appear to have an extremely strong spatial relationship to mineralisation. IOCG deposits display a similar strength in spatial relationship to mafics (4 dep, Contrast= 2.24, Confidence = 4.46 at 200-300m) compared to major faults (6 deposits, Contrast = 2.18, Confidence = 4.75 at 0-100m). There are 7 IOCG deposits within 500m of mafics compared to 8 IOCG deposits within 500m of major faults. Most of the IOCG deposits optimally distanced 0-100m from Major faults are concenctrated along the older Mount Dore detatchment Fault, whereas the IOCGs related to mafics are more regionally distributed – providing better exploration opportunities. Importantly, no granites, either collectively or individual suites, were found to have a significant spatial relationship to IOCG mineralization. Faults that intersect area of mafics (Figure 1) provide the best predictors for IOCG deposits. (8 deposits, Contrast = 7.78, Confidence = 18.73 at 0-250m). This infers that mafic rocks may be a much more dominant source of metals and sulphur for these deposits than the granites. Alternatively, pre-emplaced mafic rocks may have provided the required chemically favourable hosts for mineralisation if in fact granites were responsible for the Cu and S bearing fluids.

Additionally, the results indicate that mafic rocks may also be important in the genesis of Cu-deposits and Large deposits, and may act as a source of sulphur and some metals for All deposits.

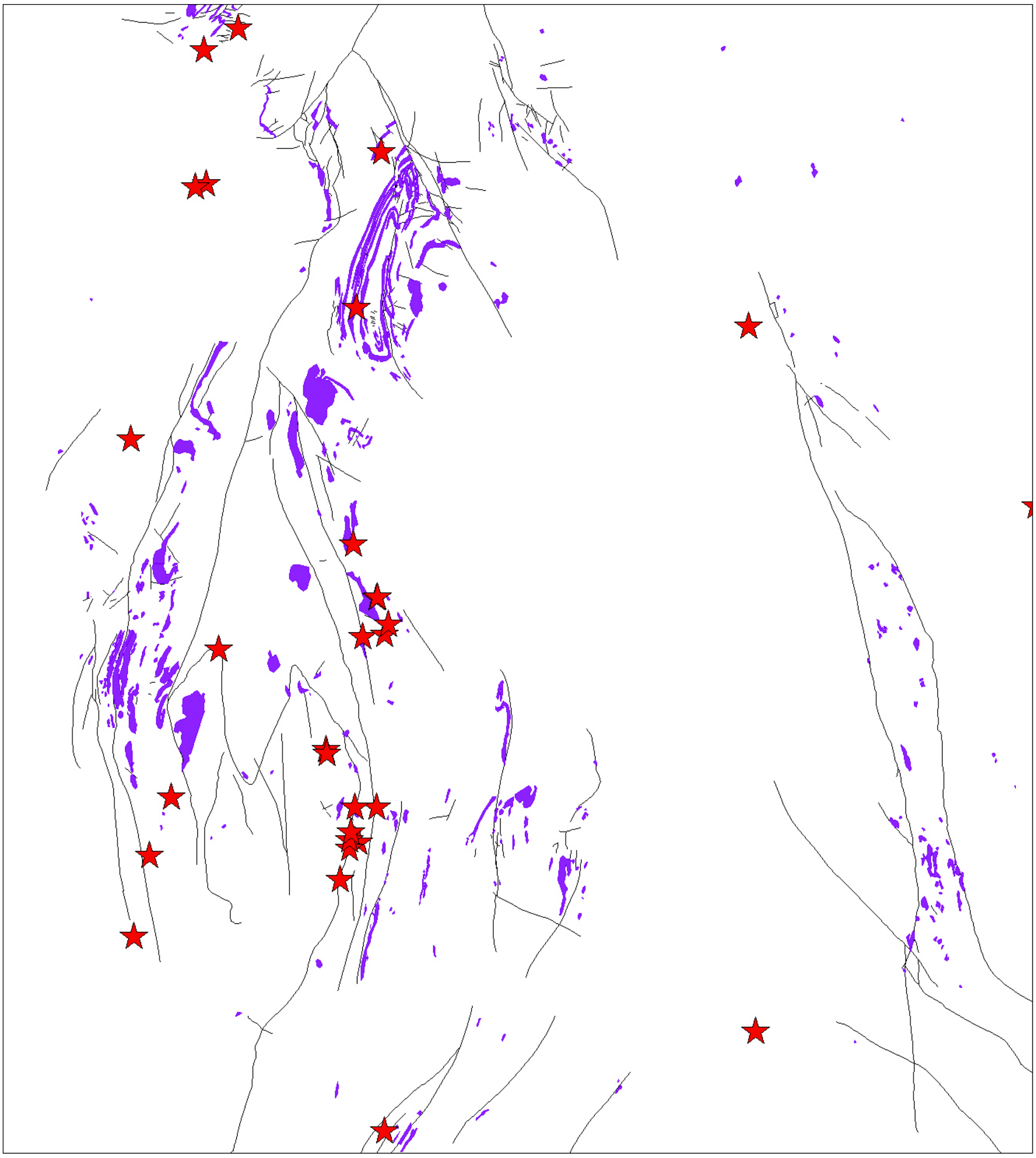


Figure 1 Map of Mafic Rocks (purple), faults that intersect a 1km buffer of those mafic rocks (lines) and IOCG deposits (red stars) in the Angelay Selwyn Sheet study area.

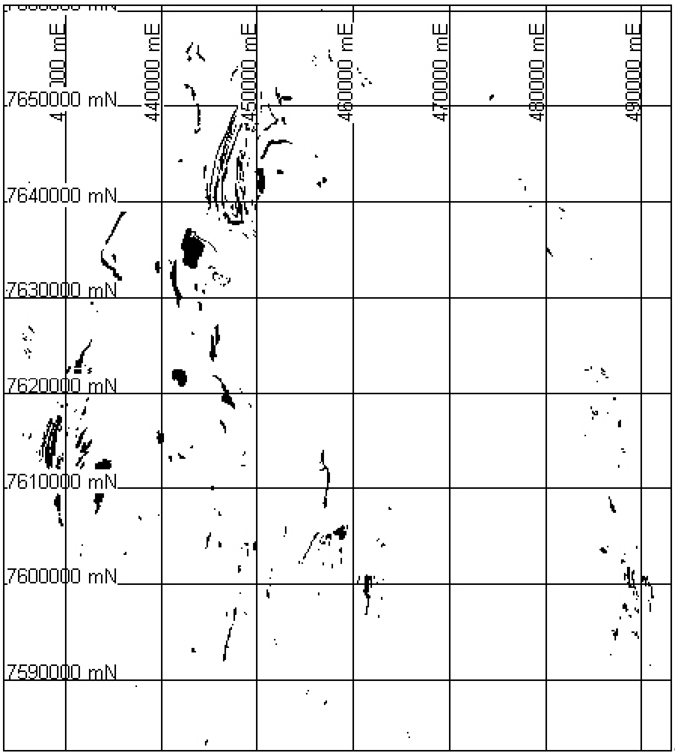
The results obtained in this study concur with the results of other Weights of Evidence studies in the Mount Isa Inlier. Mustard et al (2005) found that of all the lithological units in the whole of the Eastern Succession, mafic intrusives displayed the strongest spatial relationship with IOCG mineralisation. The study also found that granites were a lot less 'prospective', or spatially related to, IOCGs than mafics. Ford (2005) confirmed those results, finding a positive spatial association between Cu deposits and mafic intrusives using the NWQMP Report (QLD DME, 2000) geological data. The importance of these results are immense. From an exploration point of view, areas within the Eastern Succession that contain mafic rocks, or faults that intersect mafic rocks, are much more prospective for IOCGs, large, Cu- and Au-deposits, than areas that are mafic absent.

Fractal Analysis

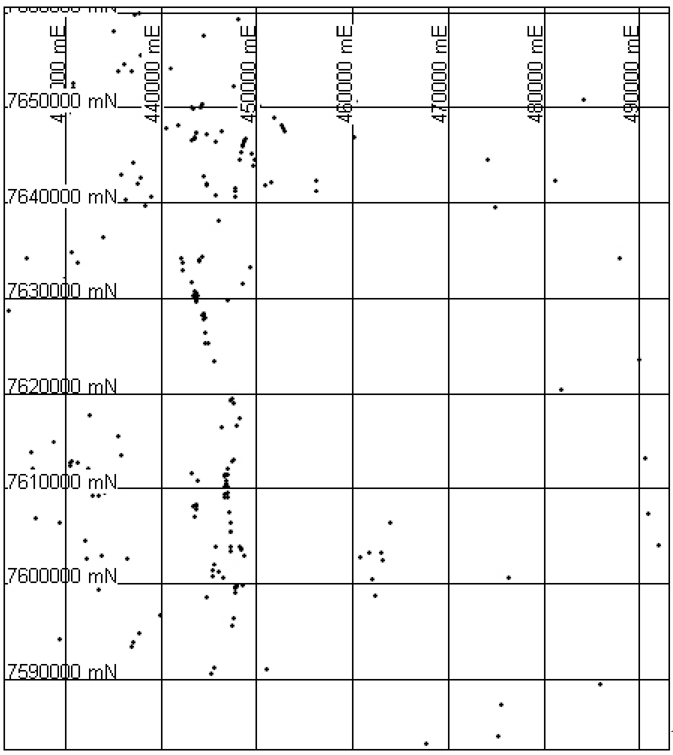
Following Mandelbrot's (1983) hypothesis that minerals in the crust might have fractal distributions, several studies have demonstrated this by applying the box counting technique to analyze the spatial distribution of mineral deposits (e.g. Carlson, 1991; Blenkinsop, 1994; Agterberg et al. 1996; Blenkinsop and Sanderson, 1999). Genetic implications about mineralising systems can be drawn from the box counting fractal dimension, which measures the degree of clustering of the deposits.

In this study the spatial distribution of metal deposits and the distribution of mafic rocks were analysed using binary images in the freeware program ImageJ. An image of the spatial distribution of deposits was produced with each deposit occupying one pixel, and box counting of this image was compared to box counting of a binary image of the distribution of mafic rocks. Box counting was initially performed over a range of box sizes from 0.34 km to 34.2 km. These data showed typical patterns of roll-off at small box sizes. The range of box sizes over which the data were linear was 8.53 km to 34.2km. Regression between these limits was used to derive the fractal dimensions, standard errors of regression and correlation coefficients.

The study area covers a 75.5km x 85.2km region of the Geoscience Australia 1:100 000 Mount Angelay and Selwyn geological sheets. The mineral deposit data were taken from the North West Queensland Mineral Province Report (QLD DME, 2000), and encompass 240 metalliferous mineral deposits (Fig 2). The mafic bodies were delineated by thorough examination of a combination of doleritic units mapped by the authors, other researchers, and the Geoscience Australia mapping program.



a



b

Fig.2) Location of a) mafic rockss and, b) mineral deposits over study area . (Map Grid MGA 94, Zone 54).

The results (Table 2) show that the fractal dimensions of mafic dykes (D = 1.43 ± 0.03) and mineral deposits (D = 1.43 ± 0.04) are effectively identical. Data points on a log-log plot are consistently within error (Fig 3). This means that the degree clustering of mineral deposits over this part of the Eastern Succession is the same as that of mafic rocks, strongly permissive of a genetic relationship between them.

	Regression Limits (km)		Number (Deposits)	Fractal Dimension	Standard Error	Correlation Coefficient
	Min	Max	N	D	E	R
Mafics	8.53	34.2	-	1.43	0.03	0.997221
Deposits	8.53	34.2	240	1.43	0.04	0.99523

Table 2. Results of fractal analysis on mafic dykes and deposits, Eastern Succession.

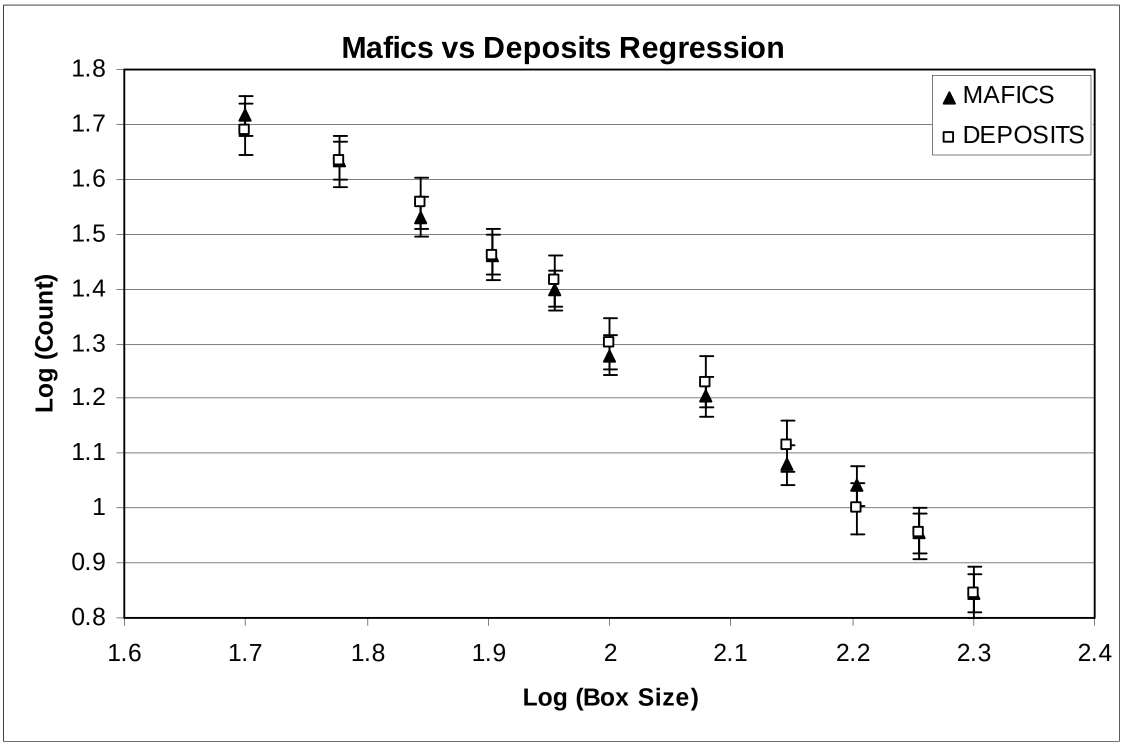


Fig 3 Log(Number of boxes containing mafic rocks/deposits) vs Log(box size) for mafic rocks and metal deposits, Eastern Succession. Error bars show regression error.

The results for the Fractal Analysis study presented here are in strong agreement with those of Ford (2005), where IOCGs within the Eastern Succession were found to have a fractal distribution of 1.423 ± 0.113, well within error of the results obtained for deposits and mafics in this study.

Synthesis of Spatial Analysis

Despite many years of exploration and research focused toward the role of regional granites in the genesis of IOCGs, the results of this spatial analysis leads us to ponder the question of why this was the case when such a strong affinity between mafic rocks, faults and mineralization is evident. Fractal Analysis and Weights of Evidence have proven to be useful tools in the study of prospectivity, and the ranking of key geological features that may be implicated in ore genesis models. According to the studies undertaken here, future emphasis on the role of mafic rocks, as opposed to granites, in the Eastern Succession IOCG province is warranted. The strength of the spatial relationships of mafic rocks to IOCGs and base metal deposits, shown by detailed studies of both Weights of Evidence and Fractal Analysis, is strongly permissive of a genetic relationship between the two, and provides a clearer understanding of the exploration indicators for mineral systems.

Conclusions: Implications for Exploration

In consideration of the strong spatial correlation between mafic rocks and IOCG deposits, it is important to consider these results in any exploration strategy. In particular, the significant difference in spatial relationship between major faults to

IOCG mineralisation, and faults that intersect mafic rocks to IOCG mineralisation, highlight the critical role of mafics in the ore deposition process. Aditionally, mafic rocks have the same fractal distribution as mineral depositions within the study area. Whether it be that the mafic rocks have acted as chemical or mechanical traps for ore minerals to precipitate, or that they have directly contributed to mineralisation via either fractionation processes or later scavenging by metamorphic fluids (Chapter 2), their presence is a crucial indicator for the potential for mineralisation to exist in a given area. This is in contrast to the Williams-Naraku Batholith of felsic to intermediate magmas, that display no significant spatial relationship to mineralisation at the studied scale.

Given the recent disappointing exploration results for IOCGs in the Eastern Succession, and the accompanying acceptance of both genetic and exploration models for IOCGs relying heavily on a felsic magmatic involvement, it may be appropriate in future exploration to consider the role of mafic rocks in ore genesis in order to increase ore discovery rates.

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CONCLUSIONS

The main conclusions from the work contained herein are:

1. There may exist an old (pre-1860Ma) crustal/mantle boundary between the Eastern and Western Successions of the Mount Isa Inlier. Variation of geochemical indicators and crustal thickness during the Palaeo-Mesoproterozoic between the Eastern Domain (Mount Isa Eastern Succession, Curnamona Province and Georgetown Inlier) and the Western Domain (Mount Isa Western Succession, Kalkadoon-Leichardt Belt and McArthur River Basin) supports this. Additionally, regional scale metallogenesis is consistent with a major intra-Isa Block boundary.

2. Mafic rocks probably contributed significantly to the accumulated metal budget of the Mount Isa Eastern Succession, via primary (1690Ma-1650Ma fractionation-exsolution) and secondary (~1600Ma-1590Ma) metamorphic leaching processes.

3. Previous genetic and exploration models for IOCG deposits in the Eastern Succession failed to adequately account for the potential for mafic rocks and magmas to have contributed significantly to mineralising processes.

4. The spatial association of mafic rocks, and faults that intersect areas of mafic rocks, to IOCG mineralisation are the strongest of any geological/lithological

units to mineralisation. This is a particularly important point mineral exploration targeting. Additionally, felsic rocks, those that have been considered important in exploration targeting over recent years, show no significant spatial relationship to IOCG mineralisation. These results also add weight to the results of the geochemical studies that highlight the potential involvement of mafics in Eastern Succession mineralisation processes.

Appendix I

JCU Samples List

JCU Sample Collection

*No residual Rock portions remain. Thin sections not available.

KB #	Lab #	Location	Easting	Northing	Description	Thin Section Available
M1	5963-01	Snake Creek	462483	7685008	Pre-D1 Layered Gabbro	No
M2	5963-02	Snake Creek	462585	7685025	Pre-D1 Gabbro	No
M3	5963-03	Snake Creek	462731	7684957	Pre-D1 Unaltered Tonalite	No
M4	5963-04	Snake Creek	462730	7685003	Pre-D1 Gabbro-Tonalite Hybrid	No
M5	5963-05	Snake Creek	462730	7685003	Pre-D1 Hybrid Gabbro-Tonalite	No
M7	5963-06	Snake Creek	462913	7684965	Pre-D1 Gabbro	No
M8	5963-07	Snake Creek	464661	7684125	Syn-D2 Dolerite	No
M9	5963-08	" "	"	"	As above, less altered	No
M11	5963-09	Snake Creek	458571	7689444	Late fresh Gabbro	No
M12	5963-10	Snake Creek	459030	7694414	Pre-D1 Dolerite	No
M13	5963-11	Snake Creek	461791	7694429	Pre-D1 Dolerite	No
M14	5963-12	Snake Creek	462951	7694451	Pre-D1 Dolerite	No
M22	5963-13	lary Kathleen F	397328	7699848	Amphibolite	No
M23	5963-14	lary Kathleen F	397397	7699748	Amphibolite	No
M24	5963-15	lary Kathleen F	397369	7699786	Amphibolite	No
M28	5963-16	Lunch Creek	402719	7709427	Lunch Creek Gabbro?	No
M32	5963-17	Lunch Creek	402493	7709279	Lunch Creek Gabbro?	No
T 1	6332-01	Kuridala Area	446336	7646611	Pre-D1 Dolerite	No
T 2	6332-02	Kuridala Area	446900	7646232	Pre-D1 Dolerite	No
T 3	6332-03		486058	7652762	Dolerite	No
T 5	6332-04	est of Snake Cre	458355	7688946	Altered Dolerite Dyke (Late)	No
T 6	6332-05	" "	"	"	"	No
T 8	6332-06	Snake Creek	458324	7689062	Syn-D2 Dolerite	No
T 9	6332-07	Snake Creek	464313	7684628	Syn-D2 Dolerite	No
T 10	6332-08	Snake Creek	463811	7684318	Syn-D2 Dolerite	No
T 11	6332-09	Snake Creek	464709	7684118	Syn-D2 Dolerite	No
T 12A	6332-10	Snake Creek	678751	467874	Syn-D2 Dolerite	No
T 12B	6332-11	Snake Creek	678751	467874	Syn-D2 Dolerite	No
T 14A	6332-12	Snake Creek	468174	7678068	Syn-D2 Dolerite	No
T 14B	6332-13	Snake Creek	468174	7678068	Syn-D2 Dolerite	No
T 15	6332-14	Snake Creek	466462	7678257	Syn-D2 Dolerite	No
T 16	6332-15	Snake Creek	466260	7681955	Syn-D2 Dolerite	No
T 17	6332-16	Snake Creek	466059	7682087	Syn-D2 Dolerite	No
T 19	6332-17	est of Snake Cre	458470	7689000	Late Dolerite	No

Appendix II

MAFIC GEOCHEMISTRY DATABASE

(AVAILABLE ONLY IN DIGITAL FORMAT)

Appendix III

Chapter 3 Reworked - Published in Precambrian Research

(Oliver et al, 2008. Oliver:50%, Butera:45%, Others:5%)

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