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CRITICAL INGREDIENTS OF IOCG MINERALISATION IN THE EASTERN FOLD BELT OF THE MOUNT ISA INLIER: INSIGHTS FROM COMBINING SPATIAL ANALYSIS WITH MECHANICAL NUMERICAL MODELLING

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Abstract - Current understanding of the critical processes in the formation of iron oxide copper-gold (IOCG) deposits in the Mount Isa Inlier, Northwest Queensland is based on more than 20 years of research on these Proterozoic hydrothermal systems and their environs. One of the most popular models for the formation of these deposits involves magmatic fluids derived from the post-metamorphic (1550 to 1500 Ma) Williams-Naraku batholith granites, and either mixing with one or more external fluid sources or reaction with favourable wallrocks to form Fe- (commonly magnetite) rich alteration zones that contain vein stockwork, breccia, dissemination or replacement style mineralisation. There is also a potential link between mineralisation and widespread mafic intrusive activity, which spans the entire range of known mineralisation ages. The majority of the copper and copper-gold mineralisation in the Eastern Fold Belt is hosted within late structures of the Isan orogeny (D_3 and D_4), many of which exhibit strike-slip movement, and these have been associated with the localisation of the bulk of mineralisation in the area. Numerical modelling using a discrete element technique is employed here to examine the response of a fault system in the Eastern Fold Belt to an applied stress regime. Modelled areas of combined low minimum principal stress (σ_3) and high mean stress (σ_m) show the best correlation with deposits, but these areas do not clearly correspond to specific fault orientations or configurations. Rather, the models produce complex zoning of stress anomalies in response to the partitioning of stress across complex fault blocks, and the interaction between more competent felsic intrusive bodies, less competent metasedimentary rocks, and the fault and rock boundary complexities. The models are consistent with mineralisation occurring (or being remobilised from earlier concentrations) during a major phase of regional fluid flow facilitated by a complex fault array, late during the evolution of the Isan Orogeny, and synchronous with the waning stages of emplacement of the Williams Batholith. In combination with numerical modelling, and to allow the investigation of the considerable range of other potential geological controls on IOCG mineralisation, a GIS was developed enabling evaluation of the current understanding of critical ingredients, and the statistical ranking of the relative importance of the parameters, to gain new insights into potential controls currently unrecognised or considered less important. A 'weights of evidence' (WOFE) approach was used due to the data-rich nature of the region, and the uncertainty about the role played by particular ingredients such as mafic and felsic intrusives. Contrast patterns were ranked from best to worst predictor. Rockchip geochemistry, including copper (>249 ppm) and gold (>0.11 ppm) are the strongest predictors, with proximity to the Corella Formation contacts the next highest predictor of copper-gold occurrences. Aero-magnetic highs are also a strong predictor, followed by north-south and northeast to east-northeast oriented faults, and proximity to mafic intrusions, lithology, gravity and fault bends associated with the same faults. New geological or exploration models for IOCG deposits in the Mount Isa Inlier must incorporate the critical ingredients highlighted in this study: (1) the significant role of the Corella Formation - Soldiers Cap contact in localising faulting, fluid flow, and juxtaposing lithologies of contrasting rheology, (2) stress partitioning, with areas that localise high strain, with low minimum principal stress being significantly more likely to have localised and focussed mineralising fluids during late stage to post Williams Batholith emplacement, (3) north-south and northeast to east-northeast oriented structures, and (4) the potential role of mafic intrusives in providing a rheological contrast and/or a potential source of sulphur facilitating copper-gold deposition. Posterior probability maps for predicting the prospectivity of the region and the distribution of copper-gold ±iron oxide deposits in the Mount Isa Inlier were produced, combining numerical results and WOFE results.

Introduction

The Mount Isa Inlier (Fig. 1) is a world class minerals district, richly endowed with major sediment-hosted Pb-Zn (Mount Isa, Hilton, George Fisher, Century, Cannington) and copper deposits, including the Mount Isa copper orebodies. With the discovery of deposits such as Ernest Henry, Starra (formerly Selwyn), Osborne, Mount Elliot-SWAN and Eloise, the Mount Isa Inlier, and in particular the Eastern Fold Belt, has emerged as a major province for iron oxide copper gold (IOCG) deposits (Pollard, 1998; Williams, 1998). Epigenetic processes are predominantly responsible for the majority of the copper and copper-gold deposits in the Eastern Fold Belt (EFB) of the Mount Isa Inlier, with most models (e.g., Williams, 1998; Mark *et al.*, 2001, 2006; Wang and Williams, 2001) favouring a role for igneous-related hypersaline fluids. Fluid inclusion characteristics, stable isotope data and the close temporal relationships of mineralisation to felsic intrusions suggest that granitic fluids were important for some copper-gold iron-oxide deposits of the Eastern Succession (Pollard *et al.*, 1998; Williams, 1998; Wang and Williams, 2001; Oliver *et al.*, 2004; Pollard, 2006). Alternative metal and/or sulphur sources (such as mafic rocks) have

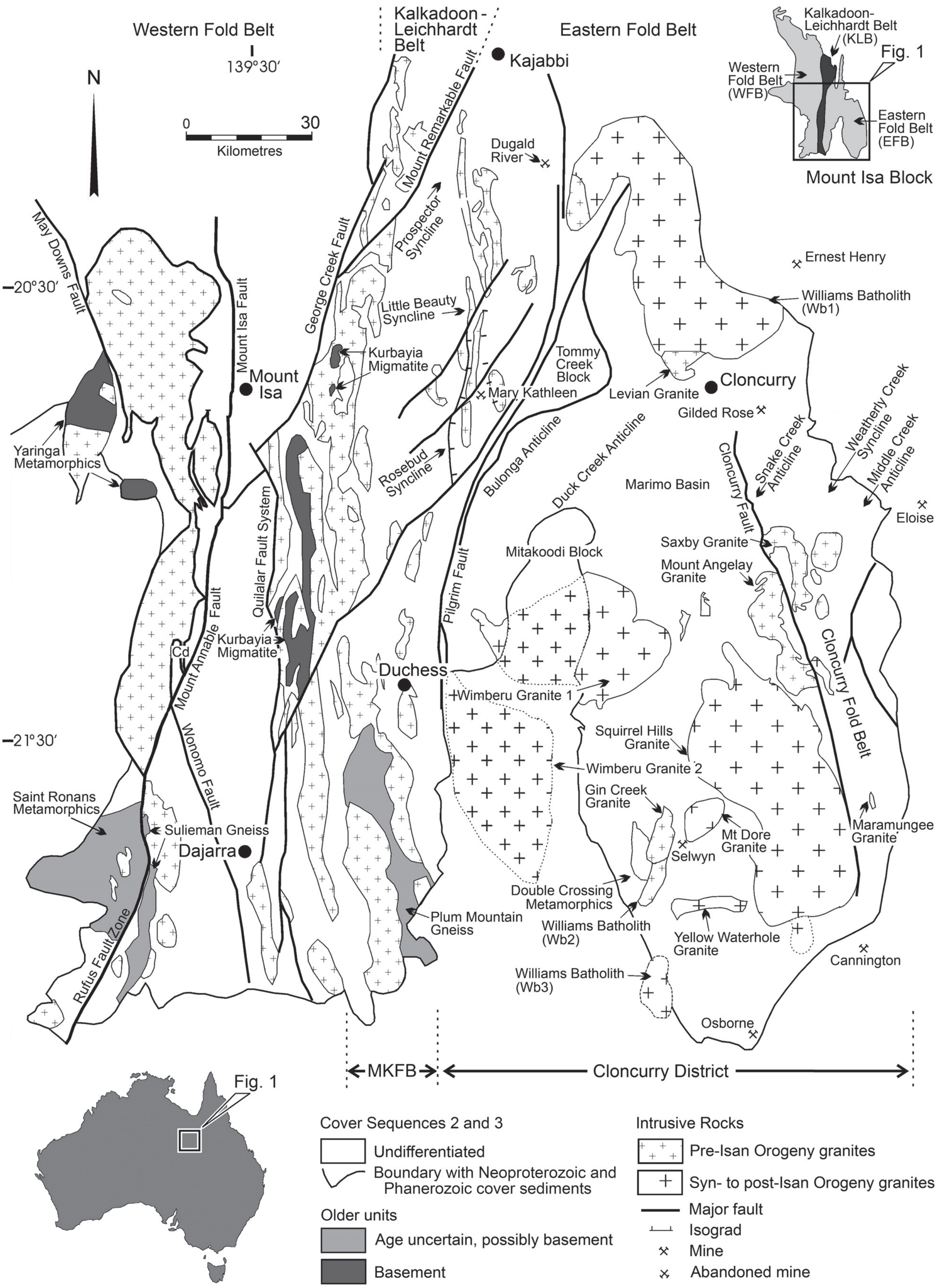

Figure 1: Location (insets) and general geology of the Western, Kalkadoon-Leichhardt and Eastern Fold Belts, showing the further division of the Eastern Fold Belt into the Mary Kathleen Fold Belt (MKFB) and Cloncurry District. The spatial distribution of Cover Sequences 1 to 3 and intrusive features pre- and syn- to post- Isan Orogeny are shown, as well as some of the major mineral deposits in the Eastern Succession (redrawn from Foster, 2003, adapted from original geology by Blake, 1987). Modifications include interpreted geology from Queensland Department of Mines and Energy, (2000).

also been considered (Butera, 2004; Oliver *et al.*, 2008). Most deposits within the region are characterised by strong structural controls (Laing, 1993, 1998; Oliver, 1995; Davidson and Davis, 2001; Marshall and Oliver, 2008) and major faults in the area have been suggested as fluid conduits responsible for mineralisation. Many of the copper-gold deposits share several characteristics, which collectively define the Cloncurry association of mesothermal ironstone-hosted copper-gold deposits (Williams, 1998). Concise descriptions of individual deposit geology can be found in Williams and Pollard (2001).

The current lack of consensus and uncertainty in genetic models for IOCG deposits in the Mount Isa Inlier, leads to inherent problems in defining a rigorous exploration model. This suggests that a data-driven approach, such as a 'weights of evidence' (WOFE) analysis, may be best suited for exploration needs. However, the clear evidence of structural controls for many of these deposits clearly suggests a role for mechanical processes and mechanical modelling. Hence both approaches have been combined in this study to maximise the outcome and to benefit a prospectivity analysis of the Mount isa Inlier for IOCG deposits.

Spatial analysis is used here at a large scale (>80 000 km^2) to assess the distribution of all known copper-gold deposits and significant occurrences within the Mount Isa Inlier, including the Eastern, Kalkadoon-Leichardt and the Western fold belts. Fifteen data layers were selected for analysis that may have had a significant influence on the Proterozoic 1550 to 1500 Ma IOCG deposits. The fifteen parameters are: (1) lithostratigraphy, (2) Corella Formation-Soldiers Cap Group contact, (3) mafic intrusives, (4) Williams-Naraku batholiths, (5) metamorphic zones, (6) faults, (7) fault bends, (8) magnetics, (9) gravity, (10) radiometrics, and (11 to 15) rock-chip geochemistry of Cu, Au, Co, Ni and As. The main aims of the study were to: (1) determine the critical processes and ingredients potentially involved in the localisation of copper-gold mineralisation within the Mount Isa Inlier by studying the spatial association of the fifteen parameters to the location of IOCG deposits; (2) rank the relative importance of the fifteen data layers based on contrast values, to gain new insights into potential controls currently unrecognised or considered less important; (3) discuss the results in relation to a geological exploration model, with the aim of improving it; (4) generate a set of posterior probability maps for the Mount Isa Inlier, including a nine-layer model that attempts to eliminate the effect of cover.

The numerical modelling presented here, is focussed on the structural scenarios pertinent to the latter part of the Isan Orogeny (<1530 Ma), in which fluid flow and mineralisation were hosted mostly in D_3 or D_4 structures (e.g., Laing, 1998; Marshall, 2003). The study area covered by the numerical simulations was approximately 24 800 km^2, which included many deposits in the EFB, from north of Cloncurry to north of Osborne. Copper-gold mineralisation, and the majority of the deposits in the Eastern Succession, have a close spatial relationship with faults and strike-slip deformation (e.g., Baker and Laing, 1998; Laing, 1998), and the structural architecture and deformation history is reasonably well known, providing a good basis for application of discrete element techniques incorporating the interaction of fault movement (slip) and stress partitioning, as used in this study. The ability to numerically simulate and 'map' the effects of deformation can provide important data in understanding the spatial and temporal consequences of such processes. This technique has been used in determining the magnitude and distribution of stress in many mineralised faulted terranes (e.g., Oliver *et al.*, 1990, 2001a; Holyland *et al.*, 1993; Holyland and Ojala, 1997; Jiang *et al.*, 1997; Mair *et al.*, 2000; McLellan and Oliver, 2008). The distinct element program UDEC (Universal Distinct Element Code; Itasca 2000) is used here to examine the effects of deformation and fluid flow along faults and rock boundaries in the Eastern Succession of the Mount Isa Inlier, during the main mineralising stage of its protracted deformation history. The main aims of the numerical simulations in this study are to determine for both regional and more local scales (~100 and 1 to 10 km): (1) areas that display anomalous stress values; (2) areas that have a good correlation between predicted or observed failure and known mineralisation; and (3) areas arising from this computational prospectivity analysis which may influence future mineral exploration in the region. Here we will focus on the EFB and the Cloncurry and Selwyn regions, and undertake a comparative analysis between the numerical outputs and the GIS analysis, with particular reference to comparisons between the results of the data driven posterior probability maps and numerical maps for the same areas.

Geological Background

The Mount Isa Inlier of Northwest Queensland (Fig. 1) comprises three major units from west to east: the Western Fold Belt (WFB), the Kalkadoon-Leichhardt Belt (KLB) and the Eastern Fold Belt (EFB), which are predominantly north-south trending sedimentological and structural domains (Blake and Stewart, 1992; O'Dea *et al.,* 1997). The Inlier is characterised by Palaeo- to Mesoproterozoic meta-sedimentary rocks, rhyolitic and basaltic meta-volcanic rocks, gabbro, dolerite and widespread I-type granitoids. An early history of basement formation and deformation (e.g., Etheridge *et al.*, 1987) was followed by several episodes of intracratonic rifting and basin formation (e.g., Blake and Stewart, 1992; Page and Sun, 1998; Southgate *et al.*, 2000). The main period of protracted deformation that is closely associated with the majority of mineralisation in the region took place during the Isan Orogeny (ca. 1600 to 1500 Ma; Page and Bell, 1986; Holcombe *et al.*, 1991; Blake and Stewart, 1992), with IOCG deposits mostly formed during the waning stages of emplacement of the Williams and Naraku Batholiths (1550 to 1530 Ma).

The EFB can be divided into the Mary Kathleen Fold Belt (MKFB) and the Cloncurry district, which are separated by the Pilgrim fault zone (Fig. 1). The pre-Isan orogeny meta-sedimentary rocks of the EFB are called the Eastern Succession, which includes coarse to fine clastic meta-sedimentary rocks and mafic volcanic rocks (Soldiers Cap Group), and calcareous meta-sedimentary rocks (Corella and Doherty Formations). Minor pre-Isan intrusions and widespread late- to post-Isan Orogeny intrusive rocks (Williams and Naraku Batholiths) occur in the EFB. The earliest intrusive phases in the Eastern Succession (ca. 1740 Ma) are coincident with the 'Big' event (Jackson *et al.*, 2000) and include the Wonga Batholith and the Dipvale, Levian and Gin Creek Granites (Table 1). This intrusive period was accompanied by large-scale Na-Ca-K metasomatism, NaCl-rich scapolitisation and skarn development (Oliver, 1995). The Ernest Henry Diorite in the EFB and the Sybella Granite (ca. 1670 to 1660 Ma) in the WFB (Table 1) were intruded contemporaneously with the 'Sybella' or 'Gun' event (Jackson *et al.*, 2000). The 'Williams and Naraku' event (Table 1) comprises multiple K-rich intrusive phases which have been spatially and temporally associated with at least some of the Proterozoic iron oxide copper-gold-cobalt mineralisation in the Cloncurry district (Pollard *et al.*, 1998; Williams, 1998), and represents the most voluminous episode of intrusion in the EFB. Older intrusions of the Williams and Naraku Batholith (1550 to 1530 Ma) are the Marramungee, Mount Margaret, Saxby and Mount Angelay granites (Page and Sun, 1998). A younger suite (1530 to 1500 Ma), includes the Mount Dore, Squirrel Hills, Wimberu and Yellow Waterhole granites (Page and Sun, 1998; Table 1). There are no clear temporal links between the Williams and Naraku event and major intrusive activity in the WFB, although Connors and Page (1995) recognise minor intrusions in the WFB of a similar age (Mica Creek Pegmatites).

Deformation and Metamorphism

A complex and protracted deformation and metamorphic history is evident within the Mount Isa Inlier, related to cycles of extension and shortening between 1900 and 1500 Ma. Following the 'Wonga' extensional phase (ca. 1750 to 1730 Ma), four main deformation events during the Isan Orogeny (D_1, D_2, D_3 and D_4) were proposed by Bell (1983) in the western Mount Isa inlier (see also Rubenach *et al.*, 2008). Several authors have attempted to correlate the deformation events across both the Eastern and Western Fold Belts (Page and Bell, 1986; Etheridge *et al.*, 1987; Holcombe *et al.*, 1991; O'Dea *et al.*, 1997; Adshead-Bell, 1998; Bell and Hickey, 1998; Laing, 1998; Mares, 1998). Within the EFB, D_1 is thought to have taken place during a north-south shortening event (Page and Sun, 1998; Rubenach and Lewthwaite, 2002) and may have been responsible for the juxtaposition of Cover Sequence 3 against Cover Sequence 2 (Laing, 1998). A major east-west contractional event (D_2; ca. 1590 to 1550 Ma), resulted in north-south trending, tight to isoclinal upright folds, and pervasive steep axial-plane foliations. Several major shear zones have also been attributed to D_2, for example the Mount Dore and Eloise shear zones (Laing, 1998). The peak of metamorphism in the Mount Isa Inlier (greenschist to upper-amphibolite facies) was reached during D_2 (e.g., Rubenach, 1992; Oliver, 1995; Rubenach and Barker, 1998; Rubenach and Lewthwaite, 2002), with the metamorphic peak in the southeast region at ca. 1590 Ma (Perkins and Wyborn, 1998; Giles and Nutman, 2003). Overprinting of many D_2 structures is attributed to one or more (ca. 1540 to 1500 Ma) compressional or transpressional events such as D_3, resulting in north-northwest trending folds reactivating the S_2 fabric, and D_4 which resulted in northeast trending folds and reactivation of S_2 fabrics, faults and shear zones, and broad coincidence with emplacement of the Williams and Naraku Batholiths. The majority of the copper and copper-gold mineralisation in the EFB is hosted within D_3 structures, many of which exhibit strike-slip movement that has been associated with the localisation of the bulk of mineralisation in the area (Carter *et al.*, 1961; Laing, 1998).

The EFB shows extraordinarily extensive regional sodic-calcic metasomatism in both the Mary Kathleen Fold Belt (Oliver, 1995) and in the Cloncurry district (de Jong and Williams, 1995; Williams, 1998; Oliver *et al.*,

Table. 1: General events, geochronology and mineralisation of the Mount Isa Inlier (after McLellan & Oliver, 2008).

Event (Ma)	Intrusions	Cu-Au mineralisation	Age dates (Ma)	Faults - general trends
Pre-Isan Orogeny				
Big (1750-1735)	Wonga Batholith		1750-1730 U-Pb	
	Dipvale Granite		ca. 1746 ± 7 U-Pb	
	Levian Granite		ca. 1746 ± 8 U-Pb	
	Gin Creek Granite		ca. 1741 ± 7 U-Pb	
Gun (1680-1670)	Sybella Granite		ca. 1673 - 1655 U-Pb	
	Ernest Henry Diorite		ca. 1660 - 1657 U-Pb	
Isan Orogeny				
D1 (1610 ± 13)				thrust faults
D2 (1590 - 1550)			ca. 1590 Ar/Ar	N-S striking shear zones
			1584 ± 17 U-Pb	
		Osborne Cu-Au	ca. 1540 Ar/Ar	
			1595 ± 6 U-Pb	
Williams-Naraku Event				
(1550-1500 Ma)	Maramungee Granite		1545 ± 11 U-Pb	
	Mica Creek Pegmatites		1532 ± 7 U-Pb	
D3 (1530 - 1500)		**Eloise Cu-Au**	ca. 1530 Ar/Ar	strike-slip reactivation
	Mt. Margaret Granite		1530 ± 8 U-Pb	NE - dextral
	Mt. Angelay Granite		1523 ± 4 U-Pb	N - sinistral
	Mt. Dore	**Ernest Henry Cu-Au**	1514-1504 Ar/Ar; 1516 ±10 U-Pb	NW - sinistral
	Squirrel Hills Granite	**Monakoff Cu-Au**	1508 ± 10 Ar/Ar; 1508 ± 4 U-Pb	
	Wimberu Granite	**Starra Cu-Au**	ca. 1505 Ar/Ar; 1508 ± 4 U-Pb	
	Yellow Waterhole Granite	**Mt. Elliot Cu-Au**	ca. 1505 Ar/Ar; 1493 ± 8 U-Pb	

Age dating compiled from several sources (Holcombe *et al.*,1992; Pearson *et al.*, 1992; Connors & Page, 1995; Little, 1997; Pollard & McNaughton, 1997; Pollard & Perkins, 1997; Page & Sun, 1998; Perkins & Wyborn, 1998; Pollard *et al.*, 1998; Rotherham *et al.*, 1998; Mark *et al.*, 1999, 2000; Davis *et al.*, 2001; Gauthier *et al.*, 2001; Williams *et al.*, 2001; Giles & Nutman 2002, 2003). Structural data compiled from (Page & Bell, 1986; Holcombe *et al.*, 1992; Laing, 1998; Davis *et al.*, 2001).

2004). Two major metasomatic events are distinguishable: (1) pre- to syn-regional metamorphism (1600 to 1590 Ma) which has been noted around the Osborne deposit and elsewhere (Rubenach *et al.*, 2001, 2008); and (2) post-peak regional metamorphism (1540 to 1480 Ma), during granite emplacement (e.g., Williams and Naraku Batholiths) in the Cloncurry district (de Jong and Williams, 1995; Pollard *et al.*, 1998; Mark, 2001; Pollard, 2001). Metasomatic fluids utilised major structural conduits (e.g., the Cloncurry Lineament; Austin and Blenkinsop, 2008; and the Pilgrim Fault) for infiltration into the surrounding country rocks, although the metasomatism is also very widespread. Sodium-calcium alteration commonly predates mineralisation in several of the IOCG deposits (Adshead, 1995; Perkins and Wyborn, 1998; Williams, 1998; Mark *et al.*, 2006) suggesting relatively late stages of mineralisation (post 1540 Ma) for many of the copper-gold deposits. One exception to this is the Osborne deposit, where recent dating studies have highlighted a potential syn-peak metamorphic timing to mineralisation (based on 1595±5 Ma Re-Os age dates on molybdenite and a 1595±6 Ma U-Pb age date on hydrothermal titanite; Gauthier *et al.*, 2001), with no apparent proximal major intrusion. Hence, there is a strong argument for two distinct periods of IOCG mineralisation in the district. Oliver *et al.* (2008) indicate that spatial and geochemical data on mafic rocks suggests that the concentration of copper and gold into some of the mineral deposits involved a significant component of metre- to kilometre-scale remobilisation and reworking of early enrichments formed during basin evolution and initial inversion, by later regional metamorphic and magmatic-hydrothermal fluids. Osborne (eastern domain) and Eloise-type ores (or ore precursors) initially formed during or before the 1600 Ma regional metamorphic peak, by interaction of basinal or early metamorphic fluids with mafic rocks and ironstones, whereas younger oxidised brines released by the Williams/Naraku intrusions at ~1530 Ma overprinted magnetite±sulphides at Osborne (western domain) and Starra to produce the presently mined hematite-chalcopyrite ores. This study mainly focuses on the structurally controlled, post-regional metamorphic deposits. Even though some deposits may have formed or pre-concentrated metals relatively early, many now reside in younger fault-related structures (e.g., McLellan and Oliver, 2008; Oliver *et al.*, 2008).

IOCG Genetic Models and Metallogenesis

A review of the literature suggests that IOCG deposits worldwide display great variability (e.g., Hitzmann, 2000; Skirrow and Walshe, 2002) and occurrences in the Mount Isa Inlier are no exception. The diverse range of copper-gold deposit styles found in the Mount Isa Inlier includes magnetite-rich breccias (Ernest Henry), ironstone hosted (Osborne, magnetite-rich, Starra, hematite-rich), skarn hosted (Mount Elliot-SWAN, Trekelano), and carbonaceous metasediment hosted (Mount Dore, Victoria, Stuart). The key variable that gives rise to differences in copper-gold ±iron oxide deposits within the Mount Isa Inlier may be the local host rock-types, which are very diverse (Mustard *et al.*, 2004). These can produce a spectrum of structural styles (vein, breccia, replacement), iron oxide association (magnetite, hematite), alteration and iron sulphide ore mineral assemblages (pyrite, pyrrhotite or both), minor element association (±Co ±Ni ±Ag ±F ±As ±Mo ±Ba ±REE ±U), and Cu:Au:Ag ratios. A number of characteristics have been considered as common to many IOCG deposits in the Mount Isa Inlier, including: (1) regional temporal association with intrusions of the 1550 to 1500 Ma Williams-Naraku batholiths, but lack of a local intimate spatial relationship such as that exhibited by porphyry and related skarn deposits (e.g., Budd *et al.*, 2002; Williams *et al.*, 2001); (2) alteration sequence from early sodic-calcic, to iron and potassic-rich alteration, to muscovite (Williams *et al.*, 1993; Williams, 1994); (3) brines (200 to 500°C) directly associated with ore deposition; and (4) strong structural controls, localised by a range of brittle-ductile and brittle shear zones (e.g., Laing, 1998). These similar characteristics have been interpreted to imply a common genesis for many of the IOCG deposits. Specific published ore-genesis models for IOCG deposits in the Mount Isa Inlier range from a single-stage hydrothermal system with one evolving fluid source, to complex multiple-stage hydrothermal systems involving two or more fluid sources (Kendrick *et al.*, 2008; Mark *et al.*, 2004).

A deposit model for the genesis of copper-gold-iron-oxide deposits in the Mount Isa Inlier would generally involve:

- Metal-rich, sulphur-poor, moderately oxidised, aqueo-carbonic brines, derived from oxidised alkaline-intermediate intrusions of the (1550 to 1490 Ma) Williams-Naraku batholith, which were emplaced at mid-crustal levels (~175 to 200 MPa; >7 km depth).
- As the ore-forming fluids moved away from their source, they were focussed along ductile-brittle shear zones, interacting to varying degrees with a range of different rock types, partially modifiying their character.
- Initial fluid-wall rock interaction (between degassed magmatic fluids and country rocks) produced early, barren, regionally extensive Na-Ca alteration. Subsequent, areally restricted, K-Fe rich alteration ± later rare carbonate-muscovite was intimately associated with copper-gold mineralisation; -or- there is a general sequence from (1) sodic to (2) potassic to (3) sericitic alteration and silicification with time.
- Within an overall compressional tectonic setting, ore bodies were formed locally at favourable trap sites, where either chemical reactions and/or a rapid change in physical conditions (↓P, ↓T, ↓fO_2, fS?, pH?) occurred.
- Precipitation of copper-gold ore/mineralisation involved one, or a combination of, depositional mechanisms including: (1) cooling; (2) a number of wall-rock reactions (reduction by magnetite or carbonaceous matter, sulphidation of iron silicates, sulphur-rich rock, mafic intrusives); (3) un-mixing of a magmatic fluid into low salinity CO_2-bearing aqueous fluid and brines; and (4) fluid mixing between magmatic and one or more fluids of a different origin (mantle/metamorphic/basinal-evaporate/meteoric).

The deposits discussed in the EFB are considered to represent deep-seated copper-gold systems, with a depth of formation of around 7 km. Many workers believe that this would greatly restrict fluid convection, resulting in single pass systems (Hitzman, 2000). In contrast, other terrains possess IOCG systems developed at shallower levels, ranging from 4 to 6 km, to near surface, for which models involving hybrid, or dominantly amagmatic fluid sources are realistic. Yet researchers do not fully agree on major issues such as (1) the relationships between early sodic-calcic alteration, later potassic alteration and copper-gold mineralisation, (2) sources of fluid responsible for ironstone formation, (3) the role of magmas versus other sources of ore metals and fluids, (4) the role of mafic intrusions as a source of ore metals and fluids (Mark *et al.*, 2004).

The IOCG deposits of the Mount Isa Inlier have yielded more than 900 000 t copper, 27 t gold and 28 t silver from those exploited to date, with 3 300 000 t copper, 167 t gold in global resources and reserves. Resources of some of the main deposits in the EFB include *Ernest Henry* (167 Mt @ 1.1% Cu, 0.54 g/t Au), *Eloise* (3.2 Mt @ 5.8% Cu, 1.5 g/t Au, 19 g/t Ag), *Osborne* (11.2 Mt @ 3.51% Cu, 1.49 g/t Au), *Mount Elliot* (3.3 Mt @ 3.6% Cu, 1.8 g/t Au), *Starra* (6.9 Mt @ 1.65% Cu, 4.8 g/t Au) and *Mount Dore* (26 Mt @ 1.1% Cu, 5.5 g/t Au) (Williams and Skirrow, 2000). There have been some recent discoveries in the region, in particular the CuDECO Ltd *Rocklands* copper discovery (>25 Mt @ 2% $Cu_{eq.}$; CuDECO Website, 2009) in 2006, and more recently some interesting prospect results from the *Amethyst Castle* and *Mount Elliot-SWAN* prospects by Ivanhoe Australia Ltd (475 Mt @ 0.5% Cu, 0.38 g/t Au; Brown *et al.*, 2009) which has led to renewed interest in this area by exploration companies. This is an indication of the unknown and undiscovered potential of the region.

Spatial Data Analysis

In order to investigate the considerable range of potential geological controls on IOCG mineralisation, a spatial data analysis was undertaken, aimed at evaluating the relative importance of a range of spatial variables, including host rock type, proximity to particular stratigraphic contacts, proximity to mafic intrusives or the Williams-Naraku batholiths, metamorphism, structure, geophysics (including aeromagnetics and gravity), radiometrics and rockchip geochemistry (Cu, Au, Co, Ni and As).

Weights of Evidence Method

The spatial data analysis employed the ‘weights of evidence’ (WOFE) technique (cf. Bonham-Carter, 1994) using the ‘Spatial Data Modeller’ extension developed for Mapinfo software (see Avantra Geosystems Pty Ltd, MI-SDM Users Guide).

The process used in WOFE modelling is essentially a quantitative version of overlaying maps of different *spatial variables* (i.e., *spatial data layers* comprising for example, host rock type, geochemistry, geophysical anomalies, etc.), to identify areas most prospective for mineralisation of a specified style. Spatial variables are also known as *evidential themes* or *layers*, which when entered into a GIS such as Mapinfo, may be referred to as *binary evidence maps*. The significance of particular spatial data layers, or combinations of layers, in delineating prospective areas is determined mathematically by making a comparison of the spatial variable with the real distribution of a *training set*, i.e., a set of mineral occurrences of the type sought, whose locations are known and are plotted as a spatial data layer.

In this application, WOFE analysis is a map-correlation and map-integration process, applied by formulating the mathematical odds, both for and against (i.e., positive and negative), of a mineral deposit being associated with a spatial variable within a spatial data layer. The odds of this association between the training set and each spatial variable are measured and expressed as *weights*, defined as the natural log of the odds. Positive and negative weights are calculated for each spatial variable, which are then combined, using Bayesian statistical techniques, to produce a mineral potential map (Bonham-Carter, 1994).

The WOFE method is based on the analysis of *prior* and *posterior probabilities* (defined below) using measures of the number of *unit cells* in the study area, the spatial data layers, and the mineral occurrences of the training set. In these calculations, each mineral occurrence in the training set is assumed to occupy a small area, corresponding to a *unit cell*, allowing the probability of a point location to be defined as the probability per unit area. The remainder of the study area is similarly divided into unit cells of the same dimensions. The choice of a unit cell size affects the prior and posterior probabilities, but has relatively little influence on the weights.

The *prior probability* P(D) is the odds for a new deposit occurring within a unit cell of the study area by chance alone, expressed by the formula: **P(D) = N(D) / N(T)** where N(D) = the total number of unit cells containing a mineral deposit/occurrence and N(T) = the total number of unit cells in the study area. The *posterior probability,* P(D|B) is the odds of a new deposit occurring within a unit cell based on additional evidence provided by a spatial variable B (SVB; e.g., a host rock type), expressed by the formula: **P(D|B) = P(D) * F(B)**, where P(D) is the prior probability, and F(B) is the factor for SVB. F(B) in turn = P(B|D) / P(B). The numerator, P(B|D), is the probability of a mineral occurrence being associated with SVB, and is calculated by the formula P(B|D) = N(B|D) / N(D), where N(B|D) = the number of unit cells within the study area containing a mineral deposit/occurrence that is associated with SVB, and N(D) is as defined above. The denominator in the P(B|D) formula, P(B), is the probability that a unit cell within the study area is associated with SVB, and is calculated by the formula P(B) = N(B) / N(T), where N(B) is the number of unit cells within the study area corresponding to SVB, and N(T) is as defined above.

Consequently, if the study area covers 4 km^2, and the unit cells are each 0.1 x 0.1 km, there are 400 unit cells within the study area. If the training set comprises 10 mineral occurrences, then the *prior probability* P(D) = 10/400 = 0.025, or 2.5%. If SVB covers a total area of 100 unit cells, and 7 of the 10 mineral occurrences of the training set fall within this area, P(B|D) = 7/10 = 0.7, P(B) = 100/400 = 0.25, and therefore F(B) = 0.7/0.25 = 2.8. Consequently, the *posterior probability,* P(D|B) = 0.25 * 2.8 = 0.07, or 7%, i.e., the probability that a unit cell associated with SVB will embrace a new mineral occurrence/deposit.

Using these same concepts, ***weights*** can be assigned to the spatial variable. Positive weight $\mathbf{W^+}$ is the odds that the spatial variable and the mineral occurrences/deposits of the training set <u>do</u> occur together, while negative weight $\mathbf{W^-}$ is the odds that the spatial variable and the mineral occurrences/deposits of the training set <u>do not</u> occur together. The formula for these two weights is as follows: $\mathbf{W^+ = log_e [\ P(B|D)\ /\ P(B|D^-)\ ]}$ while conversely, $\mathbf{W^- = log_e [\ P(B^-|D)\ /\ P(B^-|D^-)\ ]}$. P(B|D) is a probability calculated as in the previous paragraphs, while $P(B|D^-) = N(B|D^-) / N(D^-)$, $P(B^-|D) = N(B^-|D) / N(D)$, and $P(B^-|D^-) = N(B^-|D^-) / N(D^-)$, where $N(B|D^-)$ = the number of unit cells associated with SVB that <u>do not</u> include a mineral deposit, $N(B^-|D)$ = the number of unit cells <u>not</u> associated with SVB that <u>do</u> include a mineral deposit, $N(B^-|D^-)$ = the number of unit cells <u>not</u> associated with SVB that <u>do not</u> include a mineral deposit, and $N(D^-)$ = the total number of unit cells that <u>do not</u> contain a mineral deposit/occurrence.

The *contrast*, or *C value* is a measure of association between a spatial variable and the mineral occurrences of the training set and is defined as: $\mathbf{C} = \mathbf{W}^{+} - \mathbf{W}^{-}$. The higher the contrast, the greater the spatial association between mineral occurrences/deposits and the particular spatial variable, while a value of zero indicates no spatial association and only a random distribution.

Another of the measures applied in WOFE analysis is the *confidence* of the posterior probability. This is the ratio of the posterior probability to its standard deviation. High confidence values indicate that the uncertainty is relatively small compared to the probability value itself, whereas low values of this ratio (that may be in areas of low or high probability) indicate relative large uncertainty. Confidence values of more than about 2 are regarded as having a high degree of certainty.

The display and handling of spatial data depends on the data type, which may be: *point* (e.g, mineral occurrences, rock-chip geochemical data), *line* (e.g., faults, lithological contacts), *grid* (e.g., magnetic susceptibility or gridded geochemical soil sample data) or *polygons* (e.g., host rocks, alteration zones). Grids may be either *numeric*, used to define continuously varying surfaces of information, such as gravity readings, in which grid cell values are either mathematically estimated from a table of point observations or assigned real numeric values, or *classified*, where each cell is referenced to a descriptive attribute. *Buffers* are allocated to point and line data representing their radius of influence or proximity, a procedure that involves generating a series of buffer zones around the feature being tested for spatial association. The buffer zone with the maximum *contrast* is defined as the *optimal buffer distance*.

Study Area and Training Data Set

The study area for the spatial analysis occupies 82 733 km^2 and is located between 325 000 and 525 000 mE, and 7 955 000 and 7 535 000 mN. It extends from 17 km west of Mount Isa township to 75 km east of Cloncurry, and from 23 km south of Osborne to 110 km north of Mount Oxide. The selected area encompasses three full 1:250 000 sheet areas, including Dobbyn (SE54-14), Cloncurry (SE54-2) and Duchess (SE54-6), as well as portions of the surrounding sheets. The area includes all of the exposed Eastern Fold Belt (12 455 km^2, 15%), Wonga Fold Belt (3 924 km^2, 5%), Kalkadoon-Leichardt Fold Belt (6 879 km^2, 8%) and eastern parts of the Western Fold Belt (12 410 km^2, 15%), with the remaining 47 065 km^2 or 57 % of the area comprising post-mineralisation Phanerozoic basin cover. A large portion of this cover (16 162 km^2 or 20 %) is <100 m thick, and this part of the study area is where much of the future mineral discovery potential is located.

A total of 567 copper-gold occurrences are recorded in the Mineral Occurrence 2002 database within the study area (Queensland Department of Mines and Energy, 2002). A subset of 181 of these were selected as the training data set, based on the presence of both commodities (copper and gold), and either recorded historical production or the existence of a cited geological resource (Fig. 2a). The training sites selected are a critical factor in determining the meaning of a model (Raines, 1999). The shared characteristics of the IOCG deposits in the Mount Isa Inlier provide a sound basis for treating the deposits as a single related group or training data set with common genetic features, despite the wide range in geological styles. The subset of 181 copper-gold±iron-oxide occurrences was chosen because the targeting was aimed at the larger, more significant examples.

Data Analysis

Spatial correlations were calculated using the 'weights of evidence' technique as summarised above. A unit area of 0.25 km^2 was used in these calculations, assuming the known deposits have a 0.25 km^2 area of influence.

Geological data, such as lithological and structural information, was derived from the Northwest Queensland Mineral Province Report (Queensland Department of Mines and Energy, 2000). The report provides a solid geology map of Proterozoic basement and structural framework, based on an integrated interpretation of outcropping geology, combined with aeromagnetic and gravity data. As a result, this data enables areas under cover to be included in the analysis. The high resolution regional aeromagnetic and radiometric data was supplied by Xstrata, while regional gravity data was provided by Geoscience Australia. Surface rock chip geochemistry was obtained from the Geological Survey of Queensland geochemical database (Queensland Department of Natural Resources and Mines, 2003) and the Rockchem database from Geoscience Australia.

The creation of binary evidence maps from the spatial data is described briefly below:

- Buffers, representing the proximity to a feature were assigned to point and line data. The procedure adopted involved generating a series of buffer zones around the feature being tested for spatial association. The buffer zone with the maximum contrast was defined as the optimal buffer distance. In the instance of the Williams-Naraku batholith, the first buffer or granite polygon was excluded as sub-optimal, while in the case of mafic intrusives, the first buffer or mafic intrusion polygon was included as optimal.
- Gridded data (e.g., magnetic, gravity and radiometrics) were subdivided into a number of classes using the *MI-SDM> grid analysis tool> classify grid by histogram* tool. 'Weights of evidence' were run on classified grids to determine the contrast for each class. The classes producing a contrast of 0.5 or greater were then combined in a final reclassified grid. The results of the grid analysis were used without buffering.
- Polygons were utilised for spatial variables such as lithologies, and metamorphic zones. All features with a contrast value of 0.5 or greater were combined into a reclassified map.

Parameter 1 - Host-rock Lithostratigraphy: The digital basement geology map was subdivided into 22 lithological groups. The most favourable lithologies that have contrast values of >0.5 include: siliciclastics-carbonaceous shale to siltstone, mafic intrusives, felsic extrusives, very fine to fine grained carbonate rocks, mafic extrusives, jaspilite/chert, intermediate intrusives and medium to fine grained carbonates. The binary map produced from the grouped lithologies is shown below (Fig. 2b).

Parameter 2 - Lithological Boundaries: A statistical review of the proximity of copper-gold±iron-oxide occurrences of the training data to lithological boundaries highlighted a significant number of the total located within 750 m of the contact between the Corella Formation and other lithologies, with many of the larger known occurrences close to the contact with the Soldiers Cap Group. The binary map produced for the Corella Formation boundary is shown below (Fig. 2c).

Parameter 3 - Mafic Intrusives: Mafic intrusives occur throughout the Mount Isa Inlier (e.g., metadolerite, amphibolites, mafic dykes, diorites and minor gabbro). Many known copper-gold deposits have a spatial association with these intrusives, with the best contrast value being obtained when a buffer of 750 m is applied. Fig. 2d is a binary map produced for the mafic intrusives.

Parameter 4 - Williams-Naraku Batholiths: The late stage (post-D_2) intrusives of the Williams and Naraku Batholiths (Fig. 2e) crop out over at least 2400 km^2, range in age from 1520 to 1490 Ma and show a spatial association with copper±gold mineralisation (Wyborn, 1998; Wyborn *et al.*, 1994; Budd *et al.*, 2002). Using a data driven proximity analysis, Budd *et al.* (2002) concluded that fractionated

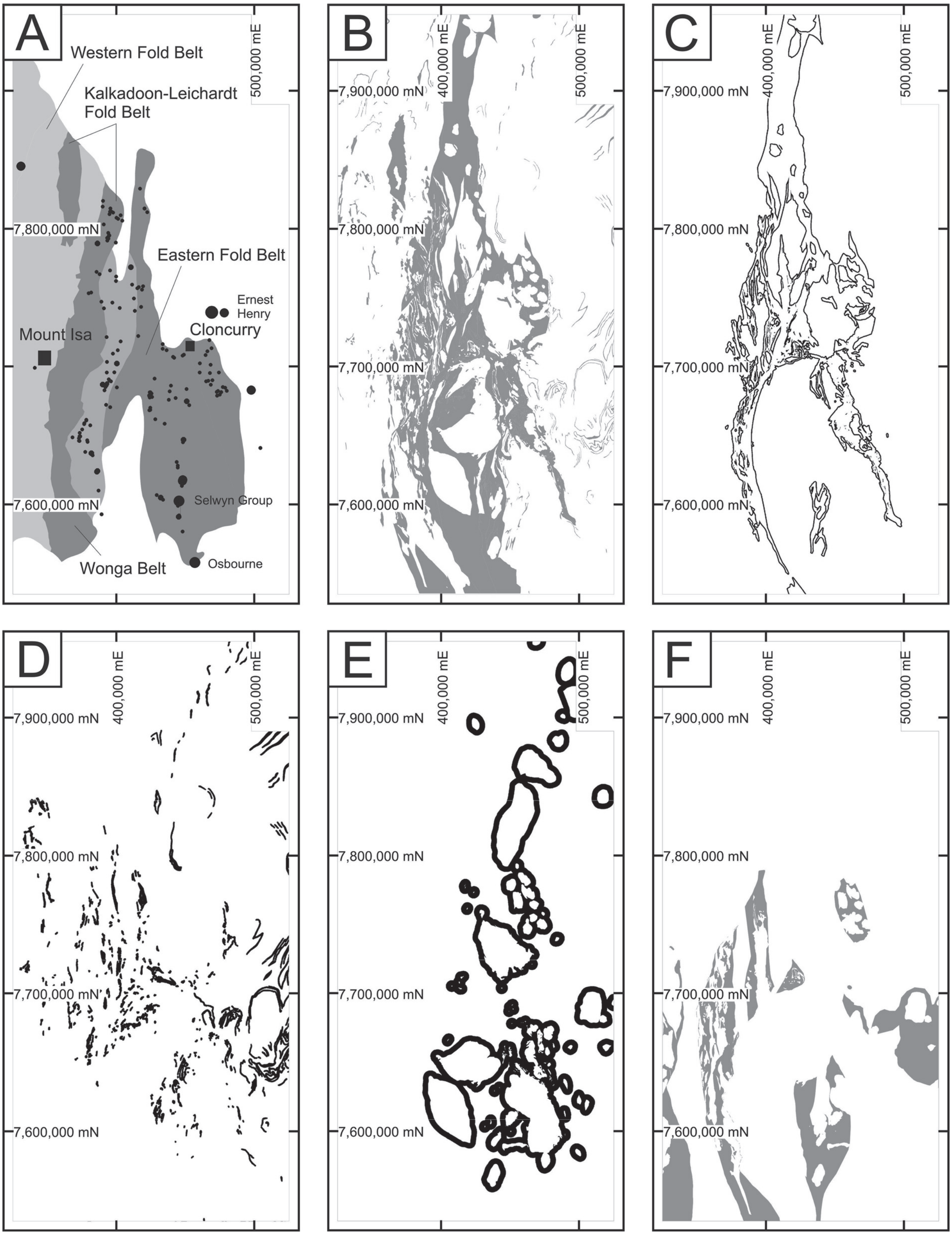

Figure 2: Spatial data analysis study area and binary evidence maps: **a)** the location of the copper-gold ± iron-oxide deposit training data for the Mount Isa Inlier study. Data is thematically mapped using total contained copper content (tonnes); **b)** binary evidence map of favourable lithologies highlighted in grey; **c)** binary evidence map of the 750 m buffer from the Corella Formation contact; **d)** binary evidence map of the distribution of mafic intrusives; **e)** binary evidence map showing the optimal 4 km buffer to Williams-Naraku batholiths; and **f)** binary evidence map of the more favourable amphibolite facies metamorphic zone.

Table. 2: Weights of evidence statistics for the seven fault orientations.

Orientation	Area (km^2)	Mineral Occurrences	Contrast	Confidence
N-S (350 to 15º)	21 265	108	1.45	9.59
NE (40 to 75º)	8 339	58	1.43	9.02
SSE (150 to 170º)	16 834	102	0.95	6.26
NNE (15 to 40º)	11 851	53	0.91	5.55
E-W (75 to 100º)	2 398	9	0.56	1.65
ESE (110 to 130º)	5 935	21	0.53	2.28
SE (130 to 150º)	9 434	29	0.39	1.94

F-poor I-type granites are most commonly spatially associated with copper-gold deposits in their study of the metallogenic potential of Australian Proterozoic granites. In their synthesis of the Mount Isa Inlier, they concluded that the Williams Supersuite, comprising the post-D_2 (post 1550 Ma) plutons of the Williams and Naraku Batholiths, had the best metallogenic potential, whereas the Burstal, Sybella, Nicholson and Kalkadoon suites had little or no potential.

Parameter 5 - Metamorphic Zones: Published age constraints indicate that peak metamorphism occurred at ca. 1600 to 1580 Ma across much of the district (Page and Sun, 1998; Giles and Nutman, 2002; Hand and Rubatto, 2002), with regional grades ranging from greenschist to upper amphibolite facies. The generalised metamorphic map (Fig. 2f) was compiled from studies by Foster (2003), and has been divided into greenschist, lower to middle amphibolite (staurolite, andalusite, cordierite zones) and upper amphibolite facies, the latter being further sub-divided into sillimanite and sillimanite/K feldspar zones. The copper-gold deposits mainly occur within the lower to middle amphibolite facies rocks, with Osborne, hosted by upper amphibolite rocks, being the exception.

Parameter 6 - Structure: The relatively young age of most gold-copper mineralisation (1550 to 1500 Ma), excluding Osborne (~1595 Ma), suggests that all faults in the database should be included in the analysis, because the protracted deformation and metamorphism of the Isan Orogeny (ca. 1600 to 1500 Ma) could have reactivated earlier structures formed between 1800 and 1600 Ma. All faults within the study area were plotted on a rose diagram, and based on their distribution, were subdivided into seven groups, namely: north-south (350 to 15°), north-northeast (15 to 40°), northeast (40 to 75°), east-west (75 to 100°), east-southeast (100 to 130°), southeast (130 to 150°) and south-southeast (150 to 170°). Although all seven fault groups were tested separately, the WOFE analysis indicated that north-south and northeast oriented faults had the strongest spatial association with the copper-gold occurrences, based on contrast values of around 1.4 and confidence of 9 (Table. 2). Many of the significant deposits are associated with either north-south (Osborne, Selwyn, Eloise) or northeast faults (Ernest Henry). All north-south and northeast oriented faults were selected to produce the binary map (Fig. 3a).

Parameter 7 - Magnetic Susceptibility: Magnetic highs were extracted from regional aeromagnetic data provided by Xstrata. This involved inspection of the cumulative histogram plots of the geophysical data for upper breakpoints and thresholding the data above this limit, and finally producing a binary anomaly map of magnetic highs (Fig. 3b).

Parameter 8 - Gravity Highs and Gradients: The gravity data was subdivided into five classes using a 'Spatial Data Modeller' and the grid classified by histograms. 'Weights of evidence' for the five classes indicated that gravity highs, and steep gradients adjacent to gravity highs and gravity lows, have a strong spatial association with the copper-gold occurrences. The gradients showing good contrast have been combined to produce the binary map (Fig. 3c).

Parameter 9 - Radiometrics (U/Th anomalies): After trying a variety of ratios, it was determined that the U/Th ratio radiometric image provided the strongest correlation with the copper-gold occurrences (Fig. 3d). Uranium has been documented as an accessory in several copper-gold occurrences including Ernest Henry (Oliver *et al.*, 2004). One of the limitations of the radiometric data is that its effectiveness is restricted to areas of outcrop. The data was clipped to areas of known outcrop to eliminate false anomalies located in areas of cover.

Parameter 10 - Rockchip Geochemistry: Rockchip geochemistry may be used to identify areas of outcropping mineralisation. The Queensland Department of Natural Resources and Mines exploration geochemistry dataset covering the Mount Isa Inlier, and Geoscience Australia's Geochemical database (OZCHEM) were combined into a single dataset. 'Gstats analysis' (the statistical analysis software program in ArcSDM) was used to create cumulative probability plots to analyse the assay data for each element. The data was reclassified according to

Table. 3: Summary statistics including confidence and contrast for Cu, Au, Ni, Co and As in rockchip samples from the Mount Isa study

	Cu	Au	Co	Ni	As
Count	30 161	20 431	17 511	7 717	14 038
Maximum	9 910 000	133	10 300	4 100	103 000
Minimum	0.00001	0.00001	0.00001	0.00001	0.00001
Mean	4 459	0.262	49.2	46.9	70.42
StanDev	60 671	2.12	154.9	117.6	934.5
Threshold	249	0.11	85	43	33
Atom	2 160	0.64	178	128	125
UA	8 300	3.1	274	364	300
Contrast	2.5	2.38	1.85	1.65	0.26
Confidence	12.37	11.97	7.66	4.76	0.65
Association	V Strong	V Strong	Strong	Strong	Weak

bottom cut, lower threshold and upper thresholds. Spatial statistics were run to determine the spatial correlations with the copper-gold occurrences. The contrast and confidence values indicate that there is a very strong spatial association between rockchips assaying ≥0.11 ppm Au (Fig. 3e), ≥249 ppm Cu (Fig. 3f), and the known occurrences (Table. 3). Co (≥85 ppm) and Ni (≥43 ppm) also possess a strong spatial association with contrast values of 1.85

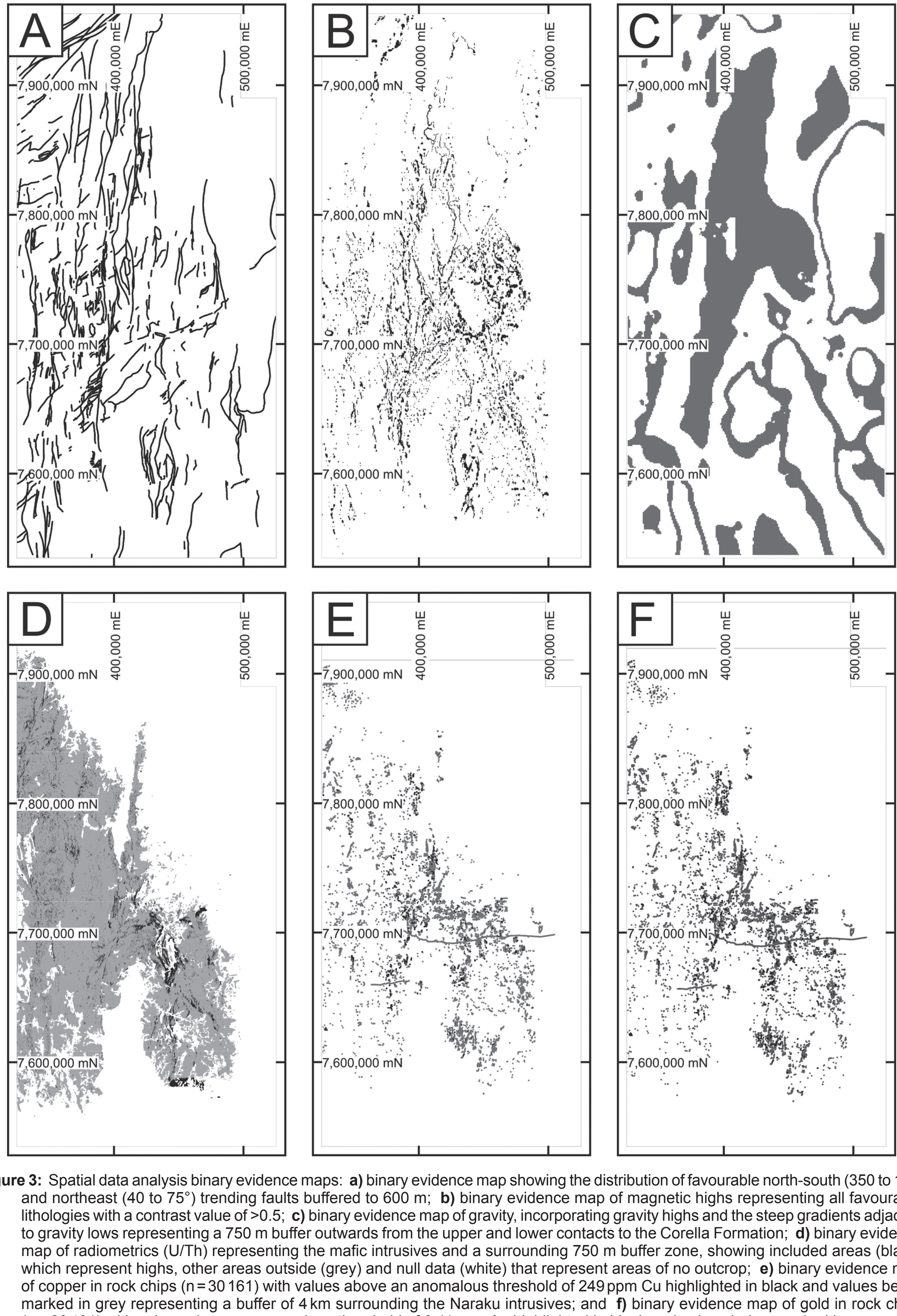

Figure 3: Spatial data analysis binary evidence maps: **a)** binary evidence map showing the distribution of favourable north-south (350 to 15°) and northeast (40 to 75°) trending faults buffered to 600 m; **b)** binary evidence map of magnetic highs representing all favourable lithologies with a contrast value of >0.5; **c)** binary evidence map of gravity, incorporating gravity highs and the steep gradients adjacent to gravity lows representing a 750 m buffer outwards from the upper and lower contacts to the Corella Formation; **d)** binary evidence map of radiometrics (U/Th) representing the mafic intrusives and a surrounding 750 m buffer zone, showing included areas (black) which represent highs, other areas outside (grey) and null data (white) that represent areas of no outcrop; **e)** binary evidence map of copper in rock chips (n = 30 161) with values above an anomalous threshold of 249 ppm Cu highlighted in black and values below marked in grey representing a buffer of 4 km surrounding the Naraku intrusives; and **f)** binary evidence map of gold in rock chips (n = 20 431) with values above an anomalous threshold of 0.11 ppm Au highlighted in black and values below marked in grey.

and 1.65 respectively. However, significantly less Co and Ni samples have been collected and coverage is less extensive. Arsenic (≥33 ppm) has a low contrast and weak spatial association.

WOFE Results and Posterior Probability Maps

Evaluation of Best Copper-Gold Parameters

Analysed parameters were ranked from one to twelve (Table 4) in terms of their spatial association with copper-gold deposits. The higher the contrast (C value) the better the spatial association. As a rule of thumb, C values above 0.5 are considered reasonable (G. Partington, 2004, pers. comm.), and confidence values above 1.5 are regarded as better than random (G. Partington, 2004, pers. comm.).

Rockchip geochemistry is clearly the best parameter for copper-gold occurrences, with copper and gold the only two parameters that produced C values above 2, (2.5 and 2.38 respectively). Note however, that geochemistry is restricted to areas of outcrop. Proximity to the Corella Formation contacts is the next highest parameter, with a C value of 1.87, and represents the highest ranking geological layer. Aeromagnetic highs are also a strong predictor of known copper-gold occurrences, with a C value of 1.82. This is by far the highest ranking geophysical parameter, well above that of gravity and radiometrics. The combined north-south and northeast oriented faults is the next best parameter, with a C value of 1.45.

Proximity to mafic intrusions, lithology, gravity and fault bends associated with north-south and northeast oriented faults, and metamorphic grade, are all moderately strong predictors of known copper-gold occurrences, with C values of greater than approximately 1. Radiometrics (U/Th ratio) is a weak predictor, with a C value of 0.83, while proximity to the Williams-Naraku batholith (using a 4 km buffer) had the lowest C value of 0.63 and is a weak predictor.

Posterior Probability Maps

The WOFE maps generated for each parameter were combined to create different cumulative posterior probability copper-gold maps for the Mount Isa Inlier.

The first of these maps comprises nine weighted map patterns, including: (1) favourable lithostratigraphy, (2) proximity to the Corella Formation-Soldiers Cap Group contact, (3) proximity to mafic intrusives, (4) proximity to the Williams-Naraku batholith, (5) metamorphic zones, (6) fault orientations, (7) fault bends, (8) magnetics and (9) gravity (Fig. 4). The nine layer model excluded surface geochemistry and radiometrics in an attempt to exclude the influence of cover to some degree.

Several observations can be made from this nine layer model (see Fig. 4):

- The Ernest Henry deposit, which is the largest known copper-gold deposit in the Mount Isa Inlier, produced the largest single anomalous region within the study area. Further analogous targets are evident to the north and west of Ernest Henry.
- The Selwyn group of deposits lie on the single largest anomalous linear trend, extending over a 40 km strike length, of which the southernmost ~10 km is under cover. Interesting areas in this same region include: northwest of Labour Victory, north of Answer and north of Hampden.
- There is a strong correlation between an anomalous region in the west and the Eloise deposit.
- The Osborne deposit is not strongly indicated, although this may reflect the lack of detailed geology in the interpretation as a result of cover.
- The Mount Elliot-SWAN, Mount Dore and Victoria-Stewart deposits are highlighted.
- Trekalano and southeast Duchess and areas northwest of Lady Ethleen are outlined in the Wonga belt.
- Numerous other areas are evident, particularly around Cloncurry township and to the west.

Numerical Process Modelling

The two main modelling techniques employed to simulate the response of rocks to deformation and contemporaneous fluid flow can be broadly categorised as continuous and discontinuous modelling. *Continuous modelling* treats rock masses as continuous elastic-plastic media and focuses on pervasive fluid flow (e.g., Ord and Oliver, 1997; McLellan *et al.*, 2004), whereas *discontinuous modelling* treats rock masses as elastic-plastic discrete blocks, and focuses on the deformation along faults and boundaries between such blocks. Areas of low minimum principal stress (σ_3) and low mean stress (σ_m) may indicate dilation and potential sites of fluid focusing, and are of great interest in mineralised hydrothermal systems. The ability to predict areas that are more susceptible to failure, and hence focus fluids, can be advantageous in defining sites of increased prospectivity within any region.

In the EFB, copper-gold mineralisation is found within varied host rocks (e.g., the ironstone-hosted Osborne and Starra, skarn-hosted Mount Elliot-SWAN, and metasediment-hosted Mount Dore and Victoria deposits) across the region, providing some evidence, and a strong argument favouring a more structural, rather than geochemical, control on the depositional sites of mineralisation. The strong relationship between structure (faults, breccias) and mineralisation, provides a good

Table 4: Ranking of critical ingredients for the Mount Isa Cu-Au study based on Contrast values.

Ranking	Key Ingredient	Contrast	Confidence
1	Copper in rockchips (>249 ppm Cu)	2.50	36.31
2	Gold in rockchips (>0.11 ppm Au)	2.38	26.45
3	Corella-Soldiers Cap contact (750 m buffer)	1.87	13.98
4	Aeromagnetics (magnetic highs)	1.82	14.36
5	N-S and ENE faults (650 m buffer)	1.45	17.20
6	Mafic intrusives (750 m buffer)	1.25	7.47
7	Lithologies (dominantly Cycle 3)	1.21	5.09
8	Gravity (gradients)	1.03	15.91
9	Bends on N-S and ENE faults	1.03	2.33
10	Metamorphic grade (amphibolite facies)	0.98	7.85
11	Radiometrics (U/Th)	0.83	4.46
12	Williams and Naraku batholiths (4 km buffer)	0.64	3.36

basis for the application of discrete element modelling to this region. Discrete element modelling using UDEC (Universal Distinct Element Code; Itasca, 2000) is a technique that can simulate fault-slip and stress-strain partitioning along faults, and is therefore a suitable approach in exploring structural control on the mineralising process. In the discontinuous approach to modelling, the interfaces, or contacts between discrete bodies must take into account two types of mechanical behaviour; (1) behaviour of the discontinuities (faults and rock contacts); and (2) behaviour of the solid material involved. Blocks of material within these models may be assigned rigidity or mechanical properties, and the contacts between blocks may also be given mechanical properties.

UDEC

UDEC, the software used in this part of the study, is a two-dimensional numerical program based on the distinct element method for discontinuum modelling (Itasca, 2000). The code enables a numerical simulation of the response of a jointed or fractured rock mass, subjected to either static or dynamic loading. The models are represented by blocks and the discontinuities (faults and rock contacts) represented as discrete boundaries between the blocks. The discrete blocks are subdivided into a finite difference mesh and each zone or element within the mesh behaves according to a prescribed linear or non-linear stress/strain law. UDEC uses a time-marching scheme to solve equations of motion and the relative motion of the discontinuities is governed by a linear or non-linear force displacement relationship for movement according to Newtons' laws of motion, in both the normal and shear directions. The stress-displacement relationship, which is assumed to be linear, is governed by the stiffness properties applied to the fractures. The fractures and discrete blocks fail in tension when the tensile strength is exceeded. In shear, the response is controlled by the shear stiffness, and shear stress is limited by a combination of cohesive and frictional strength of the fracture. Dilation of fractures may occur at the onset of slip, governed by a specified dilation angle. UDEC has been proven as a useful numerical tool in simulating geological processes (e.g., Oliver *et al.*, 1990, 2001a; Holyland and Ojala, 1997;

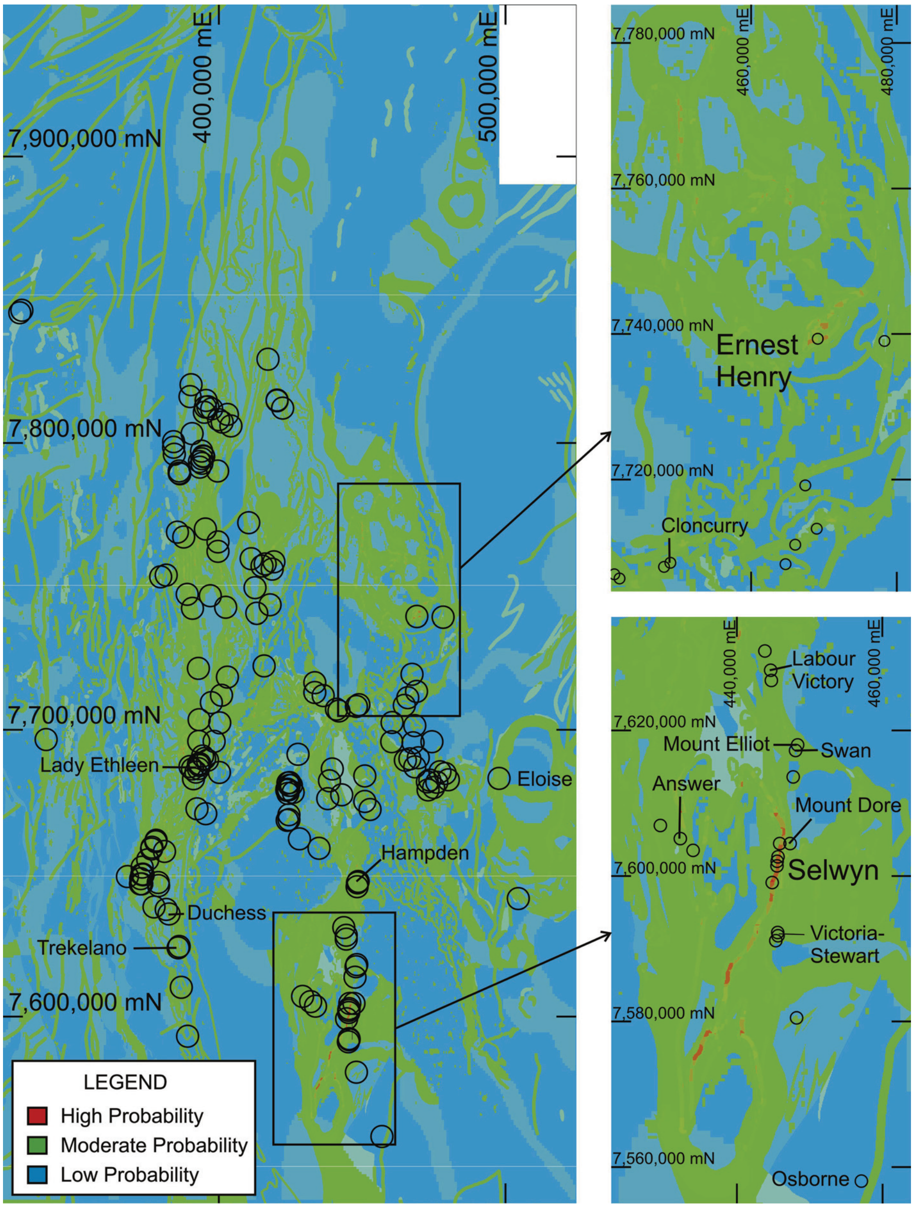

Figure 4: The nine-layer copper-gold posterior probability map for the Mount Isa Inlier, Northwest Queensland. Projection: AMG Zone 54 (AGD66). More detailed maps are displayed for the Ernest Henry (top right) and the Selwyn regions (bottom right). Colours indicate levels of prospectivity values from lowest (blue) to highest (red), where yellow and red areas could be considered as potential targets. Mineral occurrences are indicated by grey circles and the main deposits and prospects are named.

Mair *et al.*, 2000), and in particular for fault arrays and fluid flow (e.g., Oliver, 1995; Jiang *et al.*, 1997; Zhang and Sanderson, 2002; McLellan and Oliver, 2008).

Conceptual Models and Boundary Conditions

The geometry of the model (Fig. 5) was constructed by digital tracing of fractures from both the 1:100 000 maps of the area (Marraba, Cloncurry, Malbon, Mount Angelay, Mount Merlin and the Selwyn map sheets) and the Northwest Queensland Mineral Province Report (NWQMPR; Queensland Department of Mines and Energy, 2000). Due to limitations of the UDEC program, no fractures can be inserted that are not directly or indirectly connected to the model edges, hence all fractures are joined. A rounding parameter is assigned to each block, which applies to the contact mechanics, to prevent unrealistic locking of the corners during the modelling process. All blocks consist of smaller zones with a maximum of 1 km edge length. The constitutive model behaviours are elastic-plastic Mohr-Coulomb for the deformable blocks, and Coulomb slip failure for the fault and granite contacts, which provide a good representation of upper-crustal rock behaviour (e.g., Oliver *et al.*, 1990; Jiang *et al.*, 1997; Holyland and Ojala, 1997).

The applied maximum principal stress (σ_1) was varied from 90º through to 112.5º (WNW-ESE), consistent with the general understanding of the main shortening phase during D_4 (e.g., D_4 of Rubenach *et al.*, 2008), with many northwest trending faults showing apparent sinistral displacements, suggesting they were optimally oriented for shear (Sibson, 1985, 1998). The stress conditions for the models are set at a ratio of $\sigma_1 / \sigma_2 = 1.2$ and $\sigma_3 / \sigma_2 = 0.8$, resulting in a phi ($\phi$) value of 0.5 (where $\phi = [\sigma_2 - \sigma_3] / [\sigma_1 - \sigma_3]$). These are similar ratios to those used by Mair *et al.* (2000) and Zhang and Sanderson (2002). Although UDEC is two-dimensional for plane-strain, three stress values (σ_1, σ_2 and σ_3) are required to define a state of stress, with σ_2 representing the vertical in-plane stress component acting on a two-dimensional map-view plane (i.e., the depth in the crust). The imposed stresses ($\sigma_1 = 210$ MPa, $\sigma_2 = 175$ MPa, $\sigma_3 = 140$ MPa) are within reasonable ranges of CO_2 fluid-inclusion entrapment pressures estimated for the Eastern Succession, late during the Isan Orogeny, which approximate 175 to 200 MPa (e.g., Adshead, 1995; Rotherham *et al.*, 1998; Mark *et al.*, 2001, 2006). The chosen depth and stress applied to the models ($\sigma_2 = 175$ MPa at 7 km) correspond well to the independent data on the depths of ore formation for many deposits found in the district (e.g., Starra - 7.5 km; Rotherham *et al.*, 1998; Lightning Creek - 6.25 km; Perring *et al.*, 2000).

Models were run to equilibrium by examining the relationship between unbalanced forces and displacements.

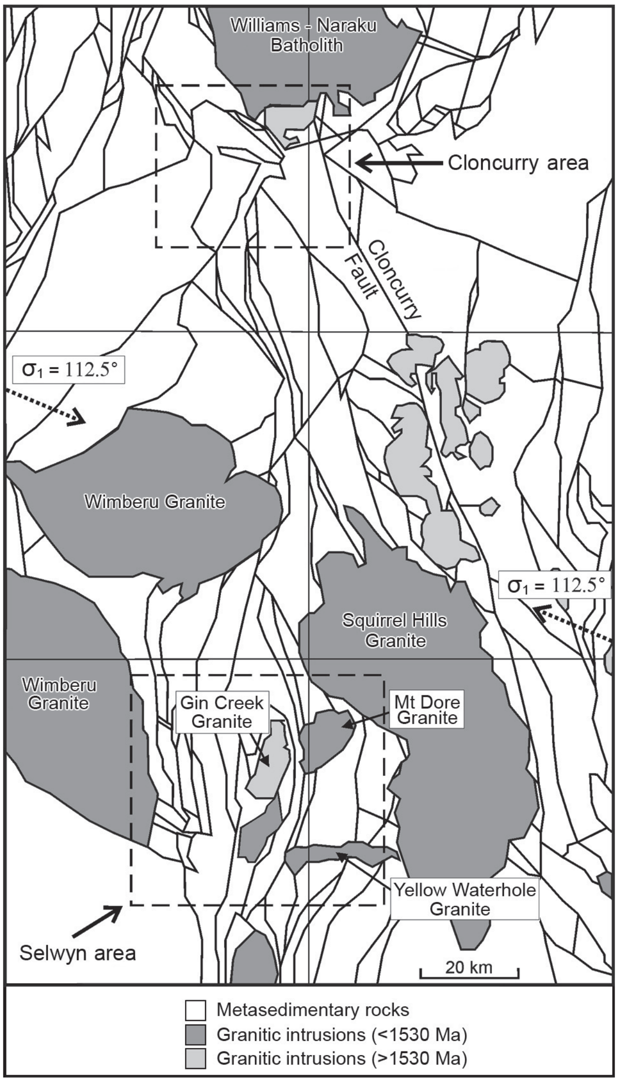

Figure 5: The conceptual model, showing complex geological features and structures. The Boundary conditions are appropriate to an east-southeast compression ($\sigma_1 = 112.5°$). Note: inset locations of the Selwyn (Figs. 6 and 9) and Cloncurry (Figs. 7 and 10) areas are shown by dashed black lines. Solid black lines indicate the known faults in the area.

For a static analysis, a model is in exact equilibrium if the unbalanced force or net nodal force vector at each block centroid or grid point is zero. The maximum nodal force vector is also referred to as the "unbalanced" or "out-of-balance" force (Itasca, 2000). The unbalanced force will never exactly reach zero for a numerical analysis, and the model is considered to be in equilibrium when the maximum unbalanced force is small compared to the representative forces in the problem. Physical properties chosen for both the rock and joint materials (Table 5) are

Table. 5: Physical properties of rocks, contacts, faults and model variations (after McLellan and Oliver, 2008).

Property	Granitic intrusions	Metasedimentary rocks	Lithological contacts	Faults
Density (kg/m^3)	2650	2850	-	-
Bulk modulus (Pa)	49e9	25e9	-	-
Shear modulus (Pa)	27e9	25e9	-	-
Cohesion (Pa)	20e6	10e6	10e2	4e2
Tensile strength (Pa)	10e6	5e6	3e6	2e6
Friction angle (°)	37	31	35	30
Dilation angle (°)	5	4	5	5
Normal stiffness (Pa/m)	-	-	5e9	5e6
Shear stiffness (Pa/m)	-	-	1e5	1e3
Permeability factor (Pa/s)	-	-	238	300
Aperture at zero normal stress (m)	-	-	0.03	0.05
Residual hydraulic aperture (m)	-	-	0.01	0.03

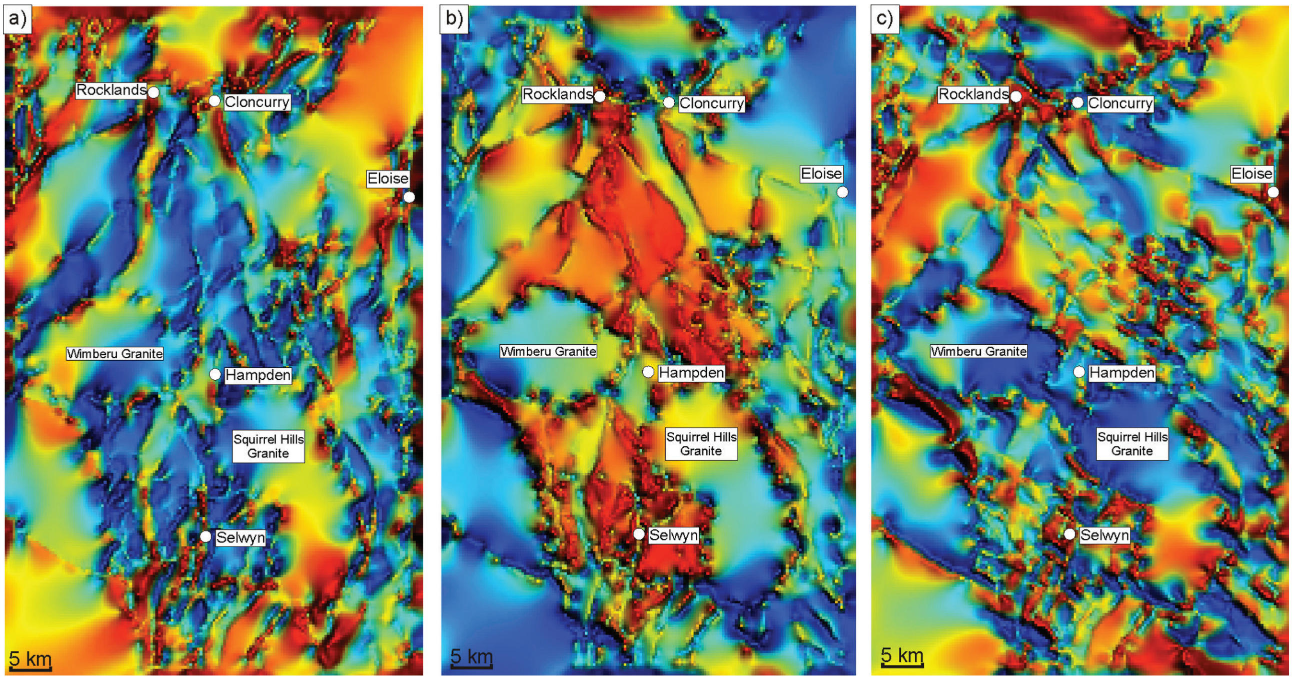

Figure 6: Regional plots of: **a)** Minimum principal stress (σ_3), warm colours (red) indicating lowest values and cool colours (blue) indicating highest values. Note: low values in the Selwyn corridor; **b)** Mean stress (σ_m), warm colours (red) indicating highest values and cool colours (blue) indicating lowest values. Note: low values in the Selwyn corridor; and **c)** Differential stress ($\Delta\sigma$), warm colours (red) indicating highest values and cool colours (blue) indicating lowest values. Note: high values in the Selwyn corridor and Rocklands locations.

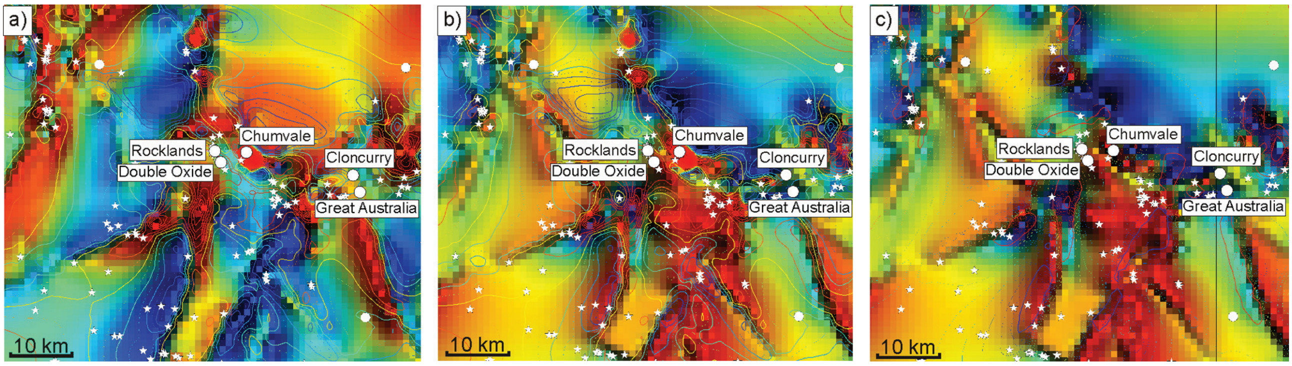

Figure 7: Cloncurry area, plots of: **a)** Minimum principal stress (σ_3), with warm colours (red) indicating lowest values and cool colours (blue) indicating highest values. Low values are evident around the Rocklands deposit and southeast of Cloncurry. Contours indicate an overlay of differential stress with warm colours (red) indicating highest values and cool colours (blue) indicating lowest values; **b)** Mean stress (σ_m), with warm colours (red) indicating highest values and cool colours (blue) indicating lowest values. High values can be seen southeast of Cloncurry and near Chumvale, but low values are evident in a 'corridor' between Rocklands and Chumvale. Contours indicate an overlay of differential stress with warm colours (red) indicating highest values and cool colours (blue) indicating lowest values; and **c)** Differential stress ($\Delta\sigma$), warm colours (red) indicating highest values and cool colours (blue) indicating lowest values. Note: high values in the Chumvale and Rocklands locations. Contours indicate an overlay of minimum principal stress with warm colours (red) indicating lowest values and cool colours (blue) indicating highest values. Stars are copper-gold occurrences.

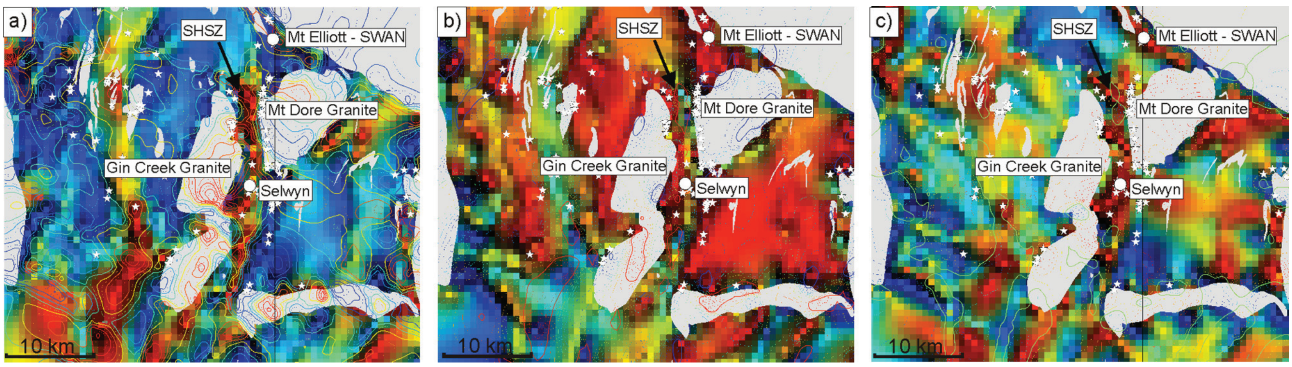

Figure 8: Selwyn area, plots of: **a)** Minimum principal stress (σ_3), with warm colours (red) indicating lowest values and cool colours (blue) indicating highest values. Low values are evident in the Selwyn corridor and in a similar corridor to the west. Contours indicate an overlay of differential stress with warm colours (red) indicating highest values and cool colours (blue) indicating lowest values. Note the large differential stress values in the Selwyn High Strain Zone (SHSZ); **b)** Mean stress (σ_m), with warm colours (red) indicating highest values and cool colours (blue) indicating lowest values. Low values can be seen within the SHSZ, with higher values noted particularly around the granites. Contours indicate an overlay of differential stress with warm colours (red) indicating highest values and cool colours (blue) indicating lowest values. High values of differential stress are coincident with low mean stress in the SHSZ, indicating good conditions for shear failure; and **c)** Differential stress ($\Delta\sigma$), warm colours (red) indicating highest values and cool colours (blue) indicating lowest values. Note: high values in the SHSZ. Contours indicate an overlay of minimum principal stress with warm colours (red) indicating lowest values and cool colours (blue) indicating highest values. Note that low values of minimum principal stress and high differential stress coincide with many known deposits/prospects within the SHSZ. Stars are copper-gold occurrences.

similar to those of previous authors (e.g., Oliver *et al.*, 1990; Holyland and Ojala, 1997; Jiang *et al*, 1997; Zhang and Sanderson, 2002; McLellan and Oliver, 2008), and represent meta-sedimentary rocks, granitoids, lithological contacts and faults. Granitoid intrusions were chosen to be the most competent rock type, and the lithological contacts were assigned a higher stiffness than the faults (Table 5).

Numerical Results

The entire regional model, and two smaller subset model domains, the Cloncurry and Selwyn regions (Fig. 5) were examined. The two smaller domains were chosen because of the abundance of mineral deposits and occurrences they encompass. Models were initially cycled in non-saturated conditions, that provided a comparison with subsequent saturated models in which high fluid pressures were established in the fractures. The variation of the orientation of σ_1 to the initial stress regime was also compared for both saturated and non-saturated conditions, where the orientation of σ_1 was varied from 90 through to 112.5º. Although many aspects of the models were investigated (e.g., displacement vectors, shear displacement, shear stress, dilation and principal strain), this contribution focuses on minimum principal stress (σ_3), mean stress (σ_m) and differential stress ($\Delta\sigma$) values as a result of the 112.5º orientation of σ_1, as these values are the most sensitive and are considered most important for the localisation of shear and tensile failure, and hence mineral deposition (e.g., Etheridge *et al.*, 1984; Sibson, 1994). As an indicator of dilation, potential failure and fluid focussing, low values of all three σ_3, σ_m and $\Delta\sigma$ may indicate areas more likely to undergo tensile failure, whereas low values of σ_3, and high values of both σ_m and $\Delta\sigma$ may indicate areas more likely to undergo shear failure. Areas showing low values of $\Delta\sigma$ and high values of σ_3 and σ_m are least favourable for conditions conducive to mineralisation.

Regional Scale Model

The overall distribution of minimum principal stress, σ_3 in the model highlights low values in several distinct areas, in particular around the southern areas of the Squirrel Hills Granite, within the Selwyn region, to the eastern side in the northern sections of the Cloncurry fault and also the Cloncurry region to the north (Fig. 6a). There is a notable partitioning of stress along faults, fault bends, intersections and around rheological contrasts (e.g., close to granite and meta-sedimentary contacts). At a large scale, there is a relatively good visual correlation with known deposits and prospects within the region, with some noteworthy deposits including Selwyn, Eloise, Hampden and the newly discovered CuDECO Ltd. Rocklands deposit. On the regional scale, there is a distinct partitioning of σ_3 into north and north-east oriented trends, these being most obvious in the Selwyn region, where apparent corridors of stress partitioning can be seen wrapping around the Gin Creek Granite (Fig. 6a). Another striking feature of these models is the compartmentalisation of both high and low values of σ_m, with highest values most notably seen in the Selwyn region and north of the Squirrel Hills and Wimberu granites towards Cloncurry (Fig. 6b). Regions of high and low σ_m, both visually correlate well with most of the known prospects and deposits in the area, which may

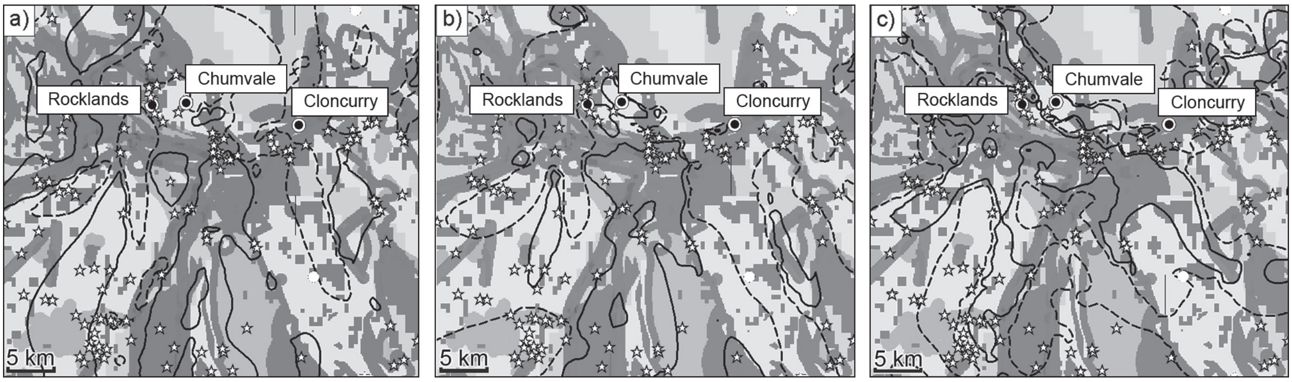

Figure 9: Cloncurry area (see Fig. 5), plots of WOFE posterior probability maps with darker greys indicating higher prospectivity values overlain by contours of: **a)** Minimum principal stress (σ_3), with dashed lines indicating lowest contour values and bold lines indicating highest contour values; **b)** Mean stress (σ_m), with dashed lines indicating lowest contour values and bold lines indicating highest contour values; and **c)** Differential stress ($\Delta\sigma$), with dashed lines indicating lowest contour values and bold lines indicating highest contour values. Stars are copper-gold occurrences.

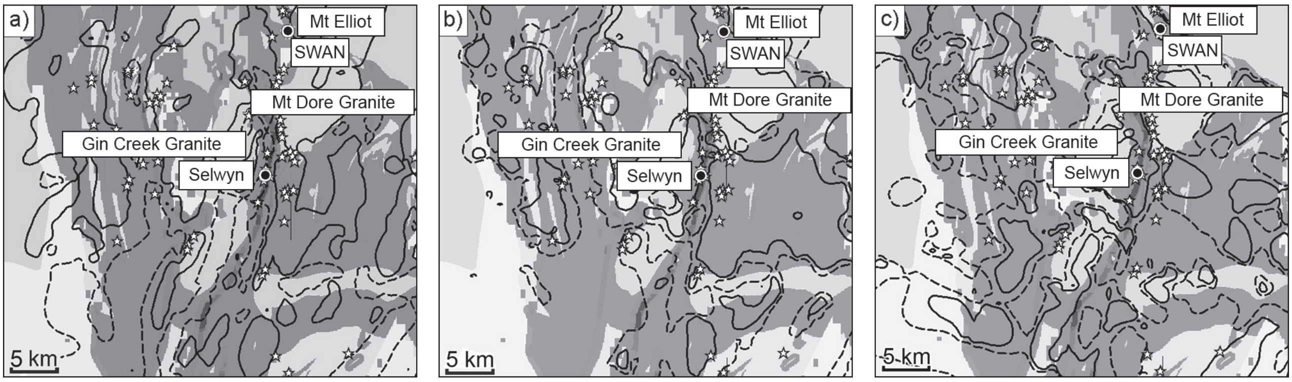

Figure 10: Selwyn area (see Fig. 5), plots of WOFE posterior probability maps with darker greys indicating higher prospectivity values overlain by contours of: **a)** Minimum principal stress (σ_3), with dashed lines indicating lowest contour values and bold lines indicating highest contour values; **b)** Mean stress (σ_m), with dashed lines indicating lowest contour values and bold lines indicating highest contour values; and **c)** Differential stress ($\Delta\sigma$), with dashed lines indicating lowest contour values and bold lines indicating highest contour values. Stars are copper-gold occurrences.

be related to deformation style (e.g., compressional shear versus extensional failure. The overall distribution of $\Delta\sigma$ is less limited to specific areas and appears to be more related to faults and fault blocks (Fig. 6c). High values of $\Delta\sigma$ are clearly related to some fault bends and fault intersections, although in the Selwyn region, the partitioning appears as corridors between faults. The orientation, or trend, of high values of $\Delta\sigma$ appears to mimic the orientation of the faults in many places, being north-south, northeast or northwest. The majority of the highest values of $\Delta\sigma$ are located along faults, granite-metasediment contacts or within the metasediments themselves, suggesting that the weaker metasediments have accommodated the majority of the strain during deformation.

Cloncurry Region

In the Cloncurry region, there are some obvious trends in the distribution of low values of σ_3, the majority of which have a close spatial relationship with faults and intrusive contacts. Two distinct trends of low σ_3 values, north-south and northeast, have a reasonably good visual correlation with some of the deposits and prospects in the Cloncurry region, including Great Australia to the south, Double Oxide and Rocklands to the west and many prospects to the southwest of Cloncurry. Several of these areas of low σ_3 values correspond to areas of high $\Delta\sigma$ (Fig. 7a) which suggests they are more likely to undergo failure in shear, whereas areas with a corresponding low $\Delta\sigma$ are more likely to undergo failure in tension. There is no consistent trend between values of σ_m and $\Delta\sigma$ in the Cloncurry region. The Double Oxide area, for example, shows high σ_m and high $\Delta\sigma$ values indicating a greater likelihood for shear failure, but there are also areas of low σ_m and low $\Delta\sigma$ values indicating conditions more suitable for tensile failure e.g., Chumvale Breccia regions (Fig. 7b). High values of σ_m appear to have a very good visual correlation with many of the copper and gold occurrences in the Cloncurry area. Copper and gold occurrences correspond to both high and low values of σ_3 (c.f. Fig. 7a). Areas of high $\Delta\sigma$ coincide with high σ_3, indicating the higher likelihood of shear failure. However, areas of high $\Delta\sigma$ and low σ_3 indicating the higher likelihood of tensile failure, can be seen in the Chumvale breccia regions (Fig. 7c) e.g., the areas south of Chumvale.

Selwyn Region

In the Selwyn region, areas of low σ_3 values are easily distinguished, occurring as corridors, particularly along the Selwyn High Strain Zone (SHSZ), between the Mount Dore and the Gin Creek Granite (Fig. 8a). Where these areas of low σ_3 and high $\Delta\sigma$ values coincide, they provide a strong indication of the likelihood of shear failure and dilation, and this is very prominent within the SHSZ and a similarly oriented 'corridor' to the west (Fig. 8a). These 'corridors' in the Selwyn region also have low values of σ_m (Fig. 8b), which again reinforces the likelihood of shear failure, given the previously described coincidence of low σ_3, and high $\Delta\sigma$ values in these areas. To the north of the SHSZ, where the Mount Elliot-SWAN deposits are located, there are higher values of both σ_m and $\Delta\sigma$ (Fig. 8c), again suggesting the higher likelihood of failure by shear in this area. As this sits close to the metasediment-granite contact, it is likely to be the result of a major competency contrast producing shear in a similar orientation to σ_1 (112.5º = east-southeast).

Numerical and WOFE Comparisons

There are some interesting comparisons between the numerical results and the WOFE models. Given that some deposits may form in conditions of shear failure (i.e., low σ_3 and high $\Delta\sigma$ values), and that others may form in a tensile regime (i.e., low σ_3, σ_m and $\Delta\sigma$ values), it is difficult to find one set of specific stress conditions that have a 'best fit' with the WOFE results, unless the numerical results are initially incorporated within the training data set and WOFE analysis. However, we believe there is evidence for a strong visual correlation of specific deposit types with the modelling results, and we focus on the same two areas, the Cloncurry and Selwyn regions.

Within the Cloncurry region, there is a good correlation between low σ_3, high $\Delta\sigma$ values, and regions of high prospectivity values (Figs. 9a, c). These areas of coincidence, in a mechanical and timing sense, could correlate with shear failure and mineralisation during D_4 deformation. Areas that display high values of both σ_m and $\Delta\sigma$ (Figs. 9b, c), also show a good correlation with areas of high prospectivity in the Cloncurry region, and could similarly be considered to have a higher likelihood of shear failure. There are also a few areas that display low values of all three σ_3, σ_m and $\Delta\sigma$ (Figs. 9a, b), and show a good correlation with areas of high prospectivity in the Cloncurry region, e.g., south and east of Chumvale, which are areas that could be considered to have a higher likelihood of tensile failure. However these types of area are less common than areas of shear failure.

The Selwyn region displays similar attributes to the Cloncurry region, with areas of low σ_3 and high $\Delta\sigma$ values having a very good correlation with areas of high prospectivity values, which is best seen in the Selwyn corridor (Figs. 10a, c). Another important area of interest is near the Mount Elliot - SWAN deposit sites, where high values of both σ_m and $\Delta\sigma$ (i.e., a higher likelihood of shear failure) coincide with medium prospectivity values (Figs. 10b, c). There are fewer areas with low σ_3, low σ_m and low $\Delta\sigma$ values, which indicate a higher likelihood of tensile failure (Figs. 10a, b). These areas appear to be restricted to the edges of, or within the intrusive rocks, e.g., the edge of the Mount Dore granite at the top of the SHSZ.

Discussion

The results of the WOFE models in this study indicate a significant proportion of the copper-gold mineral occurrences are located less than 750 m from the contact between the Corella Formation (cover sequence 2) and Soldiers Cap Group (cover sequence 3). This boundary represents a regional unconformity between the ca. 1680 to 1650 Ma Soldiers Cap Group and other units of similar age (including the Kuridala and Staverly formations, and the Marimo Slate) and the ca. 1750 to 1720 Ma Corella Formation (including the Doherty Formation). The regional unconformity was attributed to basin subsidence and tectonism by Blake and Stewart (1992). D_1 of the Isan Orogeny has been inferred to be responsible for the emplacement of younger cover sequence 3 rocks over older cover sequence 2 rocks through normal faulting or reactivation of normal faults as thrusts (O'Dea *et al.*, 1997; Betts *et al.*, 1998). The field observation that the Corella Formation - Soldiers Cap Group contact is consistently faulted and has intense localised alteration (D. Foster, pers. comm.), suggests this boundary has been active during the main metasomatic events, and consequently may have played a key role in focusing metasomatic fluids responsible for copper-gold mineralisation. The Corella Formation consists of calc-silicate rocks, marbles and minor pelitic and volcanic rocks, whereas the Soldiers Cap Group comprises siliciclastic meta-sedimentary rocks and mafic meta-volcanics. The juxtaposing of these different rock types may provide: (1) a physical barrier to upward directed fluid flow from the more permeable meta-sedimentary rocks into the less permeable calc-silicate rocks, (2) favourable sites for fluid mixing or fluid-wallrock reaction, (3) regions of significant chemical and/ rheological contrast.

Magnetic highs, which may reflect areas of magnetite±pyrrhotite precipitation, also have a strong correlation with copper-gold occurrence. Magnetics has been a major tool used in exploration for IOCG deposits in the Mount Isa Inlier, and played an integral role in the discovery of significant deposits located under shallow cover, including, Osborne, Ernest Henry and Eloise (Williams and Blake, 1993; p56). Williams and Pollard (2001) concluded that "there is no simple geophysical model that can be relied upon when exploring for IOCG deposits at regional to prospect scale" based on the complex and varied spatial and temporal relationship between magnetite and copper-gold ore in the Cloncurry District.

Many of the magnetic highs in the Mount Isa region reflect the occurrence of hydrothermal magnetite±pyrrhotite. However, the spatial relationship between copper-gold mineralisation and iron oxides (reflected by magnetic highs) is not simple, because:

- Not all copper-gold deposits are associated with iron oxides. Magnetite is absent from some ore-styles such as those hosted by graphitic schist (e.g., Mount Dore, Victoria and Stuart).
- Some deposits occur within more reduced pyrrhotite rich zones, which are less- or non-magnetic (e.g., Eloise).
- Not all ironstones are mineralised. At Lightning Creek, the largest single accumulation of hydrothermal magnetite is copper-gold poor, while many other ironstones and magnetite-bearing alteration zones are barren.
- Several generations of magnetite may be present. At Ernest Henry, an earlier (barren) generation of magnetite is overprinted by a later (mineralised) stage. Similarly, several generations of magnetite are evident at Osborne.

Never-the-less, the high contrast values generated in the WOFE study indicate that aeromagnetics is a very effective exploration tool for targeting copper-gold mineralisation in the Mount Isa inlier. It provides targets that are potentially mineralised, and significantly reduces the area of prospectivity.

In terms of structural trends, the north-south and northeast oriented fault sets have a strong to moderate association with copper-gold occurrences. All significant copper-gold deposits in the study area are associated with at least one of these two orientations. Williams and Blake (1993; p29) described a north-south trend located at longitude 140º 30' which formed a 100 km long corridor extending from Stuart (south of Selwyn) to Great Australia (at Cloncurry) as the most striking evidence of structural control on Cu±Au±Ag±Co deposits in the Cloncurry district. The importance of north-south and northeast structures is considered to reflect accommodation of continued east-west directed shortening during D_2 and D_3, by movement along pre-existing fault zones in the older basement architecture. This may be further extrapolated to now include the east-southeast shortening direction of the D_4 event (~1530 Ma) and will be fully discussed later.

The copper-gold deposits within the Mount Isa study area have a strong spatial association with mafic intrusives (e.g., meta-dolerite, amphibolites, mafic-dykes, diorites and minor gabbro intrusives) with a significant proportion located either less than 650 m from, or within, these rock types.

Mafic igneous rocks occur throughout the Mount Isa Inlier and range in style from sills to layered sills, dykes, plugs, phase of composite intrusions, net veining and other magma mingling textures. Based on field relationships and age dating, mafic igneous rocks were emplaced over a period of nearly 740 m.y., between 1850 Ma and 1116 Ma. This age range is based on:

- Net-veining documented by Blake and Stewart (1992), indicating synchronicity of emplacement with the Kalkadoon granite (~1850 Ma).
- Net-veining documented by Blake (1981), indicating synchronicity of emplacement with the Mount Erle and Myubee Igneous complexes (~1740 Ma).
- Pre-dating metamorphism (>1590 Ma; Page and Sun, 1998).
- Net-veining documented by Blake (1981), indicating synchronicity of emplacement of the Sybella Granite (1655±4, 1660±5, 1673±3 Ma; Connors and Page, 1995).
- The Ernest Henry Diorite (1660±13, 1658±10, 1657±7 Ma; Pollard and McNaughton, 1997).
- Intrusions synchronous with emplacement of the Williams-Naraku batholith (~1550 to 1500 Ma; Mark, 2000).
- Un-metamorphosed dykes cutting the Williams-Naraku batholith, all regional structures and rock types, including the Lakeview Dolerite (Rb/Sr age 1116±12 Ma; Page, 1983).

There are many documented copper-gold deposits spatially associated with mafic intrusives, e.g., Ernest Henry (Mark *et al.*, 2000), Osborne (Adshead *et al.*, 1998), Eloise (Baker, 1998), Mount Elliot and SWAN (Sleigh, 2002). Drabsch (1998) recorded a close spatial and temporal association between intra-ore trachyandesite dykes and copper-gold mineralisation in the Corbould Zone at the Mount Elliot deposit. Whole-rock analyses of these dykes by Wang and Williams (2001) indicated a distinct affinity with the Eureka Suite (cf. Pollard *et al.*, 1998). Similarly, Adshead-Bell (2000) recorded a non-foliated diorite intrusion within the Starra 276 orebody that was spatially and temporally associated with mineralisation. It is interesting to note that distance to mafic intrusives (650 m buffer) has a much higher C value than does distance to Williams and Naraku intrusives (4 km buffer). This raises the question as to what role mafic intrusions play in the genesis of copper-gold deposits. Their suggested role in the formation of IOCG deposits includes: (1) a potential source of sulphur ± metals (leached during hydrothermal activity, or contributed directly), and (2) acting as a rheological and chemical contrast (reduced). Butera (2004) implied a genetic link between mafic rocks and IOCG deposits, based on spatial data analysis using WOFE and fractal analysis, with older pre-D_1 mafic intrusives being a source of sulphur ± metals.

The WOFE results here also indicate that gravity highs, and steep gradients adjacent to gravity highs or gravity lows, have a strong spatial association with copper-gold occurrences. The gravity highs are considered to reflect large volumes of mafic rock within the middle to upper crust. The gravity gradients are interpreted to reflect a combination of crustal scale basement architecture as well as the margins of large felsic intrusions. Eloise, Starra and Mount Elliot are located on the margins of gravity lows, interpreted as reflecting the edges of Williams-Naraku type batholiths. An analogous scenario has been described by Skirrow (2000), in which several of the major gold-copper-bismuth deposits of the Tennant Creek District were observed lying broadly within, or near, a regional gravity gradient, interpreted to represent a deep seated contact with low-density granitic material. Ernest Henry occurs on the flanks of a gravity high considered to reflect a significant component of mafic intrusive rock in the upper to middle crust. Many of the smaller occurrences within the Wonga Belt overly a gravity high. The gravity high does not reflect the surface geology, which is dominated by calc-silicates and felsic volcanics, and contains only a few percent mafics, suggesting that there is potentially a significant component of mafic rock within the middle to upper crust of the Wonga Belt that is not exposed at the surface. Although O, C, H and S isotope studies suggest that magmatic fluids are a dominant source of components in IOCG deposits, there is only a moderate spatial association with coeval granites. If the Williams-Naruku granitoids are the source of the mineralising fluids, then those magmatic fluids must have travelled 4 km or more prior to deposition, while retaining their isotopic signature. Mafic intrusives cannot be ruled out as a fluid source since isotopic signatures cannot discriminate between felsic and mafic derived fluids.

The importance of deformation in the localisation of these deposits cannot be understated, and is well documented at several scales (e.g., Laing, 1993, 1998; Oliver, 1995; Pollard, 2006). Several factors and locations that appear to contain the essential mechanical ingredients for a copper-gold mineralised system in the Eastern Fold Belt have been highlighted in these models. Competency contrasts between the granitic intrusions and meta-sedimentary rocks in association with a fault or fault network, result in significant partitioning of stress around these structures (e.g., the Selwyn High Strain Zone and the Gin Creek Granite). Complex interactions of block geometry or fault blocks and variations in block displacement relative to the applied far-field stress (σ_1), assist in partitioning stress as these blocks move and deform. Many areas of interest can be highlighted, which display variations in magnitudes of mean stress (σ_m), minimum principal stress (σ_3) and differential stress ($\Delta\sigma$). These parameters indicate a higher potential for failure at specific locations within the model, and hence represent an increased prospectivity for copper-gold mineralisation based on purely mechanical influences and structural controls. In 'Mohr-Coulomb' space, higher failure potential means reduced effective stress values and is represented by a shift of the Mohr circle towards the failure envelope. This is caused by increases in $\Delta\sigma$ promoting shear failure, or decreases of $\Delta\sigma$ promoting tensile failure, or extensional shear when in conjunction with low values of σ_3.

The WOFE models have highlighted that north-south and northeast to east-northeast oriented fault sets have a strong to moderate association with copper-gold occurrences. The numerical and structural response observed in the numerical models to an imposed stress regime during a D_4 deformation event, suggests that a variety of fault orientations within the whole region may be prone to failure, due to the heterogeneous patterns of deformation and stress partitioning, caused by complex geometrical fault blocks. However, north-south and northeast trends can be seen, which are related to the orientation of the pre-existing fault structure. The mechanical or physical contrast between the more competent granitic intrusions and the less competent meta-sedimentary rocks, also causes partitioning of stress and strain. Observations made in smaller areas, such as the Selwyn region, where the deformation was compartmentalised, indicate that domains of high $\Delta\sigma$ correspond well to already recognised high strain zones, for example the Selwyn High Strain Zone, which is situated between the Mount Dore and Gin Creek granites, and hosts the Selwyn-Starra deposits. Due to shear displacement of blocks between the granitoid bodies and the fault systems, this area has accommodated higher strains. Such zones could promote broad-scale copper-leaching (de Jong *et al.*, 1998), and result in local focussing of mineralising fluids in more discrete structures, where rapid pressure drops at fault bends, intersections or jogs (e.g., Cox, 1999) could enhance mineralisation.

At the regional scale, numerical modelling may be an effective exploration tool, by highlighting areas that have undergone stress partitioning and strain localisation, and at the smaller scale, by outlining zones that show an increased potential for mineralisation as measured by stress and failure distributions. Many areas identified as prospective within these models could be re-examined and modelled at a much smaller scale, incorporating a more detailed geometry, including lithological contacts and small-scale structures, to further examine the role of smaller scale structures in stress and strain partitioning. This would allow a more precise targeting strategy at tenement-to-mine-scale based on the structural approach. These models provide a good basis for further modelling studies, and highlight the basic conditions required to ascertain why certain areas may be more prospective than others. Further analysis could involve a closer integration of data from the existing WOFE models and the numerical process models (a complete WOFE integration), which could be carried out at various scales.

Conclusions

In summary the main conclusions from this work are as follows:

(1) The WOFE method provides a simple and effective technique to test the spatial association of a diverse range of geologic information with copper-gold ± iron oxide deposits in the Mount Isa Inlier, Australia. This is particularly effective, due to the large amount of publicly available digital data and good exposure.

(2) The WOFE method allows a ranking of the best copper-gold predictors, refinement of current geological understanding of the potential critical ingredients involved in copper-gold deposit formation, and accordingly, modification of geological/exploration models.

(3) The mechanical numerical models offer insights into the processes that produce the observed WOFE results.

(4) The close correlation between the mechanical numerical model results, the prospectivity maps and the observed distribution of deposits, suggests that fluid flow and stress distributions during the late Isan Orogeny are the most important influences on IOCG deposit formation in the Eastern Fold Belt of the Mount Isa Inlier.

(5) Combining mechanical numerical modelling with WOFE is an extremely useful technique to gain insight into mineralising processes involving syntectonic hydrothermal mineralisation.

(6) The data driven approach highlights the importance of the following factors in IOCG distribution in the Eastern Fold Belt of the Mount Isa inlier:
   (a) Proximity to the Corella Formation contact, particularly that with the Soldiers Cap Group.
   (b) Proximity to magnetic highs, despite the complex spatial relationships between copper-gold mineralisation and magnetite described by Williams and Pollard (2001).
   (c) Proximity to north-south (350 to 15°) and northeast to east-northeast (40 to 75°) structures (potentially representing reactivated older basement architecture).
   (d) Proximity to mafic intrusive rocks (and amphibolites) providing sulphur or a reducing environment.
   (e) Proximity to gravity gradients (interpreted to reflect crustal scale basement architecture) and gravity highs (possibly reflecting large volumes of mafic rock in the middle to upper crust).

(7) The data driven approach also highlights the relatively weak spatial association between copper-gold occurrences and intrusions of the Williams-Naraku Batholiths. If these granitoids were considered a source of metals in many of the deposits, then the magmatic fluids would have travelled significant distances from their source (commonly more than 4 km) prior to deposition. This tends to suggest that the fluids may have been sourced elsewhere, but that the granitoids have had a substantial role to play in the mechanical models, and have determined the distribution of stress and consequent fluid flow patterns.

(8) The posterior probability copper-gold maps generated clearly highlight the main deposits, as well as new areas including 'Ernest Henry' and 'Eloise' type analogues.

(9) The distribution of minimum principal, mean and differential stress (σ_3, σ_m and $\Delta\sigma$) are very good indicators of high strain zones, deformational styles and areas of fluid focussing with potential for copper-gold mineralisation.

(10) These results imply that fluid pathways and sites of fluid mixing are much more important than fluid sources in controlling the distribution of IOCG deposits. This understanding may explain some of the diversity in the range of IOCG deposit types and models. A common mineralising process could generate deposits in a variety of host rocks depending on the fluid pathways. The dominance of the fluid pathways means that fluid sources cannot be clearly recognised from spatial associations of the deposits alone, and mineralising fluids may be complex and heterogeneous in view of their possible interactions with a variety of wall rocks. A detailed understanding of fluid pathways and structures at all scales is the most important direction for future research. Continued mechanical modelling, directed at understanding fluid flow in the Mount Isa Eastern Succession, based on this structural knowledge, will also be an important tool.

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