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Asymmetric Extension of the lithosphere and its influence on Palaeoproterozoic Pb-Zn deposits of the Western Fold Belt, Mount Isa terrane

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Abstract: The Palaeoproterozoic Isa Superbasin hosts several large Pb-Zn-Ag deposits and is arguably one of the richest mineral provinces in the world. This basin initially evolved during a NW-SE directed extensional event termed the Mount Isa Rift Event between ~1708 Ma and ~1653 Ma. A sag basin continued to evolve thereafter until ~1595 Ma. There is a notable difference in the locus of syn-rift sedimentation, syn-rift magmatism, and post-rift subsidence. Tectonic subsidence was focussed along the ~N-S oriented Mount Isa Rift where 3-5 km of fluvial to shallow marine clastic sediments were deposited. Magmatic provinces, along the western and north western rift flanks, mark the locus of significant sub crustal lithospheric thinning, asthenospheric upwelling, and mafic underplating, and are the locations of palaeogeographic highs during the rifting. The position of maximum sub crustal lithospheric extension is determined by the position of greatest post-rift subsidence. This occurred beneath the northern Mount Isa terrane where the thickest post-rift sequences are preserved and the depositional history is more protracted. These relations indicate the Mount Isa Rift Event involved asymmetric lithosphere extension.

This lithospheric architecture has significant implications for exploration of large sediment hosted Pb-Zn orebodies in the Western Fold Belt. These deposits spatially associated with faults active during the Mount Isa Rift Event but they are hosted within post-rift sequences of the Isa Superbasin. The spatial distribution of the deposits on the flanks of the Mount Isa Rift shifts away from conventional models for the formation of SEDEX deposits that are generally considered to form within rifts. The asymmetric extension lithosphere model provides the insight into the distribution of deposits. Mineralisation is coincident with maximum asthenospheric upwelling that provides a heat source for driving fluid flow throughout the basin. In addition, the location of maximum post rift subsidence may enhance the appropriate redox geochemical conditions for precipitation of base metals. This does not necessitate syn-depositional mineralisation. Finally, if fluid flow was gravity driven, then the asymmetric extension model for the Isa Superbasin predicts fluid flow to the deepest parts of the sag-basin in the northern Mount Isa terrane. Extensional faults may have provided the local, upper crustal control for mineralisation.
Key words: Asymmetric extension, Isa Superbasin, Mount Isa Rift Event, Pb-Zn mineralisation, Mount Isa.

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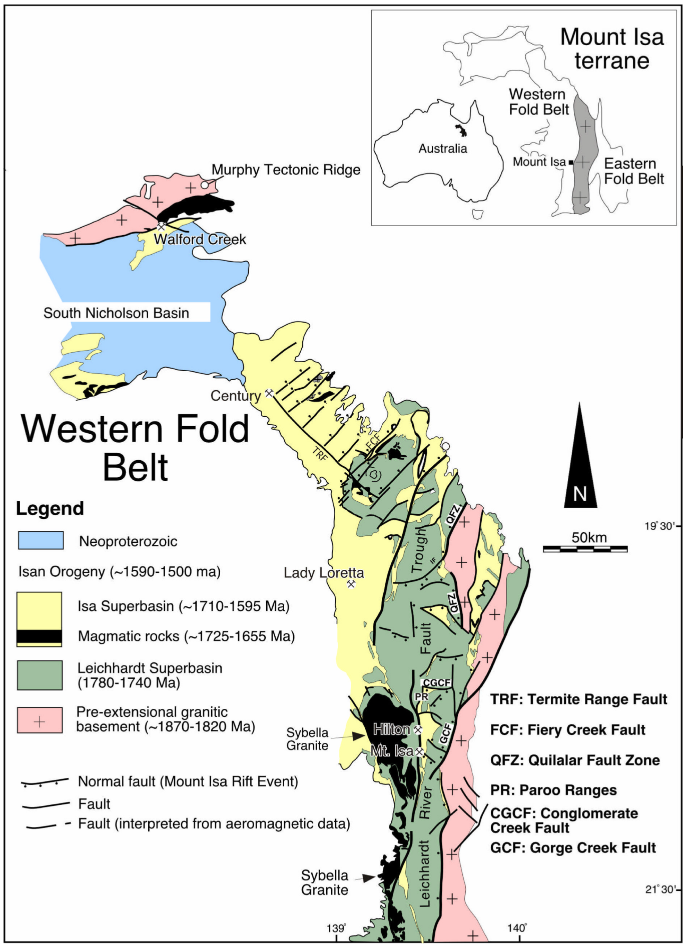
Introduction

The Western Fold Belt in the Palaeproterozoic Mount Isa terrane has one of the highest density of large sediment hosted Zn-Pb deposits (Figure 1). These deposits display a wide morphology and belong to different deposit class, and include the giant Mount Isa SEDEX orebody (McGoldrick and Keays, 1990) and the Mississippi Valley-type Century deposit (Broadbent et al., 1998). All major deposits of the Western Fold Belt are hosted within the extensionalsag Isa Superbasin (Figure 1 : Southgate et al., 1998; Betts et al.,1999).

Figure 1. Map of western Mount Isa terrane



Geological map of western Mount Isa terrane highlighting the distribution of major structural elements, MIRE-aged magmatic

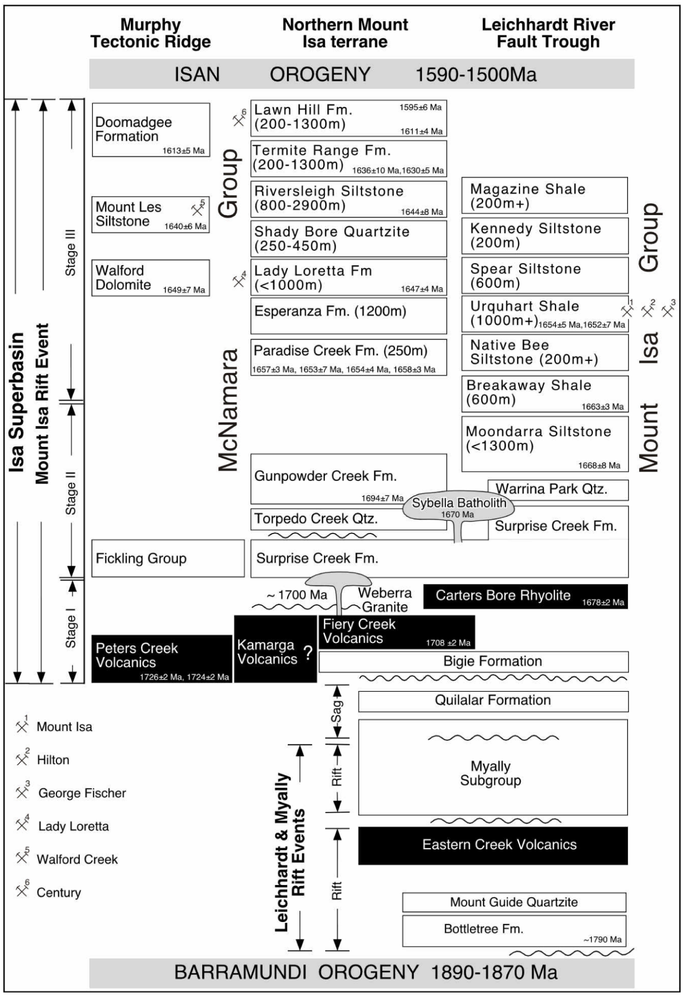
provinces, preserved areas of Isa Superbasin, major normal faults, and large Pb-Zn deposits. The map is summarised from Blake, 1987b.

Increased geochronological resolution of the stratigraphy of the Isa Superbasin suggests that these deposits did not form at the same time but rather developed during discrete episodes of mineralization throughout the evolution of the basin. Despite the apparent differences between these deposits they do share some common features. These include their proximity to the intersections of extensional faults (Lister and Betts, in review); their absence within syn-rift sequences of the Isa Superbasin; and their spatial distribution away from the locus of maximum crustal extension. Recent studies on the basin architecture, extensional evolution, and geochronology of the Isa Superbasin (O'Dea et al., 1997b; Betts etal., 1998; 1999; Southgate et al., 1998; Page and Sweet, 1998) has provided the necessary framework to place these deposits into context. Moreover, recent study by Betts et al. (1998) has postulated an asymmetric extension model for lithospheric extension during the Mount Isa Rift Event (O'Dea et al., 1997b; Lister et al., 1999; Betts et al., 1999). This model reconciles the basin architecture during and after the Mount Isa Rift Event and explains the variation in the basin geometry between the rift and post-rift evolution of the basin. In this paper the influence of asymmetric extension on the development of Pb-Zn deposits is explored.

Geological Background

The tectonic history of the Mount Isa terrane can be divided into two major phases. The early phase is dominated by intracontinental extension and basin development (ca 1800-1590 Ma). Three major episodes of extension are recognised in the Western Fold Belt. The Leichhardt Superbasin (ca 1800 Ma- 1740 Ma) (Figure 1 and 2) (Southgate et al., 1998; Page and Sweet, 1998) formed during superimposed E-W and N-S extensional events termed the Leichhardt Rift Event and Myally Rift Event respectively (O'Dea et al.,1997b). Coarse clastic, quartzite and tholeiitic basalt sequences were deposited into a N-S rift zone (Leichhardt Rift) in which the deformed remnants are preserved in the Leichhardt River Fault Trough (Figure 1). The Myally Subgroup (Figure 3) was deposited into north thickening half graben that were bounded by EW normal faults (O'Dea et al., 1997b). Laterally extensive quartzite-carbonate sequences (Quilalar Formation: Figure 3) were then deposited during thermal subsidence (Derrick et al., 1980; Jackson et al., 1990).

Figure 2. Tectono-stratigraphic column



Tectono-stratigraphic column of the Western Fold Belt. Summary of the major lithostratigraphic formations, regional unconformities, tectonic events, and age of igneous rocks. Data is compiled from Wyborn et al., 1988; Page, 1983; Page and Sweet, 1998; Page et al., 1994; Southgate et al., 1997. Modified from O'Dea et al., 1997a.

A period of depositional hiatus then ensued (ca 1740 and ~1710 Ma). The Leichhardt Superbasin was uplifted and eroded, and a regional unconformity developed. The cause of uplift is conjectural. O'Dea et al. (1997a, b) interpreted the uplift as the manifestation of mid-crustal extension in the Eastern Fold Belt (Wonga Event: Holcombe et al., 1991; Oliver et al., 1991). A mid-basin inversion event has also been identified in the Western Fold Belt at this time (Betts, 1999).

Sequences belonging to the Isa Superbasin (Figure 1) (ca 1710-1590 Ma) were deposited on to this unconformity (Figure 2). This basin initially developed during the NW-SE directed extension (Mount Isa Rift Event: ca 1710-1655 Ma). A new rift axis (Mount Isa Rift) was superimposed onto the Leichhardt Rift (Betts et al., 1998). Sedimentation during the Mount Isa Rift Event is dominated by W to NW tapering sequences (Betts et al., 1999; Batson, 1991; O'Dea et al., 1997a, b; Derrick, 1982; Lister et al., 1999).

During the post-rift evolution of the basin (ca 1655-1595 Ma), shallow marine to lacustrine carbonates of the Mount Isa Group and Lower McNamara Group (Figure 2) were deposited (McConachie and Dunster, 1996; Dunster and McConachie, 1998). The basin depocentre shifted to the northern Mount Isa terrane and the upper McNamara Group was deposited in an outer shelf to deep water environment (Andrews, 1996). There are no temporal or lateral equivalents of the Upper McNamara Group preserved in the Leichhardt River Fault Trough.

Development of the Isa Superbasin was interrupted by the Isan Orogeny (ca 1590-1500 Ma; Blake, 1987). Early N-S shortening and basin inversion (Bell, 1983; Lister et al., 1999; O'Dea et al., 1997a) was followed by a period of regional E-Wshortening, resulting in the development of crustal-scale upright folds. Late in the Isan Orogeny strike-slip faults were active in a brittle wrench environment (Lister et al., 1999).

Stratigraphy of the Isa Superbasin

The Isa Superbasin extends ~300 km from the eastern Leichhardt River Fault Trough through to the Murphy Tectonic Ridge (Figure 1). The basin forms part of a network of similarly aged basins that evolved across the northern Australian craton during the Palaeoproterozoic (e.g., McArthur Basin: Figure 1). The major stratigraphic packages of the Isa Superbasin are presented in Figure 2 and its distribution is shown in Figure 1.

Syn-rift sequences

Syn-rift sequences display abrupt thickness changes across normal faults, they have wedge shaped stratal geometries suggesting deposition into half graben, and their lithofacies is influenced by extensional faults. In the Mount Isa Rift syn-rift sequences are up to 3-5 km thick. Significantly thinner (< 2 km) syn-rift sequences are also preserved on the western rift flank. The lower stratigraphy of the Isa Superbasin is dominated by a east thickening wedge of fluvial to shallow marine, texturally and compositionally immature sandstone, conglomerate, minor siltstone and thin (0-40 m) trachyte volcanic flows deposited into the eastern Mount Isa Rift (Bigie Formation). Abrupt thickness changes of up to several hundred metres occur across normal faults. The Bigie Formation has a maximum thickness of 700 m but tapers rapidly westward, becoming absent in the central and western Mount Isa Rift (O'Dea et al., 1997b). The Bigie Formation was deposited into localised sub basins to the northwest of the Mount Isa Rift. It is thinner (<200 m) and is dominantly composed of proximal fluvial, coarse-grained sandstone and conglomerate (Betts et al., 1999). The Bigie Formation tapers towards the NW and is intercalated with the bimodal Fiery Creek Volcanics (Figure 2). The Surprise Creek Formation is west tapering stratigraphic package that was deposited during continued rifting (Figure 2) (Betts and Lister, in review). Along the eastern Mount Isa Rift this formation is ~2.5 km thick (Batson, 1991). It is characterised by alternating sandstone and quartzite sheets and wedge shaped siltstone horizons. The lateral continuity, the relatively large thickness, and the anoxic character of the siltstone horizons suggest deep either shallow marine or lacustrine depositional environments (Batson, 1991). The sandstone and quartzite horizons are composed of interbedded quartz arenite, quartzite and minor micaceous sandstone (Batson, 1991). Their high textural and compositional maturity suggest deposition in a distal fluvial environment or a wave dominated marine environment (Batson, 1991). Sheeted sandstone and quartzite define periods of sedimentary regression.

The Surprise Creek Formation is locally absent along the western Mount Isa Rift (O'Dea et al., 1997a, b; Derrick, 1982; Nijman et al., 1992a). Here, it overlies progessively deeper stratigraphic levels to the west, and is thinner (0-800 m) (Betts et al., 1998; Betts and Lister, in review). The lower part of the formation is characterised by proximal fluvial, coarse sandstone and conglomerate channels, which grade into near shore, mature, fine grained sandstone (Nijman et al., 1992a). These are overlain by shallow marine fine grain sandstone, siltstone, and minor carbonate horizons (Derrick et al., 1980). The overlying Torpedo Creek Quartzite and the NW-tapering Gunpowder Creek Formation are considered part of the same sedimentary package as the Surprise Creek Formation (Figure 2).

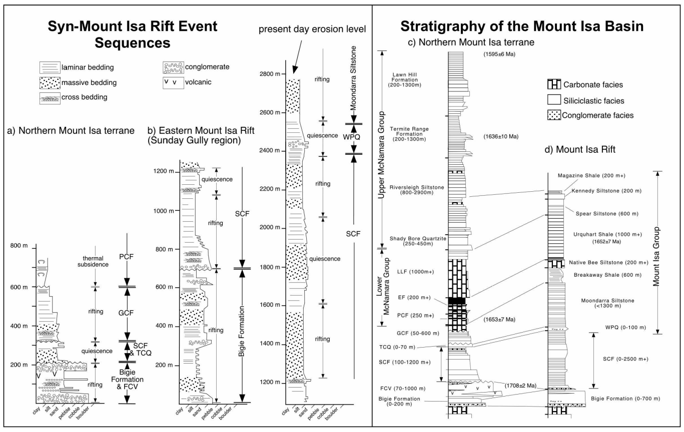
Syn-rift sedimentation continued until ~1655 Ma. The upper most syn-rift sequence is the shallow marine siltstone and fine grained sandstone of the Moondarra Siltstone. A maximum thickness of ~1300 m is preserved in the Paroo Range (Nijman et al., 1992a).

Post-rift sequences

The post-rift evolution of the Isa Superbasin began sometime before ~1653 Ma and continued until ~1595 Ma (Page and Sweet, 1998). Post-rift sequences include the McNamara Group in the northern Mount Isa terrane and by the Mount Isa Group above the Mount Isa Rift (Figure 2). The style of sedimentation changed from dominantly siliciclastic to carbonate sequences, and the basin depocentre shifted to the northern Mount Isa terrane.

The post-rift stratigraphy within the Mount Isa Rift comprises the sparsely preserved Mount Isa Group (1652±7 Ma: Page and Sweet, 1998). (Figure 2). The Mount Isa Group is dominantly composed of dolomitic and pyritic siltstone and shale, and minor conglomerate interpreted as shallow water, hypersaline lacustrine deposits with periods of sub aerial exposure (Neudert and Russell, 1981). The Mount Isa Group has a preserved thickness of ~3000 m (Figure 3).

Figure 3. Stratigraphic column



Stratigraphic columns showing thicknesses and interpreted periods of rifting and intervening tectonic quiescence during the Mount isa Rift Event: (a) section is located ~20km to the west of the Fiery Creek Dome; (b) section is located in the Sunday Gully region along the eastern margin of the Mount Isa Rift (Batson, 1991); (c) and (d) major lithostratigrapohic fomration so fghte isa Superbasin and their depositonal ages (data adapted rom Andrews, 1998; Dunster and McConachie, 1998; Southgate et al. 1997; Page et al., 1994; Page and Swet, 1998; Neudert and Russell, 1981). Comparison of the stratigraphy of the Isa Superbasin between the northern Mount Isa terrane (c) and the Mount Isa Rift (d). FCV - Fiery Creek Volcanics; TCQ - Toperdo Creek Quartzite; WPQ - Warrina park Quartzite; GCF - Gunpowder Creek Formation; PCF - Paradise Creek Formation; EF - Esperanza Formation; LLF - Lady Loretta Formation.

The McNamara Group is divided into a lower and upper member. The lower member correlates with the Mount Isa Group (Figure 2) and has a cumulative thickness of ~3000 m. It is dominantly composed of stromatolitic and dolomitic siltstone, sandstone and mudstone, deposited in a shallow water or shallow marine environment (Dunster and McConachie, 1998). The lower McNamara Group thins towards the western margin of the Mount Isa Rift (Sami et al., 1997). Equivalent sequences of the Mount Isa Group (Figure 3 d) thin towards the western margin of the Mount Isa Rift (Neudert, 1983), indicating an intrabasinal high along the western rift flank during the deposition of these formations.

The sequences of the upper McNamara Group (Figure 2) were deposited as the basin depocentre shifted to the northwest (Andrews, 1998). These sequences have a cumulative thickness of ~8 km (Andrews, 1998). There are no recognised equivalents of the upper McNamara Group above the Mount Isa Rift. This group comprises outer shelf to deeper water sandstone, siltstone and shale sequences (Andrews, 1998) overlain by turbidites (Andrews, 1998). These in turn are overlain by outer shelf sandstone, siltstone, and shale sequences (Andrews, 1998). There is abundant evidence to suggest syn-depositional fault activity occurred episodically during thermal subsidence (Andrews, 1998; Rohrlach et al., 1998). Tuffaceous horizons throughout the upper McNamara Group indicate episodic volcanism.

Structural architecture during the Mount Isa Rift Event

The most significant Mount Isa Rift Event-aged extensional structures are normal faults that bound E and SE-thickening half graben. There is a notable difference in the geometry of extensional structures between the Mount Isa Rift and the northwestern rift flanks (cf. Figure 1).

In the Mount Isa Rift, N-S and E-W trending normal faults bound half graben (O'Dea et al., 1997a, b). The Mount Isa Rift was approximately 40 km wide during the Mount Isa Rift Event and bounded by a westdipping fault that was located at the approximate position of the Quilalar and the Gorge Creek Faults (Figure 1) (O'Dea et al., 1997a). Normal faults are documented along the eastern Mount Isa Rift (Batson, 1991). These faults dip to the southeast and have marked thickness variations of the Bigie Formation and Surprise Creek Formation across them (~200 and ~950 m respectively (Batson, 1991).

Another important structural element of the Mount Isa Rift is south and north dipping cross rift structures (Lister et al., 1999). These faults initially developed during the Myally Rift Event (O'Dea et al., 1997b) and were reactivated during the Mount Isa Rift Event. They have a significant influence on sedimentation with syn-rift sequences coarsening and thickening in the hanging walls (Nijman et al., 1992a; Derrick, 1 9 8 2) . L a rger cross rift faults include the Investigator Fault and the Conglomerate Creek Fault (Figure 1).

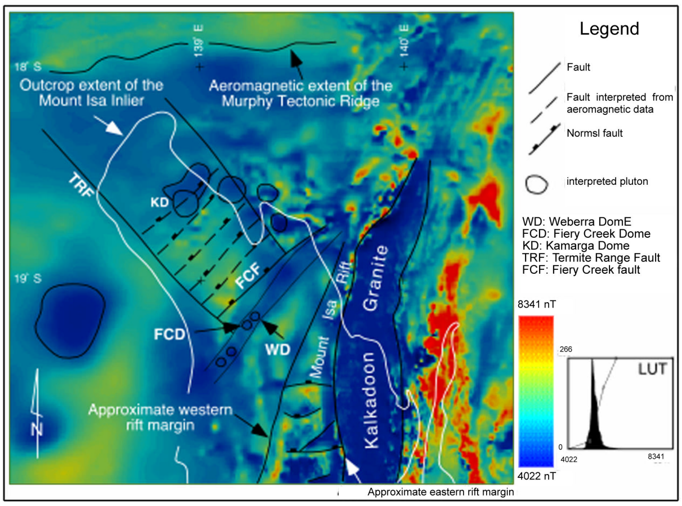
Mount Isa Rift Event-aged normal faults are best preserved in the mildly inverted (<25 % shortening) northern Mount Isa terrane (Betts et al. , 1999). NWdipping normal faults and NW-striking transverse faults are preserved. Regional-scale normal faults include the Fiery Creek Fault system and the Jacqueline Fault (Figure 1). Normal faults were active during the deposition of the Bigie Formation and the Gunpowder Creek Formation (Betts et al., 1999). Transverse faults strike perpendicular to normal faults. These faults behaved as tear or scissor faults, and evolved to facilitate differential displacement along normal faults (Betts et al., 1999). The NWstriking Termite Range Fault (Figure 1) is a basin-scale transverse fault.

Major normal faults terminate against this fault system. Differential subsidence across the fault is indicated by the absence of the upper Surprise Creek Formation to the south of the fault system.

Distribution of igneous rocks

Magmatic activity within the Mount Isa Rift was minor with thin volcanic flows extruded along the eastern margin (Batson, 1991). Granitic plutons are not preserved at the surface, nor is there any geophysical evidence for their existence in the subsurface. In contrast, magmatic units are aerially extensive and form a ~N-S trending belt to the W and NW of the Mount Isa Rift. Volcanic and intrusive units formed during two discrete spatiotemporal magmatic episodes. Early magmatism (~1710 and 1700 Ma) in the northern Mount Isa terrane involved the development of domes during shallow level pluton emplacement (Figure 1) (Betts et al., 1998; 1999). The Fiery Creek and Kamarga Domes are truncated and overprinted by northeast striking normal faults, suggesting magmatism predated faulting. Domes are characterised by low potential field responses suggesting the presence of a shallow pluton in their subsurface (Figure 4).

Figure 4. Regional aeromagnetic data



Regional aeromagnetic data of the northern Mount Isa terrane and the northern Leichhardt River Fault Trough (Mount Isa Rift).

Interpreted MIRE aged plutons and major faults are shown. Flight line spacing: 1600 metres; flight height: 200 metres; inclination: -50º; declination:6º; magnetic field strength: 52000nT. This image is released with permission of the direction of the Australian Geological Survey Organisation.

The regional geophysical signature indicates that the volume of igneous rock is significantly greater than the surface expression. (Figure 4) (Betts et al., 1998). The bimodal Fiery Creek Volcanics were extruded into half graben. Extrusion of the mafic and felsic suites was contemporaneous (Betts et al., 1998). The felsic suite displays a highly variable thickness up to ~800 m, and mainly comprises banded and massive rhyolite flows next to the Fiery Creek Fault. Altered, massive and vesicular basalts (150 m thick) (Hutton and Wilson, 1984) are exposed over a larger area. The second phase of magmatism involved the emplacement of the Sybella Granite, and the Carters Bore Rhyolite to the west of the Mount Isa Fault system (Figure 1). U-Pb SHRIMP crystallisation ages for the Carters Bore Rhyolite (1678±2 Ma: Page and Sweet, 1998) and the Sybella Granite (~1670-1655 Ma: Connors and Page, 1995) constrain the timing of this event. The Sybella Granite comprises several alkali feldspar and granodiorite plutons (Connors and Page, 1995). The regional map pattern (Figure 1) suggests that magmatic rocks are more extensive in the south. This does not necessarily indicate a greater volume of igneous rock but may simply reflect deeper levels of erosion in this part of the terrane (Betts et al., 1998).

Lithospheric Architecture

Regional analysis of the structural architecture, the distribution and thickness of syn- and post-rift sequences, and the location of major magmatic provinces has revealed a pronounced discrepancy between the location of maximum crustal extension, syn-extensional magmatic provinces, and the location of the maximum post-rift subsidence. These spatial association along with the shift in the basin depocentre after rifting, suggests the locus of crustal stretching (given by a stretching factor of ß1) was offset from the locus of sub-crustal lithospheric thinning (ß2), suggesting an asymmetric lithospheric extension (Coward, 1986; Lister et al., 1991).

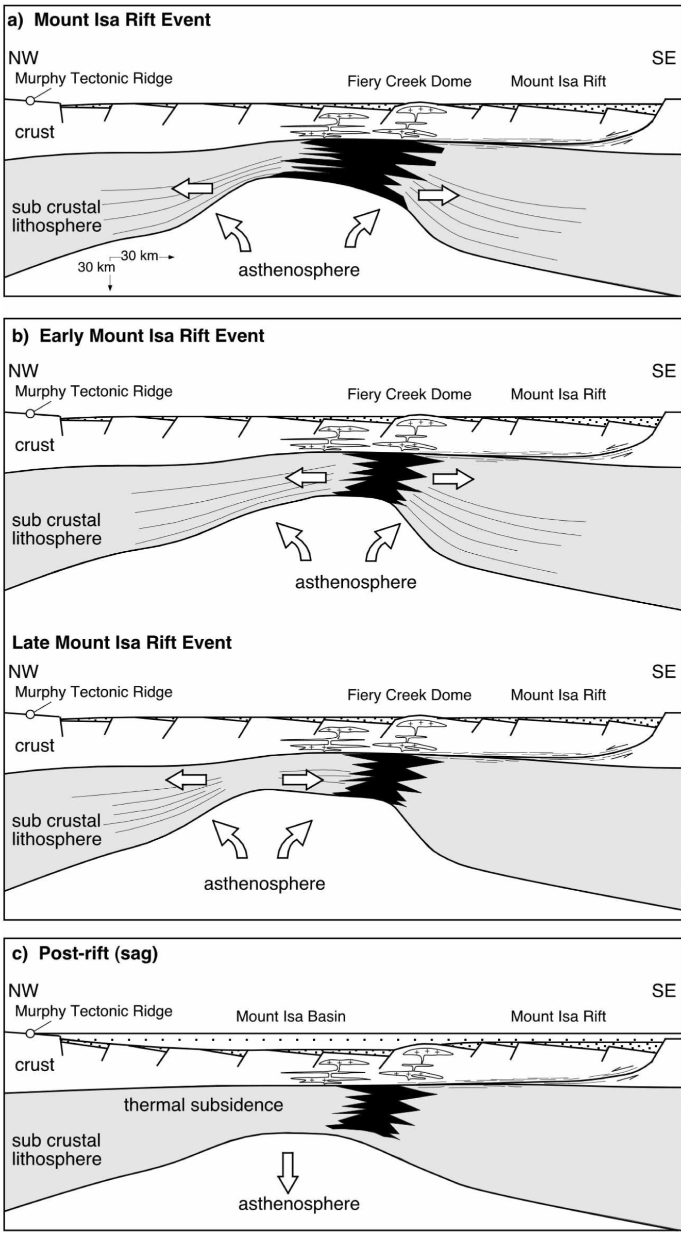
During the Mount Isa Rift Event

Crustal extension was widespread across the entire Western Fold Belt (Betts et al., 1998). Variations in fault geometry across the Western Fold Belt are interpreted as to be caused by differences the preexisting basement architecture (Betts et al., 1998; 1999). The N-S and E-W faults were reactivated during NW-SE directed extension (Betts et al., 1998). The architecture in the northern terrane resulted from orthogonal extension where normal faults developed perpendicular in the bulk extension direction. The following observations suggest that the Mount Isa Rift Event underwent asymmetric lithospheric extension during the Mount Isa Rift Event:

1. The Mount Isa Rift is characterised by a relatively high ß1 and a low ß2 (Betts et al., 1998)

The absence of magmatic rocks throughout the Mount Isa Rift indicates that a heat source associated with an upwelling asthenosphere and/or mafic underplating was relatively insignificant, and that stretching of the sub-crustal lithosphere was minor (Figure 5 a and b) (Betts et al., 1998). Tectonic subsidence associated with a crustal thinning and the development of rotational tilt blocks was not counteracted by the thermal uplift, resulting in overall subsidence (Figure 6 a). Up to ~3-5 km of syn-rift shallow marine to distal fluvial stratigraphy is preserved on the western part of the Mount Isa Rift.

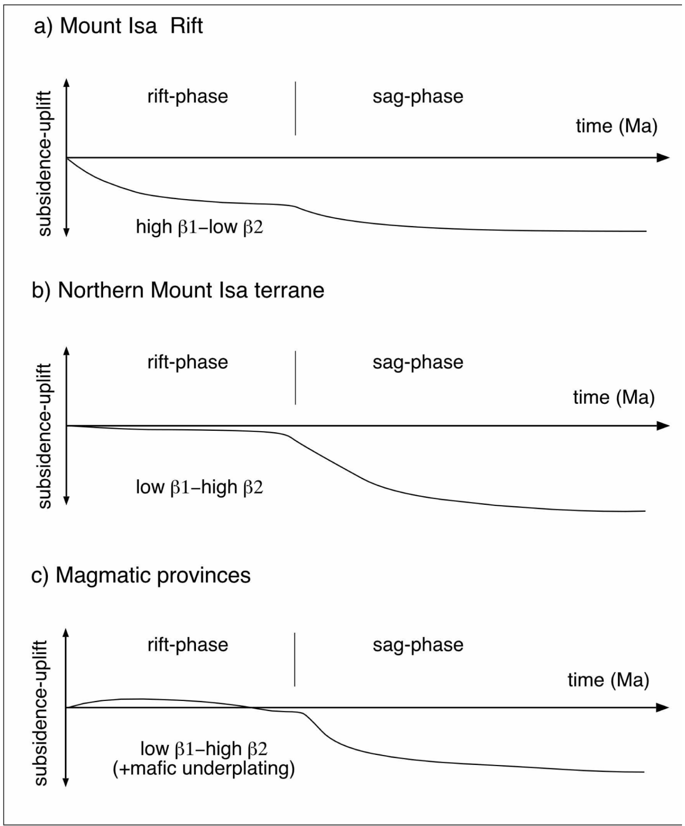
Figure 5. Schematic cross section



Schematic cross section depicting the asymmetric extension model. (a) The maximum upper crustal extension (b1) occurred along the Mount Isa Rift where the syn-rift stratigraphic pile is thickest. Major magmatic provinces are inferred to be located above significant sub crustal lithospheric extension (high b2), asthenosphere upwelling and underplating. The maximum sub crustal lithosphere stretching is inferred to occur to the northwest where the thickest accumulation post-rift sequences occur. (b) Initial sub crustal lithosphere extension focussed beneath the magmatic provinces. As the rift system evolved the focus of sub crustal lithosphere extension shifted northwest to where the maximum post-rift subsidence occurred. (c) Post-rift (sagphase) evolution of the Isa Superbasin. Dissipation of the thermal anomaly to the west of the Mount Isa Rift results in significant subsidence and the creation of accommodation space for accumulating post-rift sequences in the northern Mount Isa terrane. Subsidence along the Mount Isa Rift is limited.

2. Regions to the west of the Mount Isa Rift are characterised by low ß1 and a high ß2 (Betts et al., 1998). A thinner syn-rift sequences and evidence of prolonged periods of erosion and depositional hiatus of the western rift flanks suggest that it occupied a palaeogeographic high during the Mount Isa Rift Event (Betts et al., 1998; 1999). This palaeogeographic high is coincident with increased magmatic activity (Betts et al., 1998) The whole rock geochemistry of the Mount Isa Rift Event igneous rocks are interpreted to be A-type granitoids sourced from lower crustal melting (Wyborn et al., 1988). The mechanism for coincident lower crustal melting and the introduction of mantle derived material into the crust, was asthenospheric upwelling and mafic underplating associated with sub crustal lithospheric thinning (Betts et al., 1998). Uplift due to thermal expansion may have counteracted similar amounts of subsidence caused by crustal thinning (Figure 5 a and b) (Lister et al., 1991; Coward, 1986), resulting in a relatively stable uplift/subsidence history (Figure 6 c).

Figure 6. Typical uplift-subsidence histories



Typical uplift-subsidence histories for different parts of the MIRE rift system based on the asymmetric lithospheric extension model: (a) The Mount Isa Rift with a high $ß_1$ and a low $ß_2$. This uplift-subsidence history is characterised by syn-rift subsidence associated with thinning of the crust. Sag phase subsidence is limited compared with the northern Mount Isa terrane. (b) Inferred uplift-subsidence history for the northern Mount Isa terrane with a low ß1 and a high $ß_2$. This part of the terrane remained relatively stable during the MIRE. After the cessation of rifting the subsidence was greatest where the thermal anomaly began to wane. (c) Uplift-subsidence history of the magmatic provinces. Rifting was accompanied by permanent uplift associated with underplating. The region became submerged during the waning stages of the MIRE. As a result of the underplating the post-rift subsidence is less than the regions to the northwest. Qualitative analysis of these histories is based on calculations by Lister et al., 1991.

Periods of minor uplift resulted in depositional hiatus and erosion. Relatively small component of subsidence produced less accommodation space for accumulating sediments. A shift in magmatic activity from the north to south suggests a migrating heat source. Accretion of large volumes of mafic material onto the lower lithosphere during underplating requires either unusually high potential temperature of the asthenosphere, or a significantly thinned lithosphere (Lister and Etheridge, 1989). Underplating usually occurs late in the extensional history (Lister and Etheridge, 1989). However, magmatism, occurred early in the rift history. This suggests that the sub- crustal lithosphere was stretching long before crustal extension began, or the lithosphere was already thin and partial melting occurred at normal asthenosphere temperatures (Lister and Etheridge, 1989; McKenzie, 1978). Such a thin lithosphere is probable because of the pre-existing extensional history.

During the post-rift

The post-rift geometry of a sag-basin is strongly influenced by the position of sub-crustal lithospheric thinning (McKenzie, 1978; Coward, 1986; Lister et al., 1991). Thermal uplift may have continued after the Mount Isa Rift Event. Thinning of the Mount Isa Group and the lower McNamara Group towards the magmatic provinces may be recording permanent uplift beneath the rift flanks (cf. Figure 6 b and c) (Betts et al., 1998; Lister and Etheridge, 1989). The northern Mount Isa terrane is characterised by a low ß1 and a high ß2 during the Mount Isa Rift Event (Betts et al., 1998) (Figure 6 b).

Maximum post-rift subsidence occurred above the position of maximum sub-crustal lithospheric thinning (McKenzie, 1978; Coward, 1986; Lister et al., 1991) (Figure 5 c and 6b) in the northern Mount Isa terrane where the post-rift stratigraphy is thickest and the depositional history is more protracted (~1653 Ma to ~1595 Ma: Page and Sweet, 1998) (cf Figure 5 c and d). There is however, a disparity in the location of the thickest post-rift stratigraphy in the northern Mount Isa terrane and the position of magmatic provinces on the rift flanks. Two scenarios are considered:

1. Maximum sub-crustal lithospheric thinning occurred beneath the region of the maximum post-rift subsidence (Figure 5 a). Granite emplacement and bimodal volcanism was coincident with lithospheric thinning and asthenospheric upwelling but mafic underplating was the significant contributor to lower crustal partial melting (Figure 5 a).
2. Magmatic provinces and underplating were coincident with maximum sub crustal lithospheric thinning and asthenosphere upwelling during early rifting (Figure 5 b). The focus of maximum sub-crustal lithospheric thinning shifted westward to the location

of maximum post-rift subsidence (Figure 5 b and c) as the rift system evolved (Betts et al., 1998).

Implications for mineralisation

The Isa Superbasin contains one of the greatest concentrations of base metal (Pb-Zn-Ag) mineralisation in the world. The major sediment hosted Pb-Zn deposits include the Mount Isa, Hilton, Century, Lady Loretta, and Walford Creek, and George Fisher (Figure 1). It has been a long held view that Pb-Zn mineralisation has been intimately associated with basin forming processes and in particular an intracontinental rift settings and their subsequent sag-phase (see Goodfellow et al., 1993; McGoldrick and Keays, 1990; Large et al., 1988). All deposits post-date major epochs of intracontinental extension (Betts et al., 1999; O'Dea et al., 1997b). One of the distinct characteristics of the sediment hosted Pb-Zn deposits is that they are not hosted within a single stratigraphic horizon within the sag-phase of the Isa Superbasin (Goodfellow et al., 1990; Betts et al., 1999), and thus no single mineralising event is responsible for their formation. For example, the Mount Isa and Hilton deposits (Figure 1) are hosted within stratigraphy deposited at 1562±7 Ma (Page and Sweet, 1998), the Walford Creek deposits (Figure 1) are hosted within stratigraphy that is aged at ~1640 Ma (Page and Sweet, 1998; Rorhlach et al., 1998), and the Century deposit is hosted within stratigraphy aged ~1595 Ma (Broadbent et al., 1998; Page and Sweet, 1998). Genetic models for mineralisation are also variable. Traditionally, Pb-Zn deposits are considered to be SEDEX-types (Goodfellow et al., 1993), detailed studies are suggesting different processes of mineralisation. Some deposits have multiple genetic models for the formation (cf. McGoldrick and Keays, 1990; Perkins, 1996).

Models include early diagenesis beneath the watersediment interface (Mount Isa, Hilton: McGoldrick and Keays, 1990). Similar ore depositional processes have been proposed for the HYC deposit in the McArthur Basin and the Walford Creek Deposit (Rorhlach et al., 1998). The Walford Creek Deposit has characteristics associated with several deposit types (Rorhlach et al., 1998). These include mineralisation is similar to those formed with SEDEX deposits, cavity fill and stratiform Pb-Zn deposition during early diagenesis followed by cavity fill, replacement, and MVT-style veins. The variation of mineral style within the Walford Creek Deposit reflects the continuum of the sediment hosted mineralisatiuon processes during basin evolution and subsequent inversion (Rorhlach et al., 1998). The syn-sedimentary and early diagenetic concepts for mineralisation have been challenged. Several recent studies have suggested that mineralisation occurred during basin inversion (e.g., Century: Broadbent et al., 1996) and regional shortening of the Isan Orogeny (e.g., Mount Isa and Hilton: Perkins, 1996; 1998). The Century deposit is hosted within turbiditic siliclastic black shale and siderite-rich siltstone of the upper McNamara Group (Andrews, 1998; Broadbent et al., 1998). This differs from the deposits hosted lower in the stratigraphy that are hosted within shallow marine carbonates and evaporitic-rich sequences. Century is a shale hosted mineralization style formed during tectonically driven migration of basinal fluids during initial N-S-directed basin inversion, sharing many similarities with Mississippi Valley-type mineralisation (Broadbent et al., 1998).

An epigenetic model for Mount Isa has been applied by Perkins (1996; 1998) explaining several paragenetic and overprinting relations of alteration and sulphides. This model differs significantly from the SEDEX or diagenetic models commonly supposed for the deposit (see Large et al., 1988; McGoldrick and Keays, 1990) because sulphide deposition involves fluid-wall rock reactions rather than mixing of sea water and hydrothermal fluids. Perkins (1996; 1998) utilised overprinting relations to suggest that mineralisation occurred after the main phase of E-W shortening of the Isan Orogeny.

Despite the various genetic models for the sediment hosted Pb-Zn ores of the Western Fold Belt, a common feature of the deposits is their strong structural control, or a spatial association, with the large extensional faults (Lister and Betts, in review). Mineralising events may be related to periods of extensional faults reactivation. Post-rift seismic activity along normal and transverse faults may have localised stresses, providing pathways for the ascent of mineralising fluids. Reactivation of normal faults are documented by Andrews (1998) and Rohrlach et al. (1998). The size of the rift faults may also be significant in determining the location of mineralisation. Larg e volumes of fluid, sourced from the deep crust, are likely to be channelled along larger basin bounding faults. Smaller rift faults may not be as integral to the fluid plumbing system.

At the Mount Isa deposit, the Paroo Fault is the fundamental control of the zonal pattern of mineral distribution in the orebody whereas smaller scale dilational dolomite veins locally control the distribution of sulphides (Perkins, 1996). Other examples of Pb-Zn deposits forming along major extensional structures includes Century which is spatially associated with the Termite Range Fault (Broadbent et al., 1998) and the Walford Creek Deposit which occurs along the basin-bounding Fish River Fault (Rohrlach et al., 1998).

An asymmetric extension model for the Mount Isa Rift Event has significant implications for the formation of these large Pb-Zn-Ag orebodies. Pb-Zn- Ag deposits are located to the west of the Mount Isa Rift (Figure 1), coincident with the predicted location of maximum asthenospheric upwelling, magmatism, and the highest geothermal gradients. Most models associated with the development of sediment hosted Pb-Zn deposits, particularly diagenetic and SEDEX models, invoke a fluid convection system driving fluids throughout the basin (Russell et al., 1981; Goodfellow et al., 1993). Models commonly require a local magmatic source (e.g., shallow level pluton) as a driving mechanism for fluid convection (Goodfellow et al., 1993; Goodfellow et al., 1990). Such models also require a prolonged transit time for hydrothermal fluids to reach the sea floor (Goodfellow et al., 1990). In the Isa Superbasin, there is little evidence from exposed supracrustal sequences or from the geophysical data, with the exception of the Mount Isa and Hilton deposits, that such plutons are temporally or spatially associated with the large Pb-Zn deposits. Other convection models (eg. Russell et al., 1981) do not require a local source. Rather these models call upon a downward propagating convection cell along extensional faults that tap into elevated heat sources, caused by an elevated geotherm associated with an rifted continental crust (Russell et al., 1981). The proposed asymmetric extension model predicts the location of maximum asthenosphere upwelling and presumably highest geothermal gradients to be located to the north and west of the rift axis. The model conveniently explains the absence of Pb-Zn deposits within the rift zone. There remains a temporal problem between timing of the mineralisation (post-rift) and the timing of elevated geothermal gradients during rifting. An elevated crustal geotherm probably continued on the rift flanks after the cessation of rifting, although it gradually dissipated as the asthenosphere downwelled and the basin subsided. Thermal subsidence also promotes burial and increasing the depth extent of high geothermal gradients, effectively allowing the mid to upper crust to heat up while the Moho cools (McLaren et al., 1997), allowing favourable thermal conditions to drive convecting fluids in the basin.

Recognition of favourable or common sedimentary environments for the sequences hosting the mineralisation is significant for ground selection for Pb-Zn mineralisation. Particular sedimentary environments produce chemically favourable site for the deposition of Pb-Zn mineralisation (Goodfellow et al., 1993) regardless if mineralisation occurred at the sea floor during deposition or during later diagenesis. Favourable stratigraphic packages associated with the deposition of Pb-Zn mineralisation include carbonaceous chert, shale, siltstone, and coarser clastic lithologies deposited in a anoxic marine environment (Goodfellow et al., 1993). Lacustrine depositional environments have also been suggested (Muir, 1983). Stratigraphic studies of the northern Mount Isa terrane have shown that fluid migration may have been controlled by unconformities beneath sequence boundaries (McConachie and Dunster, 1996). Metal precipitation was due to the reduction of organic matter in shale near the top of organic-rich high-stand system tracts (McConachie and Dunster, 1996). Pb- Zn-Ag mineralisation is often hosted within condensed stratigraphic sections defined by black shale sequences (McConachie and Dunster, 1996). Although, the interpreted tectonic setting of the Isa Superbasin differs from that of McConachie and Dunster (1996) the same principles are applicable to a sag-basin. Condensed sections are likely to form where subsidence and accommodation space is greatest, throughout the northern Mount Isa terrane. Muchez et al. (1994) proposed that gravity driven fluid flow plays a significant role in the development of diagenetic Pb-Zn-Ag orebodies. During sag-phase evolution of the basin, fluid migration would be directed towards the locations of greatest thermal subsidence (i.e. the northern Mount Isa terrane).

Conclusions

The Palaeoproterozoic Isa Superbasin represents an intracontinental extensional basin that began at approximately 1708 Ma during a period of approximately NW-SE directed extension (Mount Isa Rift Event). Crustal extension and tectonic subsidence were focussed along the Mount Isa Rift where 3-5 km of clastic syn-rift sequences were deposited. On the rift flanks, in the northern Mount Isa terrane periods of depositional hiatus or episodic uplift and erosion indicating a more stable uplift/subsidence history are indicated by a thinner syn-rift stratigraphy (750-2000 m).

The Mount Isa Rift was characterised by a relatively high ß1 stretching factor and a low ß2 value, and the western rift flanks and the northern Mount Isa terrane were characterised by a relatively low ß1 value and a high ß2. The distribution of syn- and post-rift sequences throughout the Isa Superbasin, and the location of syn-rift magmatic provinces, suggests that the locus of crustal extension was offset from sub crustal lithospheric thinning and asthenospheric upwelling. Such a lithospheric structure is consistent with asymmetric lithospheric extension. Granite emplacement and bimodal volcanism is confined to the northwest and west of the Mount Isa Rift. These magmatic provinces are interpreted to occur above the position of significant sub-crustal lithospheric thinning and asthenospheric upwelling, or voluminous underplating during the Mount Isa Rift Event.

Dissipation of the thermal anomalies beneath the northern Mount Isa terrane caused a shift in the basin depocentre to the northern Mount Isa terrane. Shallow marine carbonate sequences and then deeper water sediments were deposited into a sag basin. The northern Mount Isa terrane marks the position of maximum sub crustal extension during the Mount Isa Rift Event.

Elevated geothermal gradients caused by sub-crustal lithospheric thinning to the west of the Mount Isa Rift may have provided the driving force for large scale fluid flow in the Isa Superbasin. Increased thermal subsidence may have produced ideal chemical conditions for precipitating metals during hydrothermal activity. Gravity driven fluid flow would be directed to the northern Mount Isa terrane during the sag-phase evolution of the Isa Superbasin. A combination of these conditions may explain the high density of large Pb-Zn-Ag orebodies hosted within the Isa Superbasin to the west of the Mount Isa Rift.

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