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A PROTEROZOIC RIFT ZONE AT MOUNT ISA, QUEENSLAND, AND IMPLICATIONS FOR MINERALISATION

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The Leichhardt River Fault Trough (LRFT) near Mount Isa is thought to be an ensialic or continental margin rift structure formed about 1800–1650 m.y. ago. Extension in old (1865–1800 m.y.) acid volcanic and granitic basement was followed by deposition of up to 10 km of epicontinental clastics, minor dolomite and redbeds, and marginal fanglomerates, and up to 6 km of subaerial to shallow subaqueous basalt. The latter provides characteristic gravity and magnetic signatures, which define the subsurface extent of the rift. The rift fill is blanketed by an orthoquartzite-carbonate unit about 1750 m.y. old. Deformation and uplift 1680 m.y. ago were accompanied by basic to acid volcanicity, which was followed by intracontinental sedimentation, and finally by 4–6 km of Pb-Zn-bearing dolomitic shale basin deposits. A zone of central uplift (Mount Gordon Arch) divided the LRFT into two meridional basins. Igneous rocks from the LRFT are bimodal in composition, and typical of non-orogenic terrains. They range from basement rhyolite and dacite to tholeiitic basalt, granite and alkali granite, rhyolite and trachybasalt, and finally to tholeiitic dyke swarms. The fault trough formed by extension and sagging of continental crust. Mantle upwelling and subsequent deep rifting tapped basalt sources; magma withdrawal and basalt loading of the crust led to further sagging and epicontinental sedimentation. Heat from earlier mantle upwelling caused lower crustal fusion and subsequent granite intrusion of the rift pile. Genesis of major Cu and Pb-Zn deposits has been partly controlled by early and reactivated growth faults and by the movement of subsidiary crustal blocks within the fault trough.

Introduction

Rifts, rifting processes and extensional tectonics are currently of great geological interest, as workers attempt to trace evidence of plate-tectonic processes and associated mineralisation in Proterozoic and Archaean sequences throughout the world (Wilson, 1968; Dewey & Burke, 1974; Hoffman & others, 1974; Sawkins, 1976; Ramberg & Neumann, 1978; Olade, 1980; Large, 1981). This paper presents details of the internal structure of the Leichhardt River Fault Trough (LRFT), an 1800-1650 m.y. old intracontinental or continental margin rift structure centred on Mount Isa, northwest Queensland, Australia (Carter & others, 1961; Glikson & others, 1976; Dunnet, 1976; Plumb & others, 1980). Since the paper by Glikson & others (1976), regional geophysical and geological studies by the Bureau of Mineral Resources (BMR) and Geological Survey of Queensland (GSQ) have been completed, and more geochronological (Page, 1978, 1981) and geochemical data have become available. In this paper, the new data are synthesised and integrated with recent studies of the Mount Isa Cu-Pb-Zn deposit.

In reconstructions of the Panantarctic craton (e.g. Piper, 1976; Dunnet, 1976), the LRFT occurs near the margins of the craton, flanked by Palaeozoic fold belts that extend through eastern Australia, Antarctica, southern Africa and the southernmost American Cordillera. It forms part of the Mount Isa Orogen, but also occurs within and extends beneath the Proterozoic Lawn Hill Platform (Fig. 1). To the south, the LRFT is obscured by Palaeozoic and Mesozoic cover; its geophysical expression, however, appears strong (Tucker & others, 1979), and it is thought to terminate against the Palaeozoic Tasman Orogenic Province, being separated from it by a prominent crustal lineament, the Cork Fault (Fig. 1).

The Mount Isa Orogen occupies most of the Cloncurry Regional Gravity High (Fig. 2), a region of Bouguer anomalies of from $-20°$ to $+40°$ $\mu m\ s^{-2}$ (Fraser, 1976).

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Dooley (1980) has summarised recent geophysical work in the orogen, and pointed out differences of approach by Shirley (1979) and Wellman (1976) in estimates of crustal thickness, which range from 34 km to 40 km.

Basalt of the Eastern Creek Volcanics occupies fault blocks, which are defined by a belt of positive magnetic anomalies greater than 2500 nT. Extrapolation of this belt to the south can be used to indicate the presence of basic volcanics, possibly fault-bound, in the subsurface (Tucker & others, 1979). South of the limits of Proterozoic outcrop, the magnetic basement deepens from about 400 m to over 2000 m.

From the close association of magnetic and positive Bouguer anomalies and outcrops of the Eastern Creek Volcanics, the LRFT appears to be a major basalt-filled linear crustal feature, extending nearly 600 km from near the Lawn Hill region in the north to the Cork Fault in the south, and about 50–65 km wide. It seems analogous to the 'first-order' basins noted by Large (1981) in his discussion of sediment-hosted Pb-Zn deposits. A major crustal lineament, the Gorge Creek-Mount Remarkable Fault Zone, displaces the Leichhardt River Fault Trough by 25 km, in a right-lateral sense.

The characteristics of the LRFT outlined above may be directly compared to other rift systems, such as the partly buried late Precambrian Central North American Rift (Halls, 1978), particularly the linear patterns of magnetic and gravity anomalies, and the high proportion of basaltic fill.

Stratigraphy, geochronology, and sedimentology

Stratigraphy and geochronology of the LRFT are summarised in Figure 3. Basement rocks are overlain conformably or disconformably by the **Haslingden Group,** a mainly arenaceous succession, but with substantial thicknesses of tholeiitic flood basalt; this group occurs solely within the LRFT. It is overlain conformably by the **Quilalar Formation,** a region-wide quartzite-carbonate transgressive blanket deposit. Deformation and uplift of the Quilalar Formation/Haslingden Group was followed by sedimentation and basaltic to alkalic vol-

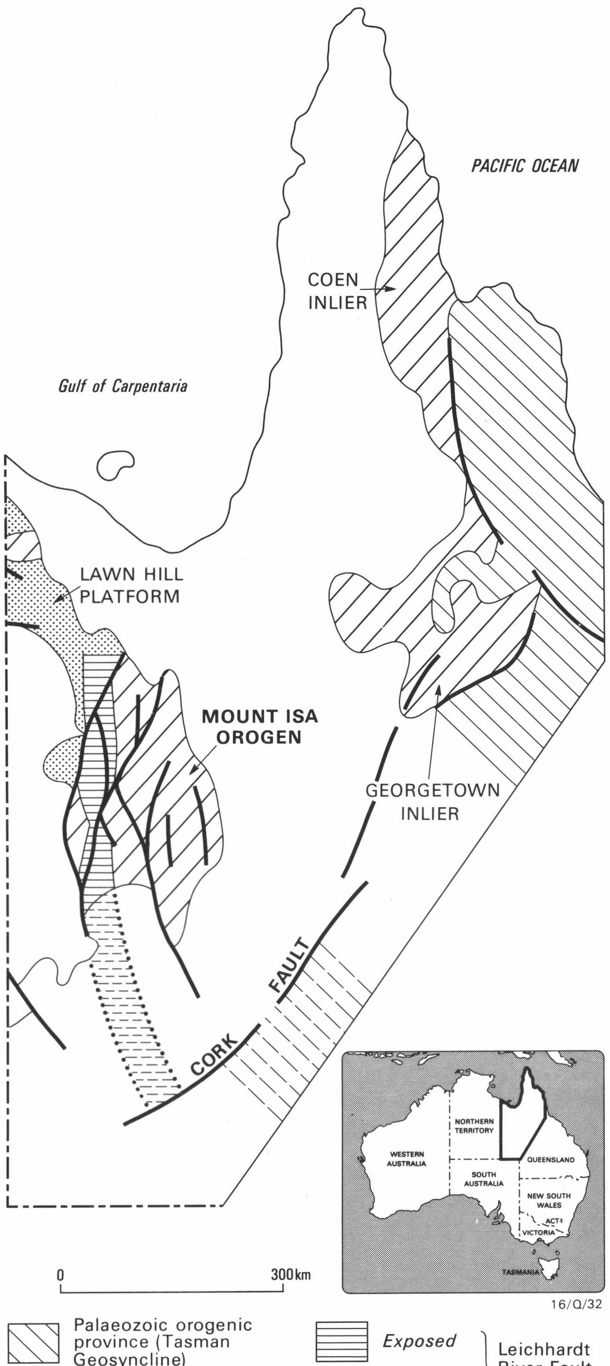


Figure 1. Regional tectonic setting of the Leichhardt River Fault Trough. (adapted from Plumb, 1979).

canism, which produced the **Fiery Creek Volcanics.** Sandstones and siltstones of the **Surprise Creek Formation** overlie these volcanics unconformably, and are overlain conformably and unconformably by sandstone, siltstone, shale, and dolomitic rocks of the **Mount Isa** and **McNamara Groups,** host to major Pb-Zn deposits in the region.

Basement rocks

East of the LRFT at least two ages of basement rocks are present; the **Leichhardt Metamorphics** are 1865 ± 3 m.y. old (U-Pb zircon), and **Kalkadoon Granite** 1862^{+27}_{-21} m.y. old (U-Pb zircon) (Page, 1978). These rocks are overlain unconformably by the **Bottletree** and **Argylla Formations,** which are 1777 ± 7 to about 1810 m.y. old (Page, 1978 and personal communication, 1980). The **Ewen Granite** has given a minimum (K-Ar biotite) age of 1772–1776 m.y. (Richards & others, 1963), but recent U-Pb zircon work indicates that it may be of similar age to or slightly younger than the Kalkadoon Granite (Wyborn & Page, in prep.).

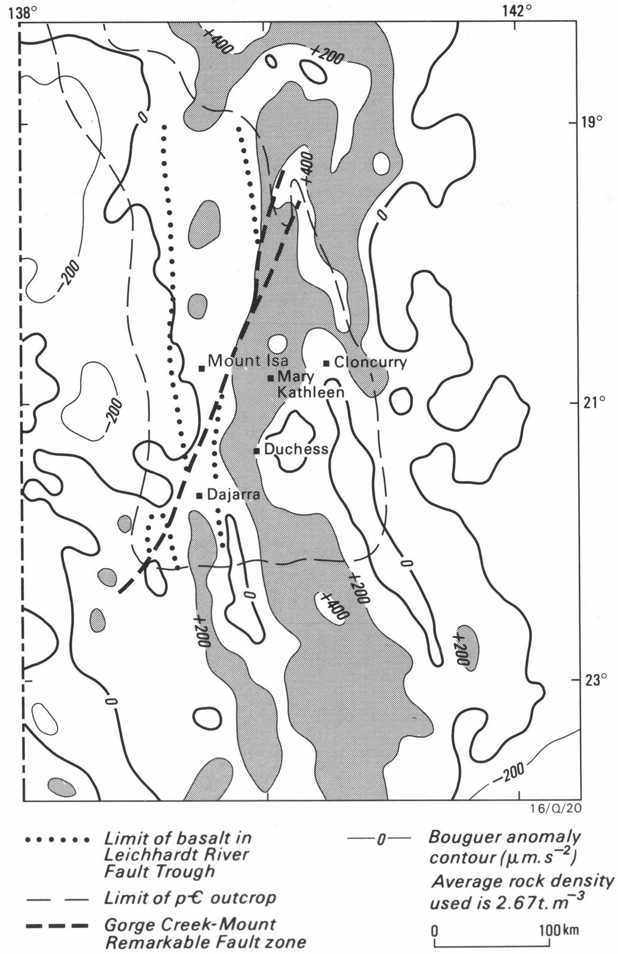


Figure 2. Bouguer anomaly map of the Mount Isa orogen.

The regional gravity high over the Mount Isa Orogen suggests it is underlain at moderate depths by extensive areas of basic crustal material. This is also supported by seismic profiles, which show velocities of 7.1-8.26 km s^{-1} (velocities characteristic of lower crust—upper mantle composition) at depths from about 30-53 km, respectively (Finlayson, BMR, personal communication, 1980).
The areas of thick basalt accumulation that help define the LRFT coincide with a series of north-trending linear 0 to +200 $\mu m\ s^{-2}$ Bouguer anomalies; sub-surface extensions of this belt to the south are probably the cause of a narrow, well-defined +200 $\mu m\ s^{-2}$ anomaly, up to 20 km wide and 200 km long, which extends to the Cork Fault.

The Bottletree and Argylla Formations along the eastern margins of the fault trough contain cobble to boulder greywacke and arkosic conglomerates intercalated with acid to basic lavas and tuffs. The conglomerates are probably volcaniclastic debris flows and scree-slope, channel, and alluvial fan deposits, and indicate the presence of elevated, possibly fault-controlled basement source areas.

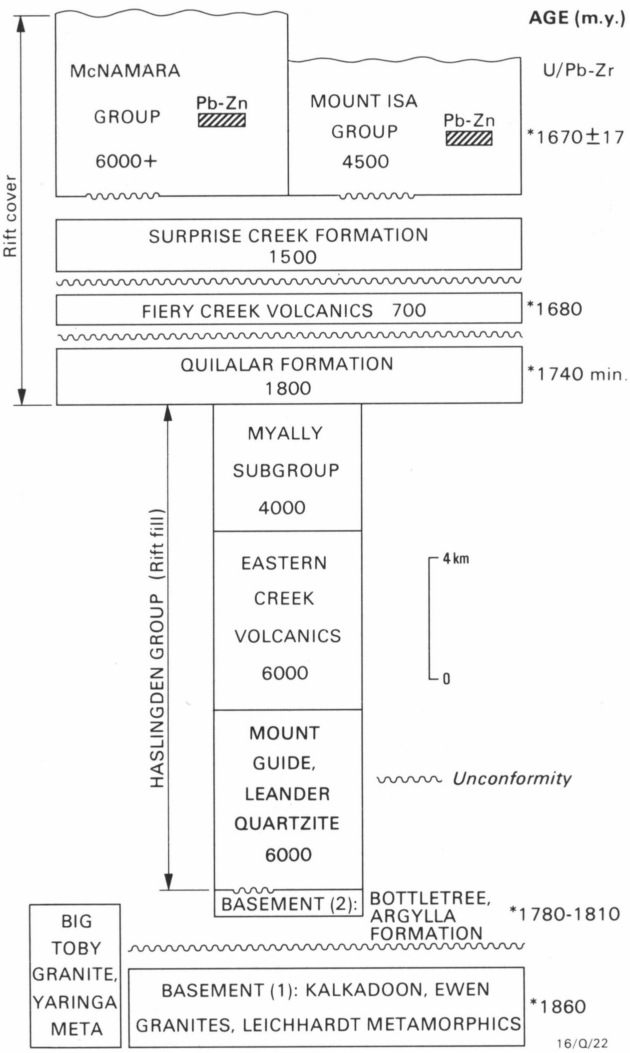


Figure 3. Generalised stratigraphy and geochronological framework of the Leichhardt River Fault Trough.

Basement to the west (cratonwards?) of the fault trough is probably represented by schist, gneiss, phyllite, and acid volcanics of the **Yaringa Metamorphics,** and the **Big Toby Granite;** the granite intrudes the metamorphics, and has been dated (U-Pb zircon) at about 1800 m.y. (Page, 1980).

The Leichhardt River Fault Trough thus appears to have been initiated on a basement about 1800–1865 m.y. old, of mainly continental plutonic and volcanic crust and its greywacke and arkosic derivatives.

Volcano-sedimentary filling of the LRFT (Fig. 4)

Overlying the basement rocks, conformably or unconformably, basal arkoses and conglomerate of the Haslingden Group—**Mount Guide** and **Leander Quartzites,** and **Yappo Formation** (Bultitude & others, 1978)—form a tabular to wedge-shaped sheet, probably deposited in coalescing braided stream and alluvial plain environments marginal to basement rocks east and west of the embryonic rift. They grade upwards to micaceous feldspathic sandstone with abundant heavy mineral banding, and to very cleanly washed, well-sorted and round-grained, medium to coarse orthoquartzites, which indicate beach and active shallow marine environments. Crossbedding and ripple marks are ubiquitous, and indicate palaeocurrents dominant from the east and southeast. The sequence suggests slow planation and regional overlap of the basement during a steady marine transgression.

West of Mount Isa, quartzofeldspathic gneiss **(May Downs Gneiss)** and glassy quartzite are thought to be equivalents of the arkosic and orthoquartzite facies of the Mount Guide Quartzite, metamorphosed by the Sybella Granite.

The sediments thicken rapidly towards the centre of the LRFT, and vertical lithological variation appears mini-

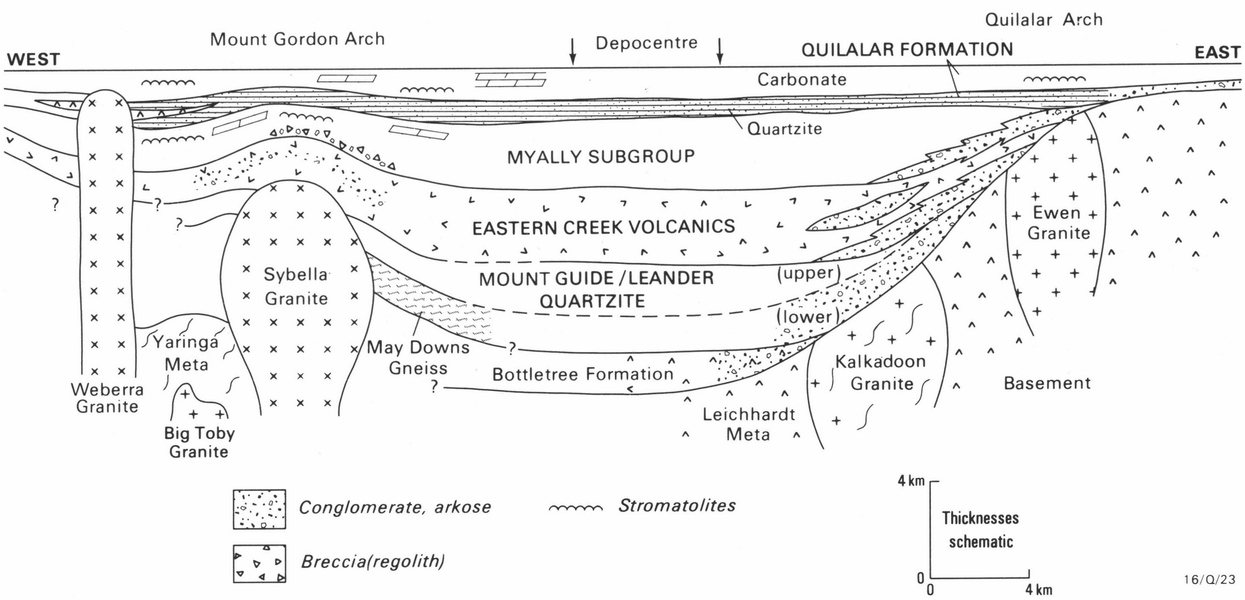


Figure 4. Schematic cross-section of the Leichhardt River Fault Trough prior to Fiery Creek uplift and deformation.

mal throughout 2000–3000 m of mainly shallow-water sandstones. Subsidence within the LRFT, therefore, has been enough to accommodate up to 6000 m of sediment in the depocentre (although thicknesses may be exaggerated by thick foreset bedding on delta fan slopes).

The quartzites are overlain abruptly and conformably by basalt of the **Eastern Creek Volcanics,** which are up to 6000 m thick, but which thin to the east and west. Eastwards the thinner sequences of basalt are associated with coarse boulder to pebbly conglomerates, which overlie Mount Guide Quartzite and overlap the basement granites and volcanics of the Ewen Block unconformably (Fig. 4). The basalts are mainly continental tholeiites (Glikson & others, 1976). The basalt pile may be divided into a lower unit, the **Cromwell Metabasalt Member** (2000–3500 m); a middle arenaceous unit, the **Lena Quartzite Member** (up to 800 m); and an upper unit, the **Pickwick Metabasalt Member** (up to 2000 m). The arenites are well-sorted sheets and lenses of orthoquartzite and feldspathic quartzite, and are ripple-marked and cross-bedded. Sandstone interbeds increase in abundance upwards in the Cromwell Metabasalt Member, culminating in deposition of the Lena Quartzite Member. In places the upper Pickwick Metabasalt Member consists almost entirely of regularly interbedded quartzite and metabasalt, and also contains one or two persistent layers of coarse to fine tuff.

The amydaloidal nature of most basalt flows, and the intercalations of sandstone and lava flow-top breccias, reddish siltstone and shale, and cross-bedded and ripple-marked orthoquartzites are interpreted as shallow-water or terrestrial depositional features. Variations in the shape of the Lena Quartzite Member from sheet to ribbon and lenticular sands are suggestive of beach and shallow-water environments, transitional to low relief terrestrial environments on which braided stream and lagoonal or muddy lacustrine deposits were formed on a largely basaltic surface. The sand lenses pass eastwards into thick wedges of coarse conglomerate and arkose derived largely from the eastern basement.

No centres or zones of volcanic eruption have yet been identified in the LRFT. Uniform thicknesses of basalt continue over 200 km north to south, suggesting voluminous extrusion from north-trending fissures.

Extrusion of the massive Eastern Creek volcanic pile was followed by deposition of the **Myally Subgroup** (Figures 3, 4), a largely shallow-water succession up to 4000 m thick. Constituent formations of the subgroup are, from top to base:

Lochness Formation (600 m): dolomitic sandstone and siltstone, dolomite;

Whitworth Quartzite (2000 m): feldspathic quartzite, orthoquartzite;

Bortala Formation (150 m): feldspathic quartzite, calcareous siltstone;

Alsace Quartzite (600 m): orthoquartzite.

The **Judenan Beds** west and northwest of Mount Isa are now known to be equivalents of the Whitworth Quartzite and Lochness Formation.

Like older units in the Haslingden Group, the formations in the Myally Subgroup thin rapidly to the east, where arkose of the subgroup overlaps Eastern Creek Volcanics and rests unconformably on basement (Ewen Granite) (Figure 4). They exhibit abundant shallow-water features, and appear to have been deposited in a shallow epeiric sea (Derrick, 1974; Wilson & others, 1977). The uppermost Lochness Formation marks the first significant appearance of redbeds and dolomite in the sedimentary fill of the LRFT. Desiccation cracks, abundant oolitic dolomite, and stromatolites indicate a slowing of subsidence in the trough and the formation of carbonate banks and shoals and associated muddy lagoons.

Distribution of the various units in the Myally Subgroup suggests the depositional basin was closed to the east and south of Mount Isa, but was open to the north and, to a lesser extent, to the west.

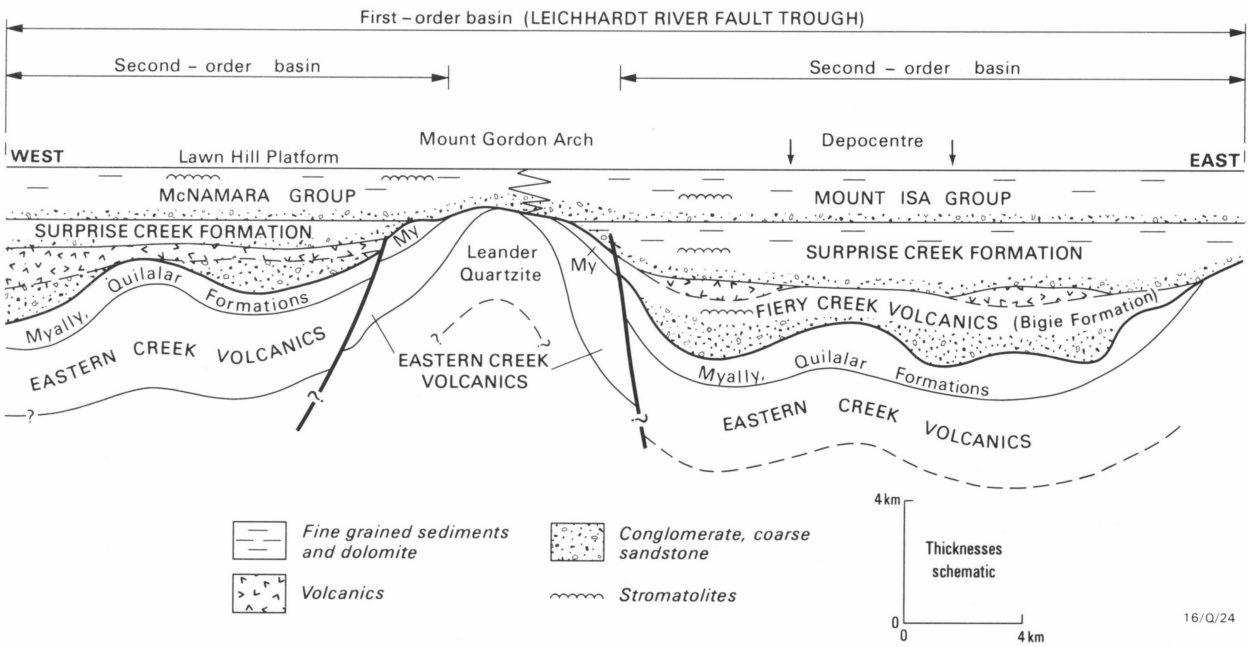


Figure 5. Schematic cross-section of the Leichhardt River Fault Trough subsequent to Fiery Creek uplift and deformation.

The easterly limit of deposition in the LRFT is thought to have been a zone of crustal uplift a few kilometres wide, here termed the **Quilalar Arch** (Figure 4). The increase in abundance of conglomerate towards this zone indicates that some long-acting fault scarps were probably present, and, given that this linear zone of crustal uplift has been a hinge zone separating stable basement from a rapidly subsiding crustal segment to the west, an abundance of step or normal faults could have been present during deposition of the Haslingden Group.

A transgressive quartzite-carbonate blanket, the **Quilalar Formation,** overlies the Myally Subgroup conformably, and extends across much of the Mount Isa Inlier (Derrick & others, 1980; Plumb & others, 1980). Local trachybasalt flows in the unit may be precursors of a later period of K-rich volcanism and uplift.

Equivalents of the Quilalar Formation to the east are intruded by 1720–1740 m.y. old granites (Page, 1980); hence the Quilalar Formation is older than about 1740 m.y., and the Haslingden Group is thought to have been deposited between about 1800 m.y. and 1740 m.y. ago, i.e. a maximum subsidence and depositional rate of 230 m/m.y.

Fiery Creek uplift and subsequent sedimentation

Uplift and moderate folding of the Haslingden Group and Quilalar Formation were followed by deposition,

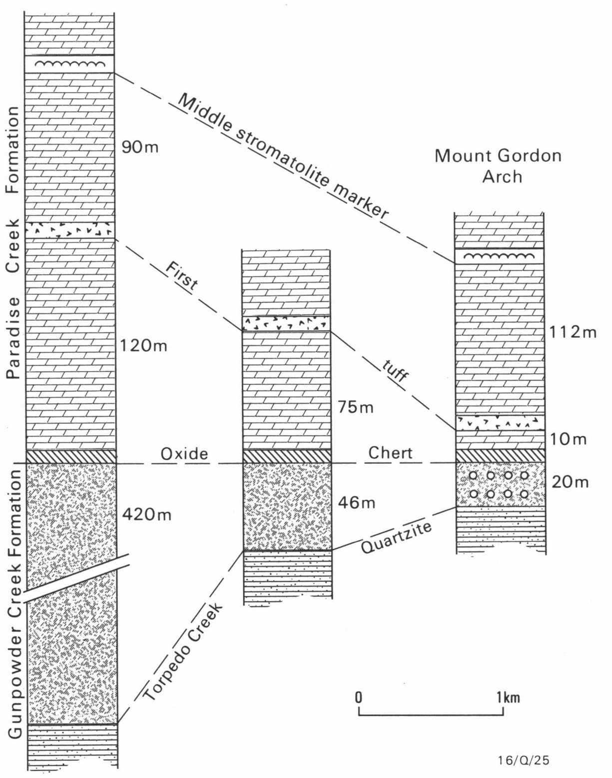


Figure 6. Thickness variations in the Gunpowder Creek Formation and lower Paradise Creek Formation of the McNamara Group.

From west to east towards the Mount Gordon Arch the silt-rich Gunpowder Creek Formation thins dramatically from over 400 m to about 20 m over 2-4 km across the depositional strike. It also becomes more arenaceous, and locally is conglomeratic. These features indicate a more proximal depositional environment near the arch, probably near-shore peritidal and, possibly, beach environments.

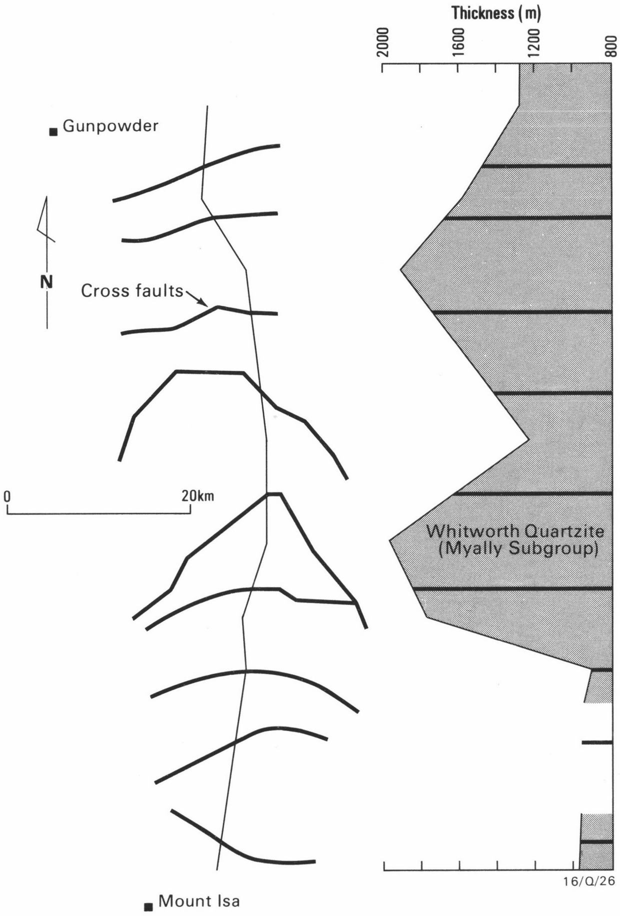


Figure 7. Thickness variations in the Whitworth Quartzite (Myally Subgroup) north to south along the LRFT, relative to east-west cross-faults.

unconformably, of the redbed conglomerate and sandstone **(Bigie Formation)** in braided streams and alluvial plains, and some siltstone and carbonate rocks in adjacent near-shore basins. Potassic lavas (rhyolites, trachytes), agglomerate, tuff, and some basalt formed a thin (up to 700 m) lenticular sheet over much of the LRFT in areas north of Mount Isa and on the Lawn Hill Platform. These volcanics, the **Fiery Creek Volcanics,** are largely subaerial, and include rhyolite domes up to 4 km across. Most of the acid lavas are altered, and devoid of sodium.

Equivalents of the Fiery Creek Volcanics have been dated at 1680 m.y. (Page, 1978). Volcanicity terminated with uplift and mild deformation and the formation of an unconformity at the top of the Bigie Formation-Fiery Creek Volcanics sequence (Figs. 3, 5).

An arenite-to-siltstone and shale fining-up sequence, the **Surprise Creek Formation,** overlies the Fiery Creek Volcanics and older rocks unconformably (Plumb & others, 1980; Derrick & others, 1980). It, in turn, is overlain conformably and unconformably by the **Mount Isa** and **McNamara Groups** (Mathias & Clark, 1975; Hutton & others, 1981). These groups, the youngest preserved sequences of the LRFT domain, contain fine-grained detrital and dolomitic sediments, and are host to major dolomitic and pyritic shale-hosted Ag-Pb-Zn deposits (Mount Isa, Hilton, Lady Loretta; Williams,

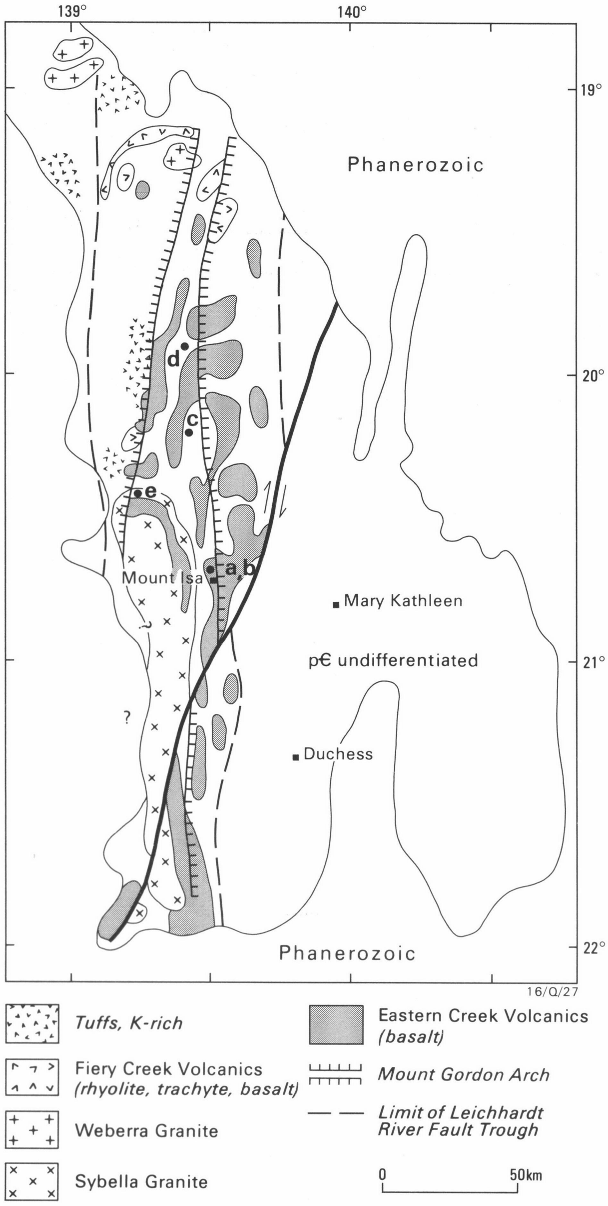


Figure 8. Spatial distribution of igneous rocks throughout the LRFT, showing their relationship to rift margins and the Mount Gordon Arch.
a,b,c,d,e—location of possible growth faults as shown in Figure 9.

1980). Their schematic distribution and thicknesses are shown in Figures 3 and 5.

Evidence for central uplift—the Mount Gordon Arch

The Leichhardt River Fault Trough may have originated as a broad crustal downwarp, up to 600 km long and 65 km wide. Sedimentological and palaeogeographic variations within it indicate that a zone of central uplift developed as the LRFT evolved. This zone is known as the **Mount Gordon Arch** (Figs. 4, 5, 8), and evidence for it is outlined below.

(i) Westwards from the depocentre of Eastern Creek basaltic volcanism, the quartzite : basalt ratio increases dramatically, and the Pickwick Metabasalt Member thins from about 2000 m to about 300 m on the Lawn Hill Platform (Plumb & others, 1980).

(ii) The contact between the Eastern Creek Volcanics and Myally Subgroup, which elsewhere is conformable, is marked by ?regolithic beds of ferruginous boulder to cobble conglomerate and breccia west of the LRFT depocentre (Fig. 4).

(iii) The two lowermost units in the Myally Subgroup, the Alsace Quartzite and Bortala Formation, thin from 700 m to 200 m, respectively, in the depocentre, to almost zero 15 km west of it, and then thicken slightly to 100 m and 150 m, respectively, further to the west and northwest on the Lawn Hill Platform. There, the two units contain abundant hematitic sandstone, siltstone, and dolomite.

These features (i–iii) are interpreted as evidence of more emergent, terrestrial conditions west of the LRFT depocentre, possibly a zone of monoclinal uplift in Eastern Creek time; the thickness and facies variations in the Myally Subgroup indicate that a broad uplifted zone was well established at this time, with units thickening both east and west of it.

(iv) Flows of the trachybasaltic member of the Quilalar Formation are restricted to west of the Mount Gordon Arch (Figs. 4, 8) as defined from Myally Subgroup variation, but fine tuffs are present both east and west of it. This suggests that the arch acted as a topographic barrier to eastwards flow of lava. Later, the Mount Gordon Arch appears to have been emphasised during uplift and deformation accompanying and following the Fiery Creek volcanic event. This is shown by:

(v) increasing angularity of the unconformity at the base of the Surprise Creek Formation and Mount Isa Group, as the arch is approached from the east (Fig. 5). In the depocentre of the LRFT these units rest disconformably on relatively complete sequences of older rocks, i.e. deposition was relatively continuous, and uplift, erosion, and deformation relatively slight. Westwards towards the Arch, the Surprise Creek Formation thins markedly and progressively overlies older rocks; 8 km north-northeast of Gunpowder, it rests with marked angular unconformity on upper Myally Subgroup, which dipped at 30° to 40° east to northeast at the time of Surprise Creek Formation deposition. The base of the Surprise Creek Formation 2 km north-northeast of Gunpowder Mine consists of a very angular breccia, possibly a scree slope deposit, which may mark the eastern palaeoslopes of the Mount Gordon Arch.

The Mount Isa Group overlaps from east to west on to the lower unit of the Eastern Creek Volcanics (Glikson & others, 1976; Derrick & others, 1977). From the depocentre westwards, probably more than 4000 m of section (Surprise Creek Formation, Fiery Creek Volcanics, Quilalar Formation, Myally Subgroup, Pickwick Metabasalt Member) has been removed by erosion and/or was never deposited on and adjacent to the Mount Gordon Arch (Fig. 5).

(vi) West of the arch, the McNamara Group (Cavaney, 1975; Hutton & others, 1981), broadly equivalent to the Mount Isa Group (Figs. 3, 5), also displays evidence for the existence of the Mount Gordon Arch and the nature of its western boundary. Thickness variations within the three lowermost formations of the McNamara Group are shown diagramatically in Figure 6. Near Calton Hills homestead, 65 km north of Mount

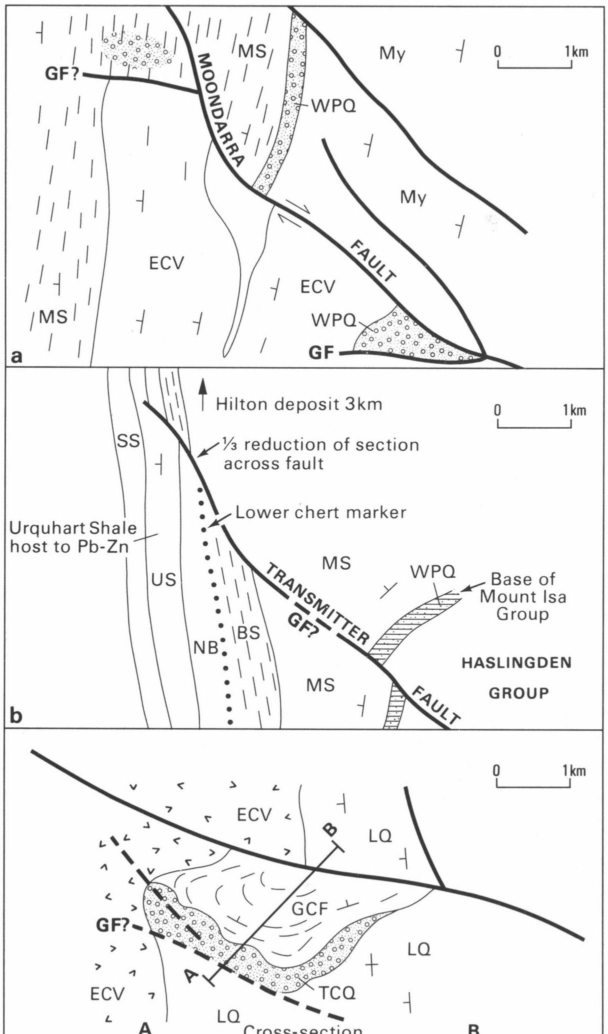


Figure 9. Examples of possible growth faulting (GF) in the Mount Isa Group and McNamara Group within the Leichhardt River Fault Trough.
(a) East of Mount Isa, conglomerate in the basal Mount Isa Group (Warrina Park Quartzite) thickens near the Moondarra Fault, and parts of the Moondarra Siltstone next to the same fault system contain interbeds of conglomerate.
(b) Near Hilton mine the stratigraphic section of the lower Mount Isa Group is markedly reduced across the Transmitter Fault (Mathias & Clark, 1975).
(c) At Bonus Basin (Wilson & others, 1979) thick wedges of conglomerate in the basal clastic unit of the McNamara Group occur along the southern margin of the basin, and are derived directly from the adjacent Leander Quartzite; the Gunpowder Creek Formation, normally a sequence of thin-bedded laminated siltstone, contains abundant conglomeratic lenses and debris-flow deposits with evidence of slumping, which grade northwards into more regularly bedded siltstone. These features indicate the southern margin of the basin to be probably fault-controlled during deposition.
(d) Near Bluff prospect, 20 km south of Gunpowder, a prominent west-trending fault (the Investigator Fault) displaces units of the Eastern Creek Volcanics and Myally Subgroup; little or no thickness variation has been observed in these units across the fault. The Gunpowder Creek Formation is also displaced, but north to south across the fault the unit shows a 20-fold increase in thickness, and contains a significant amount of granule and pebble conglomerate. Overlying units e.g. Esperanza Formation, show little or no displacement across the fault.
(e) Thickness variations and displacement across the Smith's Creek Fault, 50 km north-west of Mount Isa show that movement on this fault had ceased by the time of formation of extensive chert marker beds in the McNamara Group; most thickness variation, as near Bluff prospect, occurs in the Gunpowder Creek Formation.
Mount Isa Group: SS—Spear Siltstone; US—Urquhart Shale; NB—Native Bee Siltstone; BS—Breakaway Shale; MS—Moondarra Siltstone; WPQ—Warrina Park Quartzite. McNamara Group: EZ—Esperanza Formation; PCF—Paradise Creek Formation; GCF—Gunpowder Creek Formation; TCQ—Torpedo Creek Quartzite. CBR—Carters Bore Rhyolite; SC—Surprise Creek Formation; My—Myally Subgroup; ECV—Eastern Creek Volcanics; LQ—Leander Quartzite.
Location of areas (a) to (e) shown in Figure 8.

Isa, the basal unit of the McNamara Group (Torpedo Creek Quartzite) rests with angular unconformity on Leander Quartzite, the oldest formation of the rift fill (Figs. 5, 9c). This zone is interpreted as the area of greatest anticlinal flexure or erosion (or both) on the crest of the Mount Gordon Arch. Westwards, the Eastern Creek Volcanics, Myally Subgroup, and Surprise Creek Formation appear progressively beneath the Torpedo Creek Quartzite, thus defining a monoclinal palaeoflexure or hinge zone (Fig. 5).

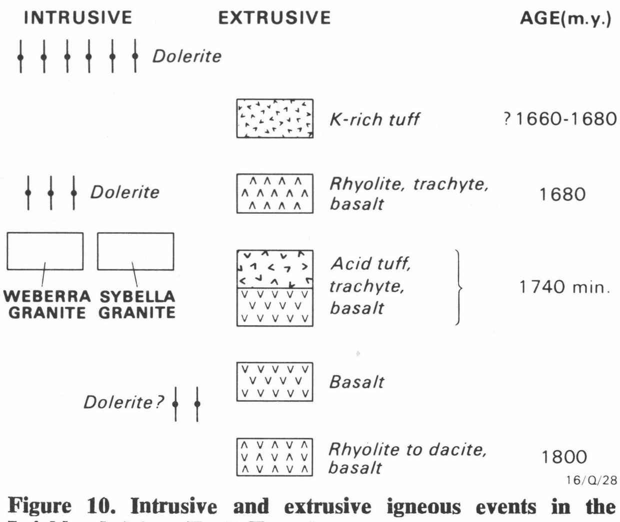
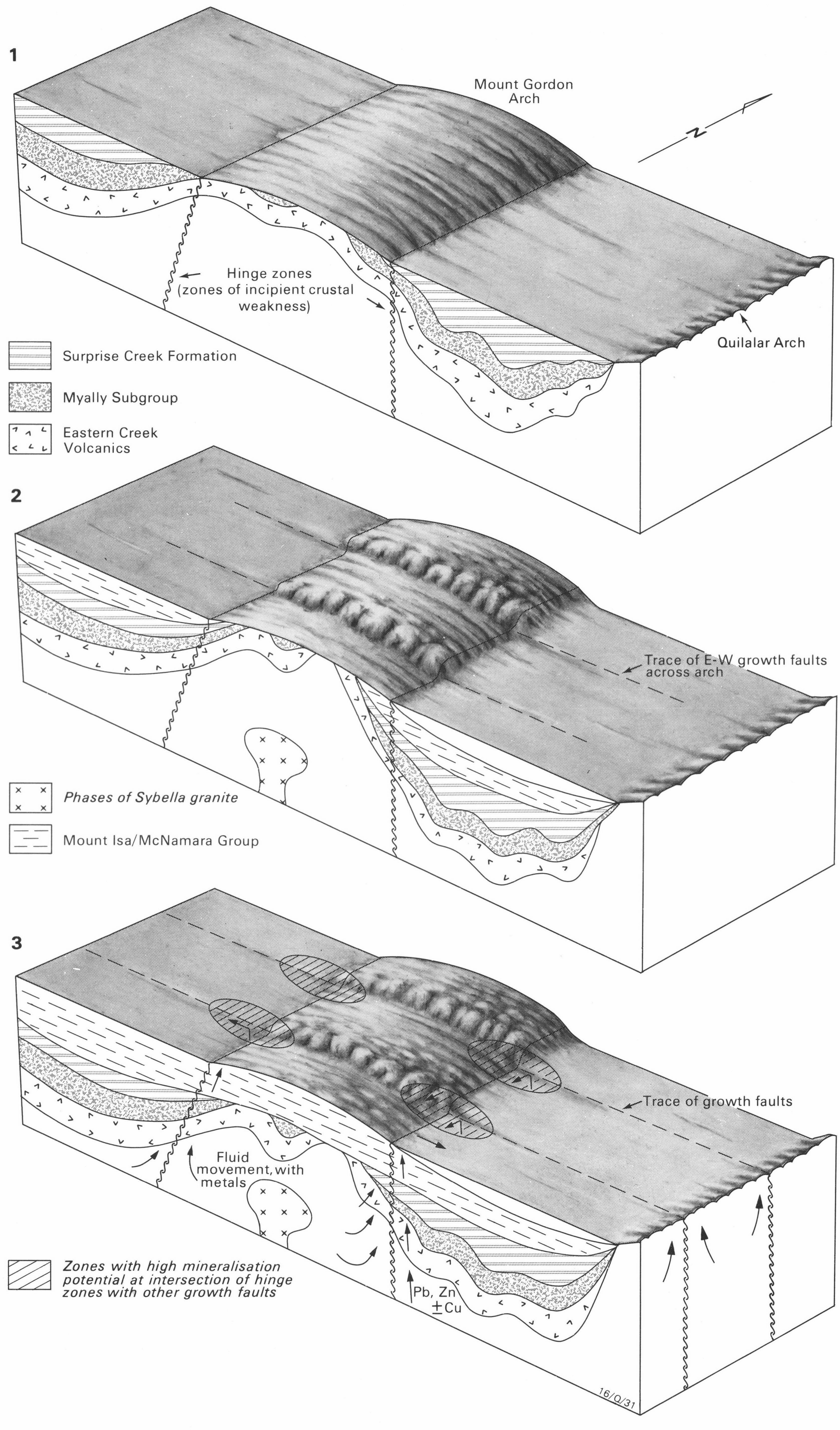


Figure 10. Intrusive and extrusive igneous events in the Leichhardt River Fault Trough.


1
Mount Gordon Arch
N
Hinge zones (zones of incipient crustal weakness)
Quilalar Arch
Surprise Creek Formation
Myally Subgroup
Eastern Creek Volcanics
2
Trace of E-W growth faults across arch
Phases of Sybella granite
Mount Isa/McNamara Group
3
Trace of growth faults
Fluid movement, with metals
Pb, Zn ±Cu
Zones with high mineralisation potential at intersection of hinge zones with other growth faults
16/Q/31

Marker beds within the Paradise Creek Formation, such as the Oxide Chert Member, tuff layers, and a 'middle' stromatolite unit (Fig. 6) are traceable from the distal parts of the basin east towards the Mount Gordon Arch. That part of the Paradise Creek Formation between the Oxide Chert and the first tuff bed displays thickness variations similar to that for the Gunpowder Creek Formation (Fig. 6); by 'middle' marker time, however, a lack of marked thickness changes in the sequence indicates that the Mount Gordon Arch was by then increasingly submergent rather than emergent.

The Mount Gordon Arch thus appears to have formed as an emergent palaeohigh up to 25 km wide and traceable for at least 250 km northwards from Mount Isa (Fig. 8). It remained as such through early Mount Isa Group and McNamara Group time, but its influence appears to have waned thereafter. The basinal zones east and west of the centrally uplifted block (Fig. 5) are analogous to the 'second order' basins noted by Large (1981).

Cross-fracturing and growth faulting in the Leichhardt River Fault Trough

It has been shown previously (Figs. 5, 8) that the LRFT has a meridional structural and depositional grain, e.g. the Quilalar and Mount Gordon Arches, separated by a linear, north-trending depositional basin. Within this latter feature some units display significant thickness variation north to south (Fig. 7). Much of this occurs across the east-trending faults that characteristically control the distribution of the metabasalt fault blocks in the LRFT (Fig. 8).

The Whitworth Quartzite does not appear to change lithologically across these fault zones, and it is suggested that the floor of the basin was transected by east-trending fractures or warps, which allowed differential subsidence and thickness variations (Smith, 1969) during Myally Subgroup time.

More direct evidence is available for the existence of west or northwest-trending growth faults in Mount Isa Group/McNamara Group time. At a number of places between Mount Isa and Gunpowder (Figs. 8, 9) such faults appear to control both thickness and lithological variation.

From this it is inferred that major growth fault activity occurred during a specific interval—namely during early McNamara Group and Mount Isa Group time, i.e. during deposition of the Gunpowder Creek Formation and its equivalent, the Moondarra Siltstone-Breakaway Shale.

Igneous rocks within the Leichhardt River Fault Trough

Spatial distribution of igneous rocks and their stratigraphic/geochronological position are summarised in Figures 8 and 10, respectively.

The dacite-basalt-rhyolite basement to the LRFT has been described by Wilson (1978). Basalts of the Eastern Creek Volcanics (Glikson & others, 1976), between 1740 m.y. and 1800 m.y. old, are the major extrusive unit within the LRFT. Their production is attributed to fractional crystallisation in the upper mantle, with rising geotherms and partial melting in the lower crust a major factor in subsequent igneous evolution in the trough.

Acid tuff and a trachytic to altered basaltic suite of lava flows older than about 1740 m.y. occur as members of the Quilalar Formation.

A strongly bimodal basaltic to rhyolitic suite of the Fiery Creek Volcanics (Hutton & others, 1981), possibly about 1680 m.y. old, is best developed in the northern half of the LRFT, in areas mainly west of the Mount Gordon Arch, K-rich tuff bands occur throughout the LRFT in the Mount Isa and McNamara Groups, and have been dated as about 1670 m.y. old (Page, 1981).

A large, multiphase, and, in places, syntectonic batholith, the **Sybella Granite,** intrudes the Eastern Creek Volcanics in the southern half of the LRFT, and is apparently localised within southerly extensions of the Mount Gordon Arch. The batholith is surrounded by a low pressure-high temperature regional metamorphic aureole (Wilson, 1972). In the far north of the trough and west of the Mount Gordon Arch, the **Weberra Granite** has metamorphosed Quilalar Formation and Myally Subgroup strata to calc-silicate assemblages of amphibolite and greenschist facies.

Most acid igneous rocks from the Quilalar Formation volcanic member and younger units, such as the Fiery Creek Volcanics, are more evolved than most of the Sybella Granite batholith and basement acid volcanics. Generally they are moderately alkalic, characterised by very high (up to 12%) K_2O contents and an absence of Na_2O, and resemble continental volcanics and associated breccias from the Redbank area in the southern McArthur Basin (Knutson & others, 1979). Though limited in extent (Fig. 8), and silica-saturated rather than nepheline-normative, they are nevertheless probably illustrative of the alkaline igneous activity characteristic of major rift zones (e.g. Baker & others, 1978).

Dolerite dyke swarms and sills of various ages intrude the rift fill, mainly the Haslingden Group. The major

Figure 11. Diagrammatic relations between Pb-Zn mineralisation, growth faults, and hinge zones of the Mount Gordon Arch.
Stages in the model are:
(1) extensive pre-Mount Isa Group folding and faulting along the margins of the Mount Gordon Arch. This deformed zone formed a belt of incipient crustal weakness during later deposition of the Mount Isa Group;
(2) reactivation and/or development of active growth faults during lower Mount Isa Group and McNamara Group time; and initiation of convective cells of meteoric? and metamorphic? fluids accompanied by deep crustal igneous activity (elements of Sybella Granite intrusion?) and Pb-Zn enrichment of fluids;
(3) migration of metal-bearing fluids into the Mount Isa Group basin (?submarine exhalation) localised by early fracturing in the hinge zone of the Mount Gordon Arch and by the growth faults that affected the lower Mount Isa Group.
The issue of whether the fluids debouched into a basin and deposited Pb-Zn sulphides at the basin floor/water interface, or whether the metals were deposited diagenetically within the sediments (e.g. McArthur River deposit—Williams, 1980; Lambert, 1980) is not canvassed here.

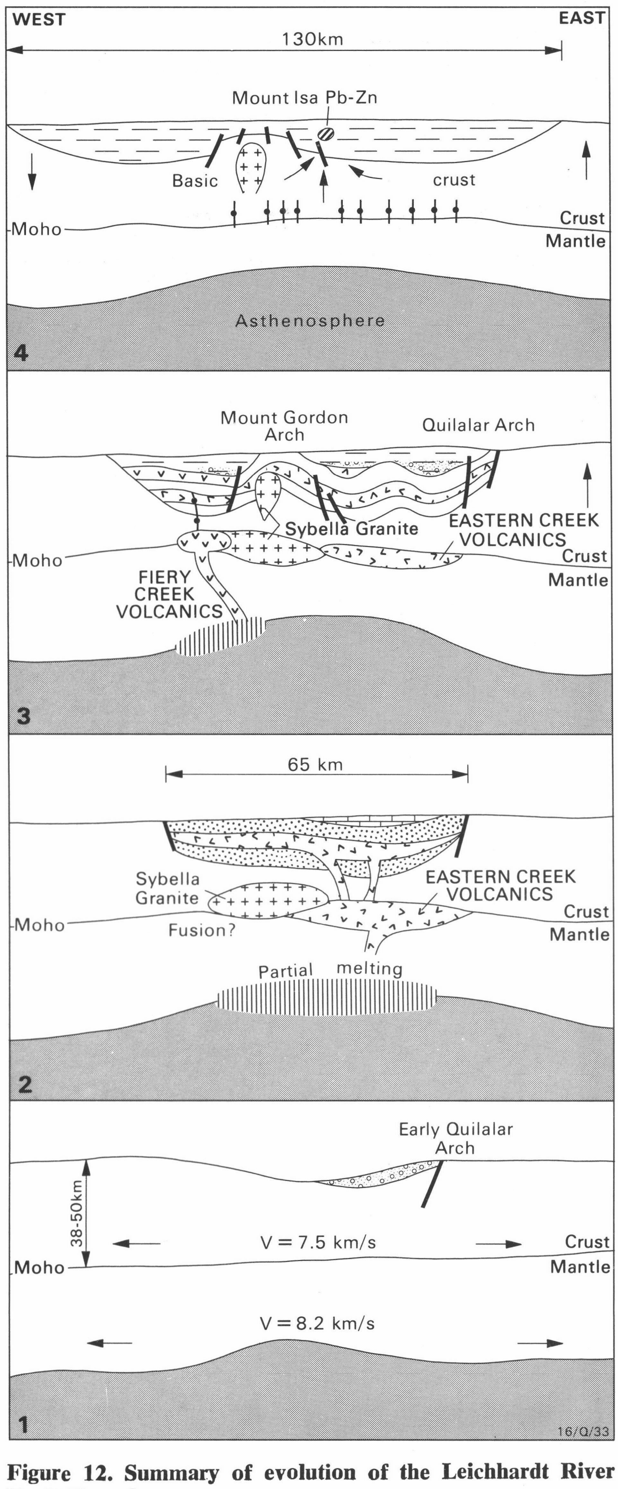


Figure 12. Summary of evolution of the Leichhardt River Fault Trough:
STAGE 1: Rifting is inferred to have been initiated by a sub-lithospheric thermal anomaly, mantle plume, or diapir, beneath an 1860–1780 m.y. old continental crust. Tension and, possibly, crustal necking initiated crustal subsidence, and formation of an elevated, fault-controlled eastern margin, the Quilalar Arch. Earliest preserved deposition is of a fining and maturing-upwards sequence of conglomerate, arkose and quartz sandstone.
STAGE 2: Deep rifting tapped large volumes of tholeiitic magma, which were extruded, probably along fissures, as sub-aerial to shallow submarine basalt flows, with intercalated fluvial and shallow shelf sands and purple siltstones. The basalts define a rift feature up to 600 km long and 65 km wide. They are shown as being derived from hypothetical, relatively high-density material located near the crust-mantle boundary; both the lava flows and their basic source are probable causes of a significant Bouguer gravity high underlying the LRFT. Depletion of the deep crustal or upper mantle magma chamber and concomitant loading of the crust by basalt flows caused further subsidence of the rift zone and deposition of Myally Subgroup arenites. Differential subsidence within the LRFT resulted in the formation of a central, relatively upstanding, block, the Mount Gordon Arch. Shallow shelf transgressive sand blankets and carbonate rocks (Quilalar Formation) reflect stabilisation of the rift zone at about 1750 m.y. ago.
STAGE 3: Rocks of preceding stages were uplifted and gently folded; continental, alkaline (K-rich, Na-poor) trachybasalts and rhyolites were extruded at about 1680 m.y., and Mount Gordon Arch increasingly influenced sedimentation, which at this stage extended far beyond the limits of Stage 1–Stage 2 rifting. Some granite plutonism (Sybella Granite) may have contributed to crustal doming near the Mount Gordon Arch. The alkali volcanics are shown as originating either as fractionation products from a source near the crust-mantle basic magma chamber, or from a partially melted zone of upper mantle material.
STAGE 4: The Mount Isa Group and McNamara Group, 1670 m.y. old and host to major Pb-Zn deposits, formed east and west of the Mount Gordon Arch respectively. Growth faulting was especially active early in Mount Isa Group and McNamara Group time. A combination of growth faulting across the axis of the rift and reactivation of deep crustal fractures along the margins of the Mount Gordon Arch is believed to have been a significant control on the occurrence of the Pb-Zn mineralisation. Cu mineralisation may have developed during post-depositional deformation near the margins of the arch.

meridional dyke phase post-dates the Fiery Creek deformation and uplift, but predates major cross-faulting (east-trending normal or thrust faults) in the LRFT (Glikson & others, 1976). It may also post-date deposition of the Mount Isa Group. West of Mount Isa, extensive dioritic to tonalitic hybrid rocks intrude metabasalt of the Eastern Creek Volcanics. They may represent Sybella Granite contaminated by the metabasalt or products of mixing of silicic Sybella Granite magma with basic magma in deep crustal magma chambers.

An AFM diagram of igneous rocks in the Mount Isa Orogen shows a marked bimodality, typical of non-orogenic, commonly tensional domains (Martin & Piwinskii, 1972). However, the gentle open folding that occurred during the Fiery Creek/Surprise Creek deformational episodes and the widespread post-depositional folding and conjugate faulting throughout the LRFT appear to be a result of compressional tectonics (Carter & others, 1961). The LRFT, therefore, may have been subjected to some degree of alternating periods of crustal extension and compression during its 150 m.y. history.

Relations to major Pb-Zn & Cu mineralisation

The LRFT contains some of the world's major 'shale-hosted' Pb-Zn deposits (Williams, 1980), and it is suggested that deposits such as Mount Isa and Hilton may be largely controlled by the interplay of two structural elements (Fig. 11), namely: north-trending hinge zones on either side of the Mount Gordon Arch; and west and northwest-trending growth faults.

The model (Fig. 11) emphasises the influence of the margins of the Mount Gordon Arch, and the role of a short but critical period of growth faulting in the migration of mineralising fluids.

Of the areas of growth faulting (Fig. 9), many show base-metal anomalies. Bonus Basin (Fig. 9c) overlies the central part of the Mount Gordon Arch and is bounded to the south by a prominent growth fault. West of Smiths Creek fault (Fig. 9e), the Gunpowder Creek

Formation (≡ lower Mount Isa Group) overlies the inferred western hinge margin of the Mount Gordon Arch. It contains anomalous levels of zinc in pyritic shales. At Crystal Creek, 20 km east-northeast of Bonus Basin, Mount Isa Group sediments overlie the eastern hinge zone of the Mount Gordon Arch, and are bounded by major east-west-trending faults. Whether these were growth faults is not known, but the Mount Isa Group contains significant base-metal anomalies, and abundant diagenetic albititic alteration (Derrick & Wilson, 1982).

The origin of the copper mineralisation at Mount Isa is still a much-debated issue (see summary by Williams, 1980). In this paper the epigenetic theories of copper mineralisation are favoured (Murray, 1961; Smith & Walker, 1971; Perkins, 1981). Nevertheless, some palaeogeographic features may have influenced the formation of the copper orebodies: for example, Smith & Walker (1971) and Perkins (1981) argued from geochemical, structural, and textural evidence that post-sedimentation folding and faulting juxtaposed pyritic dolomitic shales of the Mount Isa Group against greenstones of the Eastern Creek Volcanics, silicic hydrothermal fluids enriched in mainly greenstone-derived copper forming the copper orebodies by replacement of dolomitic pseudobreccias towards the close of a folding episode. It is suggested here that this favourable structural situation is a direct result of: (a) location of the Mount Isa deposit stratigraphically above the eastern margin of the Mount Gordon arch, a zone of early crustal weakness, which now contains the major reverse faults in the vicinity of the mine, and (b) the Mount Isa Group near Mount Isa directly overlying Eastern Creek Volcanics unconformably, near the east flank of the Mount Gordon Arch, thus facilitating later structural juxtaposition.

Summary of evolution of the Leichhardt River Fault Trough

The Leichhardt River Fault Trough is considered to be an example of a mid-Proterozoic rift, with many features in common with rifts of all ages. It evolved over a period of about 150 m.y. as a zone of major tension overlying a postulated sublithospheric thermal anomaly (Fig. 12). It is a crustal feature 600 km long and up to 65 km wide, which remained a largely intracontinental or continental margin feature throughout its history; new ocean floor was apparently never created and generally shallow-water sedimentation was dominant. Periods of tension alternated with some compression and the igneous history is typically bimodal, ranging from early basaltic to later mildly alkaline volcanicity, followed by tholeiitic dyke intrusion. Deep-seated tensional fractures, and block and growth faulting ensured favourable 'plumbing' systems were available for large-scale base-metal mineralisation, mainly in the younger Proterozoic sequences overlying the earlier rift fill.

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