BMR JOURNAL
OF AUSTRALIAN GEOLOGY & GEOPHYSICS

VOLUME 7 NUMBER 2 JUNE 1982

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CONTENTS

Front cover: Part of Landsat scene 2227223590 (path 106, row 74) taken over Mount Isa, Queensland, on 12 April 1981 (Australian Landsat Station product). The area shown is 100 km wide. The black area near the centre is Lake Moondarra, and Mount Isa mine shows as blue to the south of the lake. The papers in this issue (except for those by Derrick and Blake & others) were presented at a joint meeting on Mount Isa geology, conducted by the Australasian Institute of Mining and Metallurgy, the Bureau of Mineral Resources, Australia, and the Geological Survey of Queensland, at Mount Isa in September 1981.

AUSTRALIAN GOVERNMENT PUBLISHING SERVICE CANBERRA 1982

Department of National Development and Energy, Australia

Minister: Senator the Hon. Sir John Carrick, K.C.M.G.

Secretary: A. J. Woods

Bureau of Mineral Resources, Geology and Geophysics

Director: R. W. R. Rutland

Editor, BMR Journal: I. M. Hodgson

The BMR Journal of Australian Geology & Geophysics is a quarterly journal of research and related activities. Contributions are from officers of the BMR, from BMR officers working in collaboration with others, or requested work sponsored by the BMR. In addition to articles the Journal may include shorter notes and discussion of papers published in it. Discussion of papers is invited from anyone.

Annual subscription to the Journal is at the rate of $14 (Australian). Individual numbers, if available, cost $4. Subscriptions, etc., made payable to the Receiver of Public Moneys in Australian dollars should be sent to the Director, Bureau of Mineral Resources, Geology and Geophysics, P.O. Box 378, Canberra, A.C.T. 2601, Australia.

Other matters concerning the Journal should be sent to the Director, marked for the attention of the Editor, BMR Journal.

Cover design: Stuart Fereday.

The text figures in this issue were drafted by a cartographic team of P. Jorritsma, P. Griffiths, C. Williams, & B. Pashley.

ISSN 0312-9608

Printed by Graphic Services Pty Ltd, 516-518 Grand Junction Road, Northfield, S.A. 5085

BMR Journal of Australian Geology & Geophysics, 7, 81-92.

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

G. M. Derrick[1]

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-

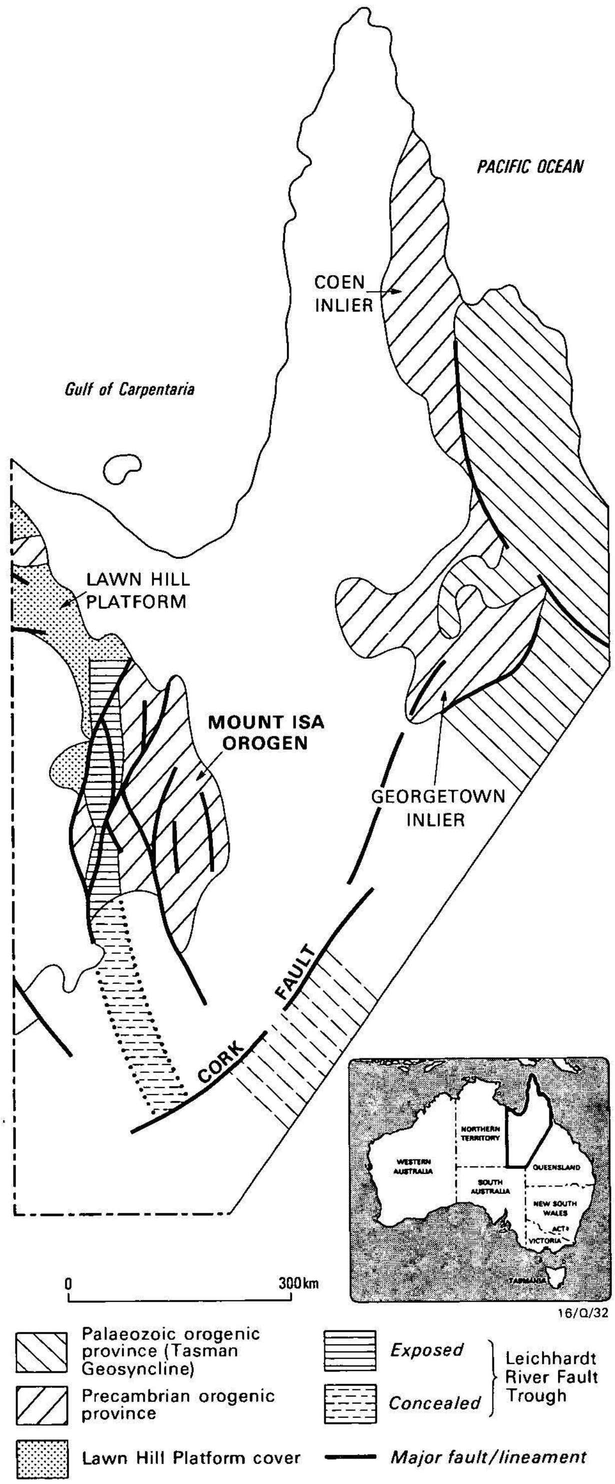


Figure 1. Regional tectonic setting of the Leichhardt River Fault Trough. (adapted from Plumb, 1979).

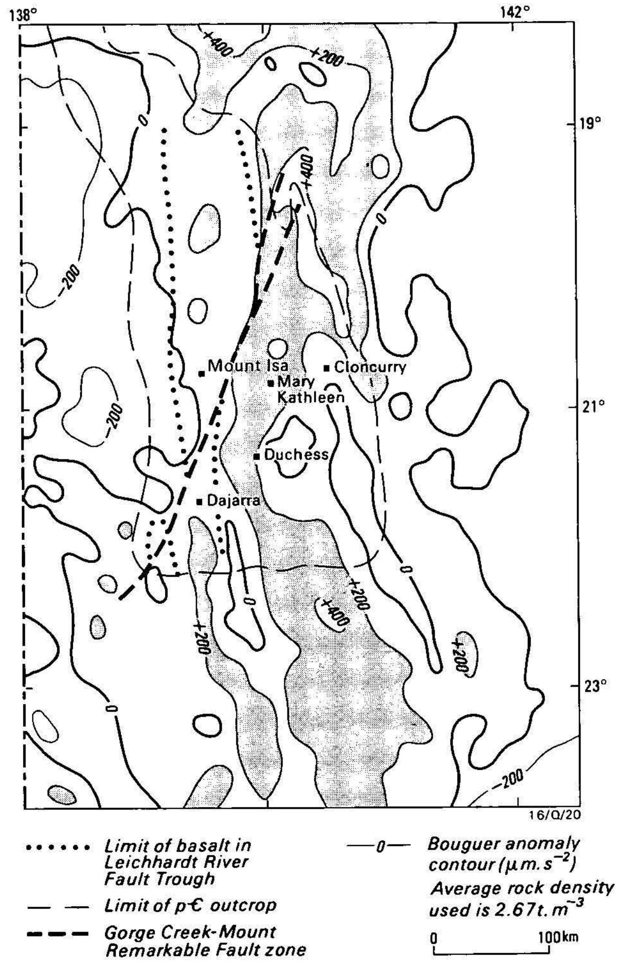


Figure 2. Bouguer anomaly map of the Mount Isa orogen.

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 μm s-2 Bouguer anomalies; sub-surface extensions of this belt to the south are probably the cause of a narrow, well-defined +200 μm s-2 anomaly, up to 20 km wide and 200 km long, which extends to the Cork Fault.

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.).

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.

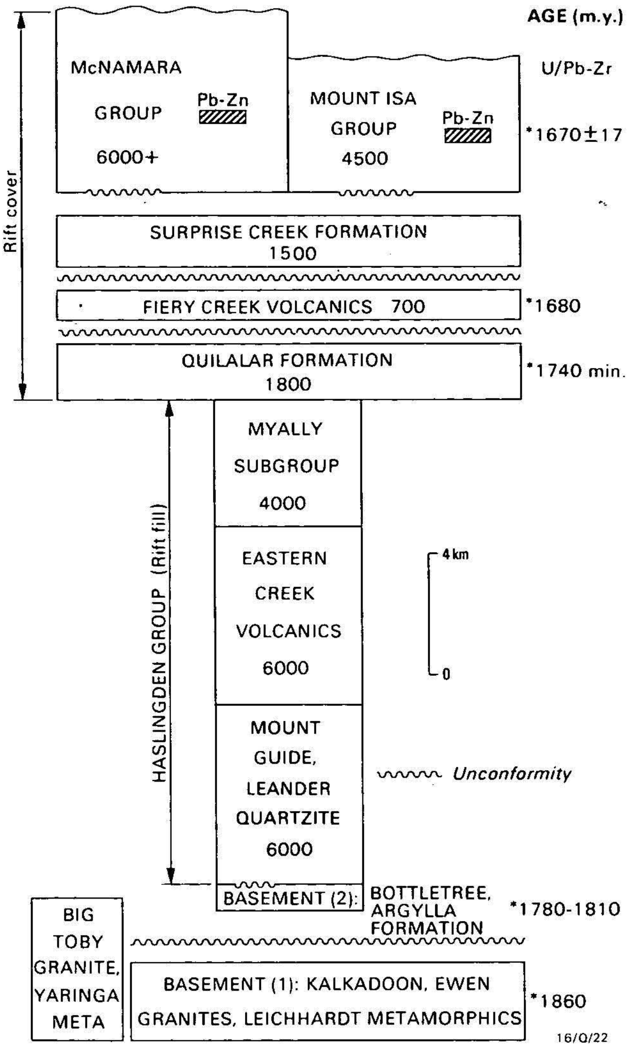


Figure 3. Generalised stratigraphy and geochronological framework of the Leichhardt River Fault Trough.

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-

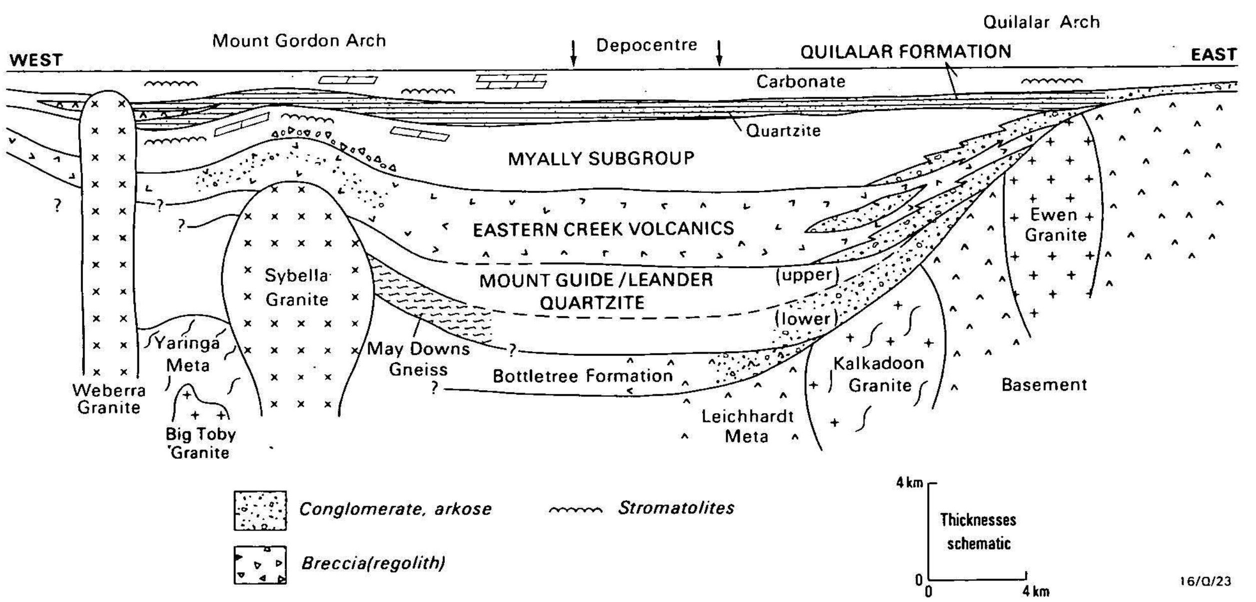


Figure 4. Schematic cross-section of the Leichhardt River Fault Trough prior to Fiery Creek uplift and deformation.

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.

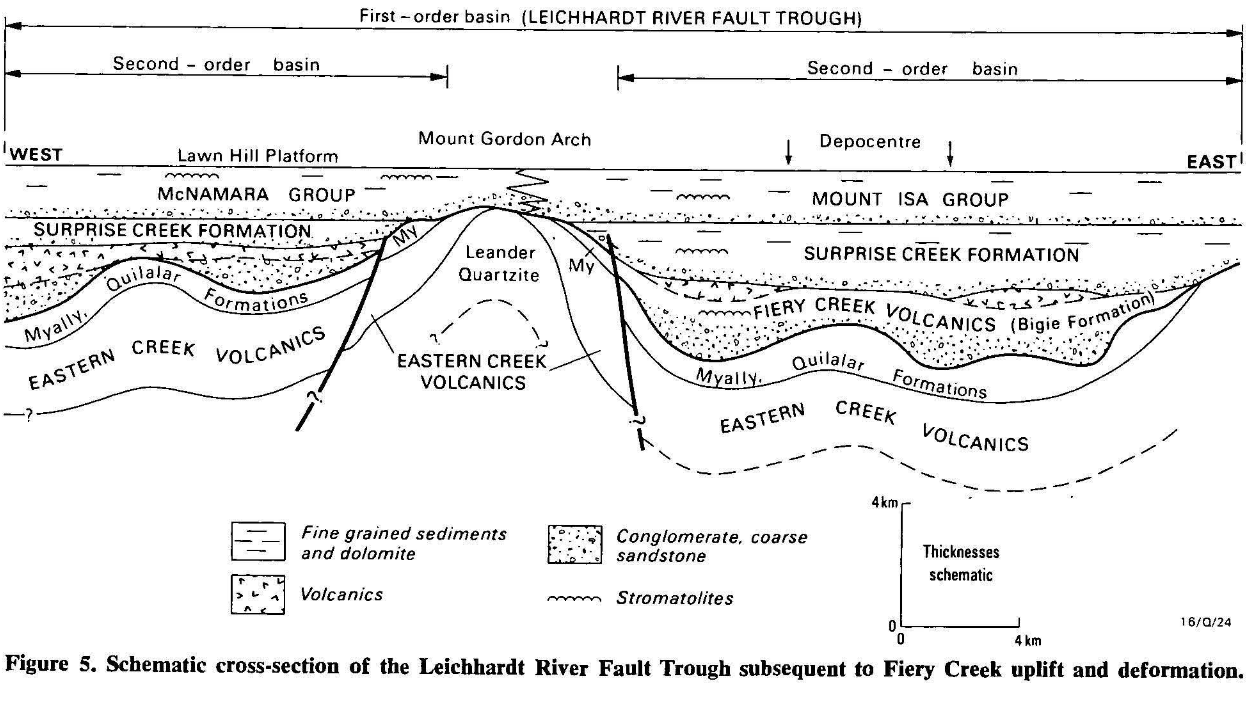


Figure 5. Schematic cross-section of the Leichhardt River Fault Trough subsequent to Fiery Creek uplift and deformation.

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,

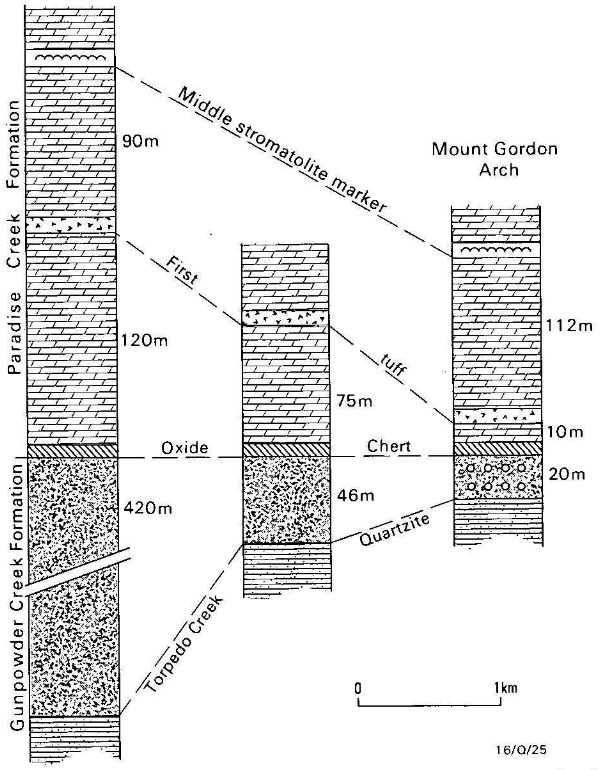


Figure 6. Thickness variations in the Gunpowder Creek Formation and lower Paradise Creek Formation of the McNamara Group.

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.

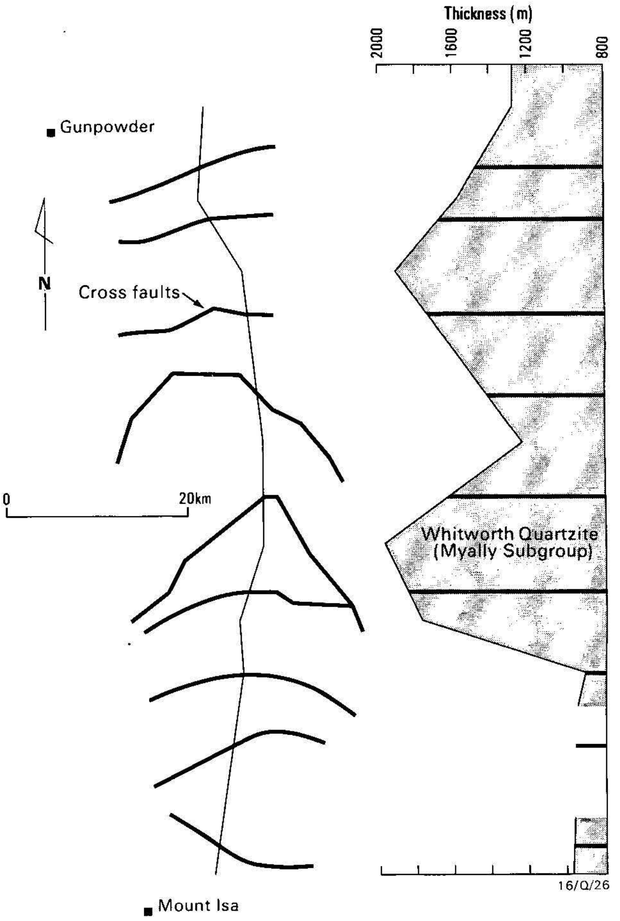


Figure 7. Thickness variations in the Whitworth Quartzite (Myally Subgroup) north to south along the LRFT, relative to east-west cross-faults.

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,

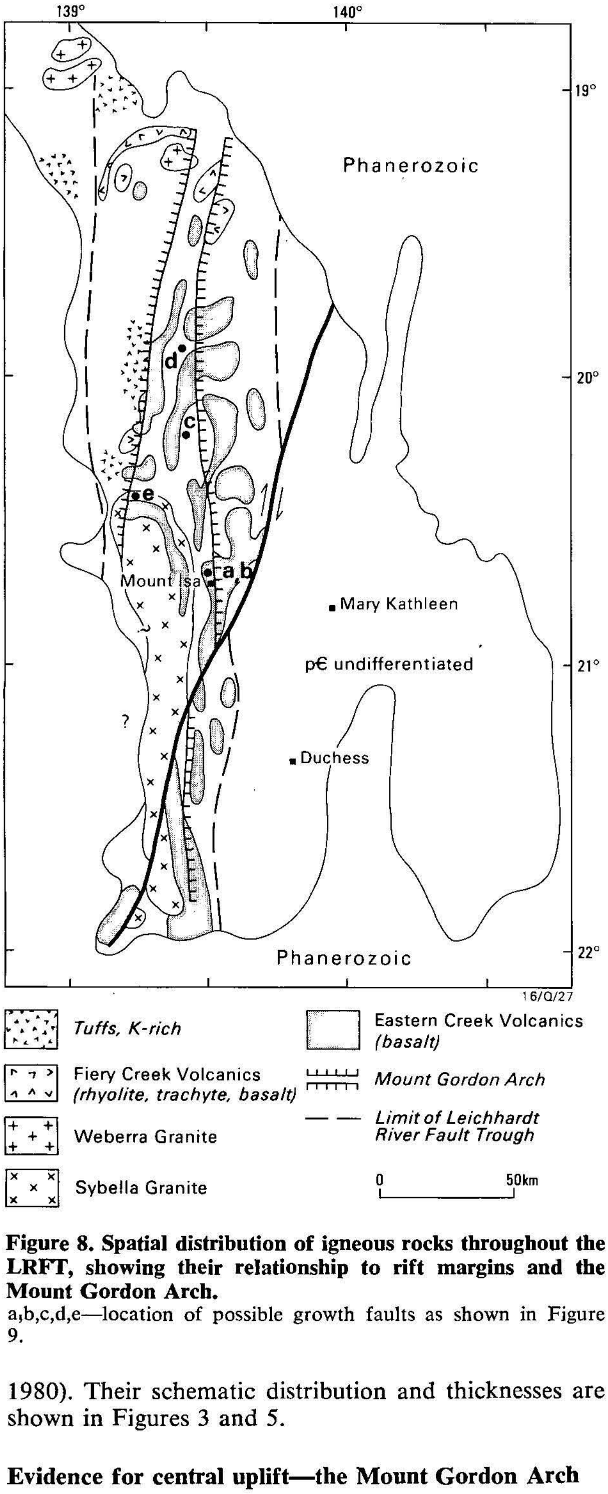


Figure 8. Spatial distribution of igneous rocks throughout the LRFT, showing their relationship to rift margins and the Mount Gordon Arch.
a,b,c,d,e—location of possible growth faults as shown in Figure 9.

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

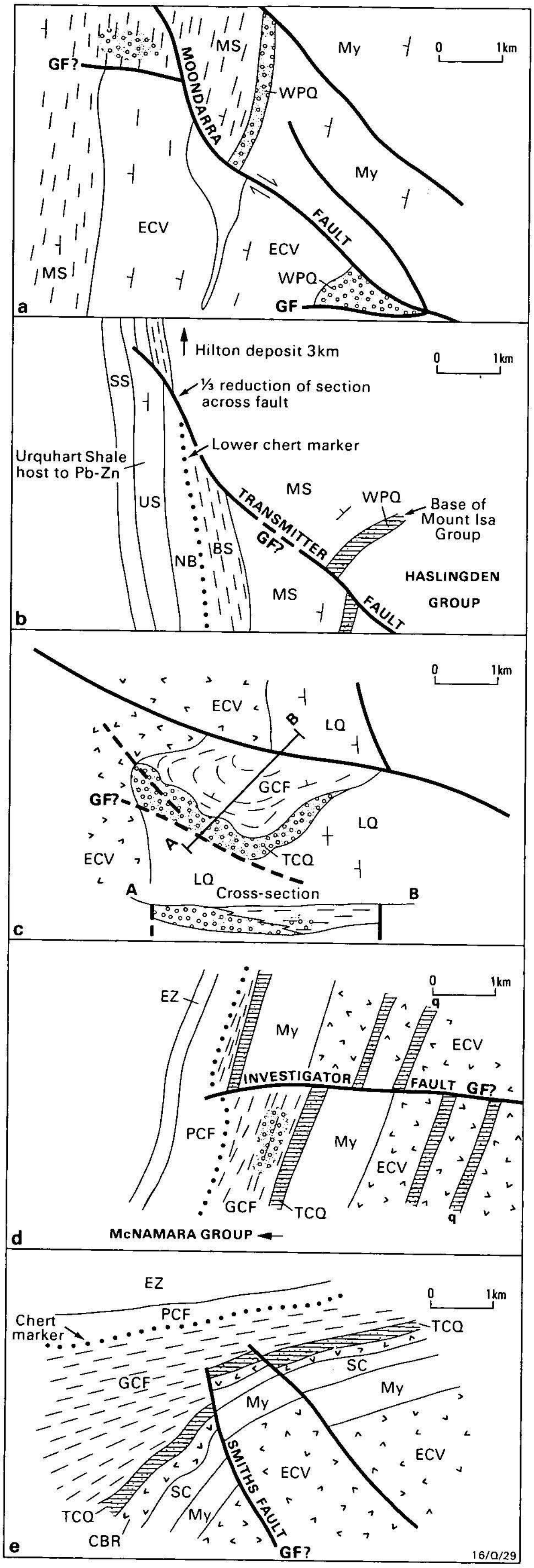


Figure 9. Examples of possible growth faulting (GF) in the Mount Isa Group and McNamara Group within the Leichhardt River Fault Trough.

(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).

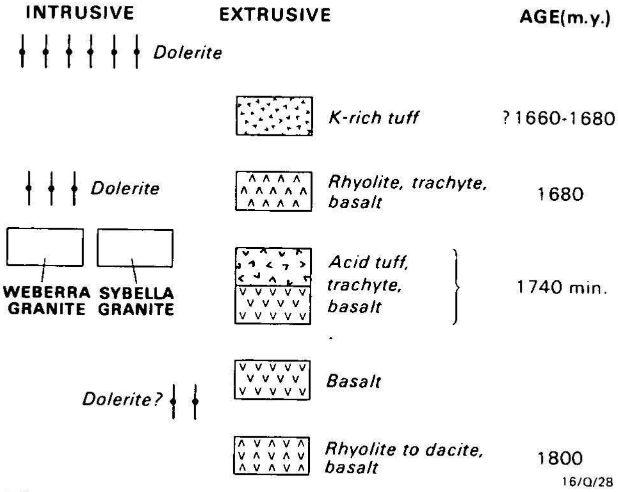
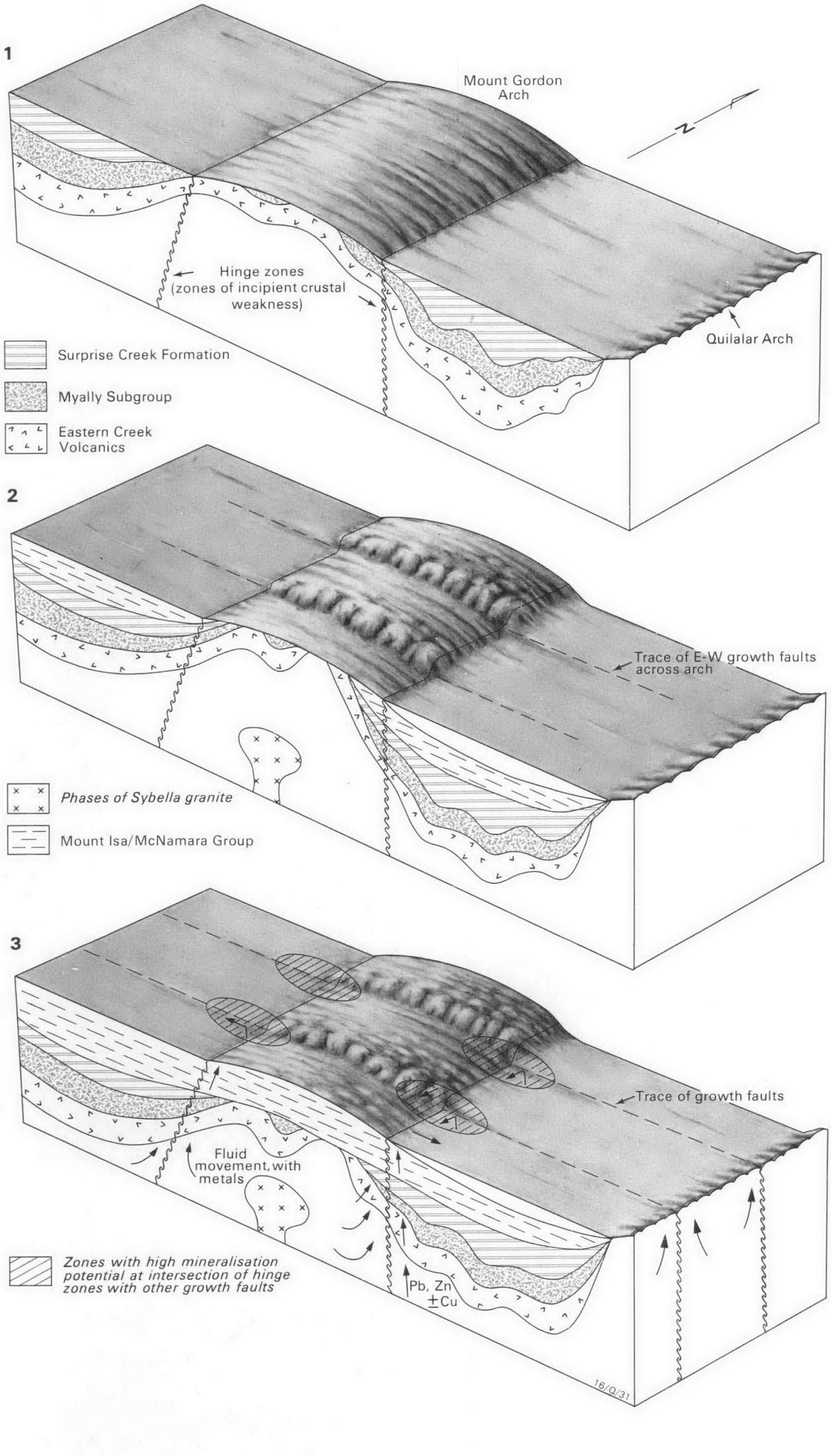


Figure 10. Intrusive and extrusive igneous events in the Leichhardt River Fault Trough.


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.

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

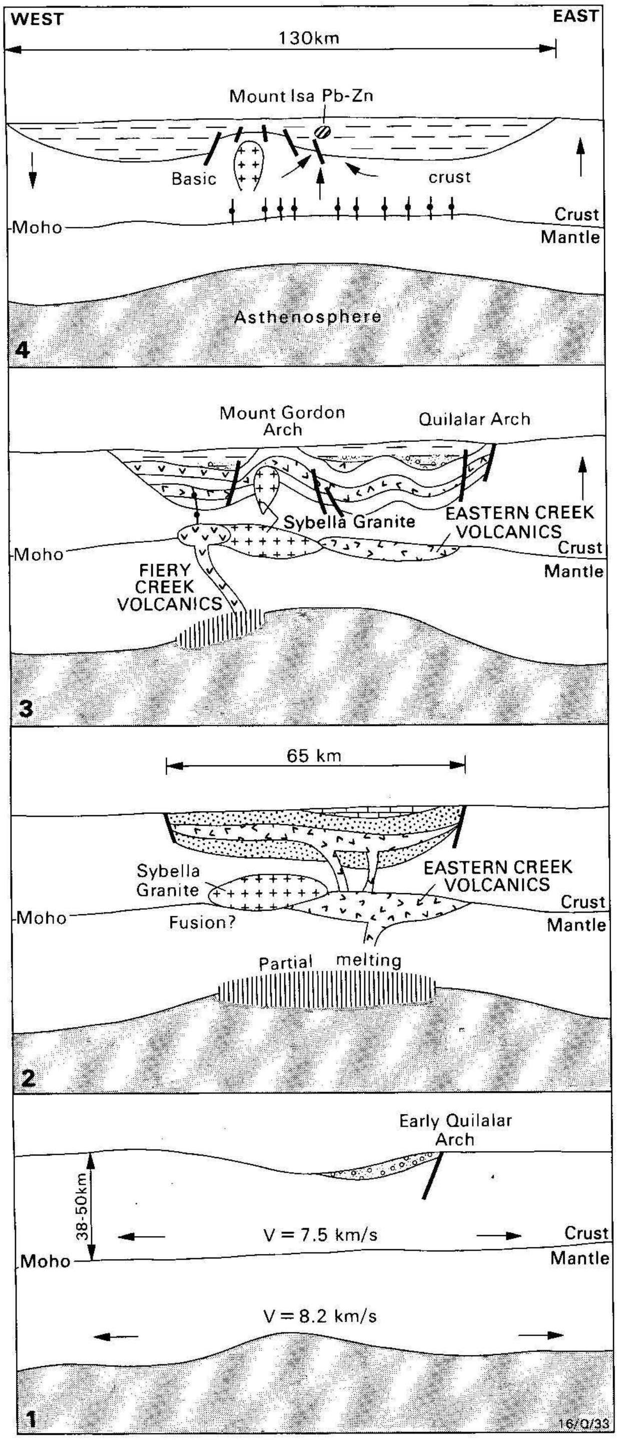


Figure 12. Summary of evolution of the Leichhardt River Fault Trough:
STAGE 1: Rifting is inferred to have been initiated by a sub-lithospheric thermal anomaly, mantle plume, or diapir, beneath an 1860–1780 m.y. old continental crust. Tension and, possibly, crustal necking initiated crustal subsidence, 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.

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.

Acknowledgements

Much field work and discussion on which this paper is based was conducted in association with former colleagues I. H. Wilson and L. J. Hutton (Geological Survey of Queensland), R. M. Hill (ex-BMR), and I. P. Sweet (BMR). Earlier versions of the paper were read at the BMR Symposium in Canberra in May, 1980, and at the International Geological Congress in Paris, in August, 1980. Assistance given by Tenneco Oil & Minerals of Australia, Inc. in the preparation of the paper is gratefully acknowledged.

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EASTERN CREEK VOLCANICS AS THE SOURCE OF COPPER AT THE MAMMOTH MINE, NORTHWEST QUEENSLAND

K. M. Scott[1] & G. F. Taylor[1]

At the Mammoth mine, epigenetic copper mineralisation occurs within the Myally Subgroup of the Haslingden Group, an arenaceous sequence that both includes and overlies basic volcanics. A basic flow in the Myally Subgroup is altered, being enriched in potassium and copper for up to 200 m from the mineralisation. However, underlying metabasalts of the Eastern Creek Volcanics up to 600 m from the mineralisation are depleted in iron and copper and enriched in potassium relative to those further away. Evidence is presented that the Mammoth ore represents copper leached from the Eastern Creek Volcanics and transported along the Mammoth-Mammoth Extended Fault system. This hypothesis is similar to one previously proposed for the copper mineralisation at Mount Isa, although there are differences in the age and lithology of the host rocks in the two areas. Thus, rocks adjacent to major faults transgressing the Eastern Creek Volcanics must be considered prospective for copper mineralisation.

Introduction

The origin of copper mineralisation within the Middle Proterozoic (Carpentarian) sediments of northwest Queensland is conjectural (Stanton, 1962; Smith & Walker, 1971; Wilson & others, 1972). The nature of both the host rocks and the copper deposits themselves differs in the two major geological regimes of the region. The many small deposits of the eastern succession occur in a variety of host rocks (metasediments, basic and acidic volcanics, and intrusives), but most are genetically associated with copper-rich (approx. 160 ppm) dolerite intrusions (Wilson & others, 1972; Krosch & Sawers, 1974). In the western succession (Fig. 1) most of the less common but larger deposits consist of chalcopyrite + pyrite ± pyrrhotite bodies in dolomitic shales (at Mount Isa and Paradise Valley), but at Mammoth chalcocite-rich mineralisation is hosted by arenites. Both dolerite dykes and metabasalts of the Eastern Creek Volcanics (ECV) are widely developed in the western succession. With copper contents commonly in excess of 120 ppm (Smith & Walker, 1971; Glikson & others, 1976), they are potential source rocks for copper mineralisation, particularly as copper occurs as disseminated chalcopyrite (Robinson, 1968; Wilson & others, 1972), which can be readily leached.

In the Mount Isa region, the lower ECV are intruded by north-south trending basic dykes (Glikson & others, 1976). As the copper mineralisation at Mount Isa is underlain across a faulted contact by the ECV (Mathias & Clark, 1975), which are locally depleted in copper, Smith & Walker (1971) have suggested the ECV (and the included intrusions) as the source of copper at Mount Isa. Recently, this view has been questioned by Gulson & others (1981) who deduced from lead isotope data that only the smaller 500, 650, and 1900 orebodies could be so derived.

In this paper, mineralogical and chemical features of two basic igneous units close to the Mammoth copper deposit are outlined and compared with regional equivalents to determine the source of copper.

Geology

The Mammoth copper deposit (Moore, 1974; Mitchell & Moore, 1975), which is situated 2 km northwest of the township of Gunpowder and approximately 115 km north of Mount Isa (Fig. 1), is one of a number of epigenetic copper deposits developed along the Mount Gordon Fault zone. Mining has been restricted to a fault-bounded block of steeply west-dipping brecciated quartzites and sandstones of the Myally Subgroup of the Haslingden Group. Structural reconstruction (G. P. Moore, Gold Fields Exploration Pty Ltd, un-

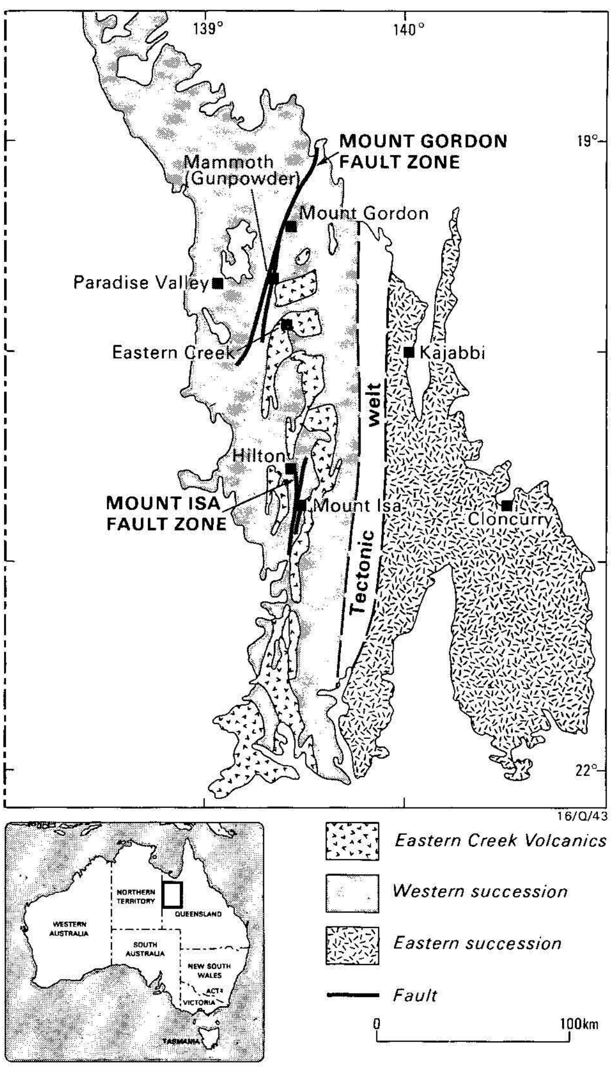

Figure 1. Distribution of the Eastern Creek Volcanics within the Middle Proterozoic metasediments of the western succession, northwest Queensland.

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published report, 1975) indicates that prior to movement along the Portal Fault, the Mammoth and Mammoth Extended Faults were a continuous system.

Chalcocite, bornite, chalcopyrite, and pyrite occur as breccia fillings and veins up to tens of millimetres thick in the arenaceous sediments and as fine-grained (< 0.5 mm) disseminations in the more silty units. The hanging wall is essentially unaltered, being rich in potassium-feldspar and magnesium-rich chlorite (Scott & Taylor, 1977). In the ore zone, the host sandstone is extensively altered, with the development of muscovite, hematite, sulphides, iron-rich chlorite, and sometimes kaolinite at the expense of feldspar and magnesium-rich chlorite. Similar assemblages are developed in the footwall, with the exception that sulphides and kaolinite are absent and hematite is more abundant. This alteration pattern suggests emanation of fluids from the footwall adjacent to the Mammoth Fault.

A 40 m thick medium-grained basic igneous unit occurs in the sandstones and quartzites of the Myally Subgroup within 50 m of the mineralisation (Moore, 1974). Because of its high potassium content close to the mine, this unit was originally considered a syenitic sill (Mitchell & Moore, 1975). However, the presence of quartz-filled amygdales and the lateral persistence of the unit at the same stratigraphic level 30 km north at Mount Gordon (M. Hunter, Gold Fields Exploration Pty Ltd, personal communication, 1976) and 20 km ESE along the Mammoth-Kajabbi track (P. Holyland, Gold Fields Exploration Pty Ltd, personal communication, 1976) indicate that it is a flow (hereafter referred to as the 40-m metabasalt).

Conformably underlying the Myally Subgroup are the ECV (Fig. 2), a 7 km thick sequence of continental tholeiite-type basaltic flows (Derrick & others, 1976; Glikson & Derrick, 1978). Three members, the Cromwell Metabasalt, Lena Quartzite and Pickwick Metabasalt are distinguished in the ECV (Table 1), with the lowest member, the Cromwell Metabasalt, making up 75 per cent of the volume. Arenaceous intercalations

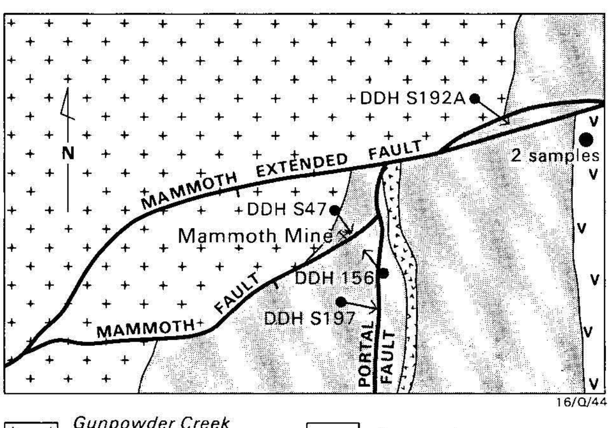

Figure 2. Location of basic rocks close to the Mammoth mineralisation, with sample locations and drill holes intersecting basic rocks.

Table 1. Stratigraphic units in the Mammoth area (after Moore, 1974; Derrick & others, 1976).

Unit	*Average thickness (m)*	*Lithology*
Gunpowder Creek Fm	400	Siltstone, quartzite, sandstone. Dolomite lenses. Conglomerate at base.
~~Unconformity~~~		
Myally Subgroup	1600	Quartzite, sandstone and minor siltstones. 40-m thick basic volcanic unit in middle (40-m metabasalt).
Eastern Creek Volcanics		
Pickwick Metabasalt Member	750*	Metabasalt, flow top breccia, quartzite, tuff and siltstone.
Lena Quartzite Member	500*	Feldspathic quartzite, minor siltstone.
Cromwell Metabasalt Member	3900*	Metabasalt, flow top breccia, sandstone, siltstone and chert.

* Average regional thickness

occur in the metabasalts, and increase in frequency up the sequence, with interbeds up to 60 m thick being recorded in the Pickwick Metabasalt (Glikson & Derrick, 1978). On the basis of their relatively similar compositions and the occurrence of the 40-m metabasalt about 600 m stratigraphically above the Pickwick Metabasalt (Moore, 1974), the former can be envisaged as representing the final stages of Eastern Creek volcanism.

Samples and methods

Eight samples of ECV from next to the Mammoth Extended Fault in DDH S192A, two less-altered rocks from about 1 km east of the Mammoth mine (Fig. 2), and two samples from Eastern Creek, 20 km to the south (Fig. 1) have been analysed. Samples of the 40-m metabasalt intersected by DDH S47, S156, and S197, and from 20 km ESE of Mammoth were also analysed. Substantial chalcocite-pyrite mineralisation occurs in the basic unit or in arenites immediately above it (as in DDH S197) adjacent to the Mammoth mine.

Samples of halved 45 mm diameter drill core (approx. 100 mm long) and outcrop (up to 500 g) were crushed in a manganese steel jaw-crusher. A 40 g representative portion of each crushed sample was then ground to -75 μm in a manganese steel ring-mill. Major mineralogical components of each sample were determined by X-ray powder diffractometry, using graphite crystal monochromated copper radiation, scanning over the range 4-70°2θ at $\frac{1}{2}$°2θ/min.

Major elements, As, Ba, Rb, Sr, Y, and Zr were determined by X-ray fluorescence spectrometry; Na, Li, Cu, Pb, and Zn by atomic absorption spectrometry; other trace elements by optical emission spectroscopy; S and total C (as CO_2) using a Leco analyser; and H_2O by gravimetric techniques.

Regional metamorphic effects

Metabasalts of the ECV to the east of Mount Isa have undergone greenschist facies regional metamorphism, resulting in the growth of albite, epidote, chlorite, and calcite, and the destruction of pyroxene, amphibole, and calcic plagioclase (Glikson & Derrick, 1978), and in some localities chalcopyrite has been remobilised

Table 2. Ranges and average compositions of metabasalts of the Eastern Creek Volcanics.

	Eastern Creek		*3–15 km east to southeast of Mammoth**			
	Epidote-rich	*Albite-rich*	*Cromwell Metabasalt (Middle-Upper)*		*Pickwick Metabasalt*	
No. of samples	1	1	33	*Range*	8	*Range*
SiO_2	46.3	42.7	47.6	44.2 –50.3	48.9	47.6 –49.8
Al_2O_3	15.0	14.6	13.0	12.2 –14.5	14.3	13.5 –15.2
FeO_{tot}	13.1	12.2	15.2	13.3 –18.4	11.5	10.4 –12.5
MgO	2.02	4.35	4.40	2.32– 6.13	6.53	5.21– 7.22
CaO	17.2	8.49	7.56	5.22– 9.39	9.19	7.76–10.3
Na_2O	<0.01	1.94	2.19	1.33– 4.04	2.32	1.76– 3.63
K_2O	0.19	0.74	1.86	0.16– 3.32	1.59	0.99– 2.17
TiO_2	2.15	2.24	3.05	2.25– 3.39	1.44	1.22– 1.67
P_2O_5	0.38	0.32	0.55	0.31– 2.42	0.15	0.12– 0.17
MnO	0.16	0.20	0.25	0.17– 0.34	0.20	0.14– 0.30
CO_2	0.20	6.67	0.29	<0.05– 3.55	0.10	<0.05– 0.45
H_2O	2.34	4.28	2.65	2.03– 3.43	2.60	2.04– 3.02
S	<0.01	0.02	—		—	
Ba	58	210	440	70–1550	470	110–1690
Co	25	25	46	35– 55	50	45– 60
Cr	40	40	61	5– 150	110	25– 250
Cu	100	100	200	20– 390	170	20– 360
Ni	20	25	49	10– 240	90	50– 140
Pb	—	—	14	5– 34	8	2– 28
Rb	<2	9	71	22– 160	54	28– 70
Sc	15	15	—		—	
Sr	1270	74	150	80– 330	180	140– 270
V	150	100	320	45– 420	280	220– 350
Y	32	33	53	40– 75	21	20– 32
Zn	40	100	160	85– 220	110	65– 170
Zr	170	190	290	190–440	110	90– 150

Major components—wt %; trace elements—ppm. * Calculated from data of Wilson & Derrick (written communication, 1981).

into quartz + dolomite + calcite veins. However, the retention of primary pyroxene and labradorite, especially in the Pickwick Metabasalt, shows that metamorphic reactions are, in places, incomplete. The effects of metamorphism are further complicated by the development of dichotomous Ca-rich and Na-rich assemblages, which at Eastern Creek are manifested as greenish-grey epidote-rich and grey albite + chlorite ± calcite assemblages. Comparison of the Ca-rich and Na-rich assemblages (Table 2) reveals that Si, Mg, K, CO_2, H_2O, Ba, Rb, Sr, and Zn have also been mobile. Generally, such dichotomy in basic volcanics is ascribed to low-grade greenschist metamorphism in an open system (Smith, 1968). In addition to the movement of these elements, within the least altered samples of the ECV 3-15 km from the Mammoth Mine, Al, Cr, and Ni appear to be enriched in the Pickwick Metabasalt, and Fe, Ti, P, V, Y, and Zr, in the middle to upper portion of the Cromwell Metabasalt (Table 2). Furthermore, the magnitude of the differences in the Ti, Cr, Y, and Zr contents suggests that, even if these elements are not completely immobile (Vallance, 1974), they reflect in part original compositional differences. Indeed, Wilson & Derrick (personal communication, 1981) have suggested that, with the deposition of the Lena Quartzite, continued differentiation of the Cromwell Metabasalt was interrupted and that the Pickwick Metabasalt represents a new magma influx. Thus, to determine the effects of subsequent hydrothermal alteration, only the Pickwick Metabasalt in the Mammoth area can be used for comparison. However, as the samples analysed by Wilson & Derrick specifically excluded epidote-rich assemblages, minor biases may be introduced for components mobile during metamorphism (e.g. Ca) by using these data as background values.

Hydrothermal alteration relative to metamorphism

Regionally metamorphosed Pickwick Metabasalt consists of assemblages of epidote, amphibole, chlorite, plagioclase, quartz, ± calcite ± sphene ± remnant pyroxene (Glikson & Derrick, 1978). At distances up to 1 km away from the Mammoth mine, epidote, chlorite, K-feldspar, mica, quartz, and hematite occur with calcite or dolomite. Closer to the mineralisation, epidote and chlorite are rare, with the Pickwick Metabasalt in DDH S192A being particularly rich in microcline and mica, and the accompanying carbonate is ferroan dolomite ± siderite. In this core, the upper samples are pale green and mica-rich, whereas lower samples are often pink and more dolomitic.

At a distance of 20 km from the Mammoth mine the 40-m metabasalt consists of plagioclase, K-feldspar, chlorite, calcite, epidote, amphibole, quartz, mica, and accessory pyrite. Within 200 m of the mineralisation, in DDH S47 and S156, the metabasalt comprises pale to dark green assemblages of adularia, dolomite, mica, chlorite, quartz, rutile, and hematite. This same unit in DDH S197 is more siliceous and hematitic at the expense of chlorite and carbonates.

Thus, plagioclase, amphibole, pyroxene, and calcite appear to be restricted to metamorphosed basic volcanic rocks more than 600 m from mineralisation. Closer to the mine, K-feldspar, mica, hematite, and either Fe-rich carbonates or silicification characterise the altered volcanic rocks. Potassium feldspar occurs as adularia in the highly altered 40-m metabasalt, but as microcline in the Pickwick Metabasalt.

Table 3. Ranges and average compositions of hydrothermally altered metabasalts near Mammoth and their unaltered regional equivalents.

	Pickwick Metabasalt					*40-m metabasalt*			
	DDH S192A		*1 km east of mine*		*3–15 km east to southeast of mine*	*DDHs-S47 and S156*		*DDH S197*	*20 km ESE of mine*
No. of samples	8		1	1	8	8		1	1
	Average	*Range*				*Average*	*Range*		
SiO_2	53.5	39.8 -62.4	45.1	46.1	48.9	52.6	48.4 -58.4	60.4	47.2
Al_2O_3	16.3	12.1 -21.6	11.8	13.3	14.3	18.7	16.2 -23.8	19.6	14.2
FeO_{tot}	3.33	1.50– 5.31	12.9	15.0	11.5	2.46	1.71– 3.82	1.56	11.7
MgO	4.02	1.32– 8.31	8.06	5.82	6.53	2.30	0.75– 3.55	0.83	3.78
CaO	3.99	0.30– 9.25	5.16	4.03	9.19	2.45	0.57– 4.48	0.62	7.58
Na_2O	0.08	0.04– 0.10	0.04	0.04	2.32	0.09	0.06– 0.13	0.11	3.13
K_2O	9.40	7.19–11.5	3.19	3.83	1.59	10.1	8.51–11.1	11.6	2.76
TiO_2	1.71	1.15– 2.11	1.41	1.59	1.44	2.85	2.29– 3.60	2.87	2.34
P_2O_5	0.22	0.16– 0.29	0.12	0.13	0.15	0.35	0.31– 0.41	0.48	0.39
MnO	0.15	0.01– 0.32	0.14	0.14	0.20	0.06	<0.01– 0.13	0.01	0.17
CO_2	5.98	0.23– 9.75	7.55	3.54	0.10	2.99	<0.05– 5.51	—	0.39
H_2O	2.41	1.23– 3.20	5.03	5.94	2.60	3.06	2.20– 4.21	—	3.91
S	<0.01	<0.01– 0.01	<0.01	<0.01	—	0.12	0.01– 0.23	0.01	0.04
As	<10	<10– 10	10	20	—	27	10– 90	20	10
B	120	10– 200	20	—	—	260	40– 400	100	—
Ba	600	220– 830	200	340	300*	570	440– 700	470	480
Co	12	<10– 20	40	60	50	14	<10– 40	<10	40
Cr	18	<15– 25	15	20	110	140	90– 150	100	80
Cu	8	5– 15	85	380	170	570	<5–2340	50	85
Ga	14	2– 20	10	15	—	15	2– 30	10	15
Li	22	<5– 75	27	27	—	11	5– 15	4	30
Ni	21	6– 30	30	60	90	20	6– 80	8	20
Pb	<30	–	<10	30	8	<30	—	4	55
Rb	290	160– 460	—	—	54	250	170– 280	300	70
Sc	66	40– 100	30	60	—	57	30– 70	—	40
Sr	11	<5– 20	25	20	180	19	5– 45	20	210
V	300	150– 400	200	200	280	350	150–1000	250	250
Y	20	10– 30	40	30	21	26	20– 30	—	36
Zn	160	20– 450	105	35	110	23	<10– 25	15	170
Zr	140	90– 190	120	120	110	240	290– 320	240	230

Major components—wt %; trace elements—ppm. * One anomalously high value omitted from average.

The Pickwick Metabasalt in DDH S192A has generally higher Si, Al, K, B, Ba, Sc, V, and Zn, and lower Fe, Mg, Ca, H_2O, Co, Cu, Ni, and Sr, than the less-altered metabasalt from 1 km east of the mine (Table 3). The latter is in turn enriched in Fe, K, CO_2, H_2O, Cu, Pb, and Y, and depleted in Si, Al, Ca, Na, Cr, Ni, Sr, V, and Zn relative to samples from east and southeast of Mammoth.

Close to the mineralisation at Mammoth, the 40-m metabasalt has higher Si, Al, K, CO_2, As, Ba, Cu, and Rb, and lower Fe, Mg, Ca, Na, Mn, Co, Li, Pb, Sr, Y, and Zn than the surface sample from 20 km away (Table 3). Whereas alteration of the metabasalt in DDH S47 and S156 is characterised by the development of dolomite, in DDH S197 the metabasalt is Si-rich with lower Mg and Ca contents than elsewhere.

Primary compositional differences between samples of the two basaltic units remote from the mineralisation are evident from the data in Table 3, with, in particular, Ti, P, and Zr consistently richer in the 40-m metabasalt, even where it is altered. This suggests that compositional changes occurred during the waning phase of volcanism, i.e. just as the Cromwell Metabasalt becomes more differentiated with time (Wilson & Derrick, personal communication, 1981), so too the Pickwick Metabasalt to 40-m metabasalt sequence reflects differentiation. Furthermore, compositional changes (e.g. K-enrichment) may occur by reaction of the magma with the quartzofeldspathic intercalations (Glikson & Derrick, 1978). As the result of alteration, Ca, Mn, CO_2, and Zn levels are higher and S, As, Cr, and Cu significantly lower in the Pickwick Metabasalt, whereas the levels of K, Na, and most of the trace elements are similar in the two units.

Discussion

In the vicinity of copper mineralisation at Mammoth, both the Pickwick Metabasalt and 40-m metabasalt have undergone alteration with considerable enrichment of K, Ba, and Rb, and depletion of Fe, Mg, Ca, and Na. This alteration pattern is consistent with decomposition of epidote and amphibole and the formation of authigenic feldspar incorporating Ba and Rb during potash metasomatism of the reactive metavolcanics. Such alteration is attributed to movements of fluids through the rock pile. Movement of the resultant K-deficient fluid along the Mammoth-Mammoth Extended Fault system into the arenites then caused destruction of original K-feldspar, a rise in pH (Hemley, 1959), and precipitation of Fe and Mn, producing the Fe-rich, K-Ba-Rb-depleted assemblages of the footwall arenites adjacent to the Mammoth Fault (Scott & Taylor, 1977).

The movement of Cu and Zn during alteration is significantly different, with Cu being depleted in the Pickwick Metabasalt, whereas most samples of the 40-m metabasalt show an enrichment in copper. On the other hand, Zn is consistently depleted only in the 40-m metabasalt.

Although further from the Mammoth mineralisation, the Pickwick Metabasalt represents a far greater volume of potentially leachable rock than does the 40-m metabasalt. Assuming that 160 ppm Cu is available for leaching (as suggested in Table 3), and that 10^7 tonnes ore at 3% Cu (Kume & Suzuki, 1976) are contained in the Mammoth deposit, the total volume of source rock needed for the Mammoth mineralisation is less than 1 km^3. Thus, the copper-deficient Pickwick Metabasalt in the vicinity of the deposit is considered to be the source of copper. Lead isotope ratios of ore and Pickwick Metabasalt are consistent with this hypothesis (Vaasjoki, 1980).

Two explanations are considered for this accumulation of copper in the 40-m metabasalt and adjacent arenites. First, after reaction with the Pickwick Metabasalt the resultant copper-bearing fluid reacted with the 40-m metabasalt to produce potassium-rich assemblages similar to those in the Pickwick Metabasalt. However, as the pH of the fluid had been raised by passage through and reaction with the feldspathic arenites, copper was precipitated, possibly with iron sulphides being replaced as in the Mammoth mine (Moore, 1974). Alternatively, fluids permeating through the rocks reacted with the 40-m metabasalt to form K-feldspar and, as in the Pickwick Metabasalt, leached base metals and iron from it. The presence of adularia in the 40-m metabasalt suggests that the temperature of the fluid may have been lower than during alteration of the Pickwick Metabasalt, and that, rather than being transported for hundreds of metres, copper was deposited either in the volcanic unit or immediately next to it. The zinc content of about 1.38 per cent associated with chalcocite-bornite immediately above the metabasalt in DDH S197 is substantially higher than the values below 100 ppm found in similar sulphides in the Mammoth mineralisation, where zinc is partitioned from copper, particularly into the footwall of the orebodies (Scott & Taylor, 1977). As leaching of zinc from the Pickwick Metabasalt has been minimal and its distribution in and next to the 40-m metabasalt is erratic, a local source for the mineralisation associated with the 40-m metabasalt is likely.

Conclusions

Basic volcanics next to the Mammoth-Mammoth Extended Fault system and within 600 m of the mineralisation at Mammoth have undergone potash metasomatism and depletion in Fe, Mg, Ca and Na. However the Pickwick Metabasalt Member of the Eastern Creek Volcanics close to the mine is depleted in copper, whereas the 40-m metabasalt is enriched in copper, except locally, where it has been mobilised into adjacent hanging wall arenites. The Pickwick Metabasalt Member is considered to be the source of copper for the Mammoth mineralisation. Mineralisation associated with the 40-m metabasalt is considered to represent local precipitation of copper from a fluid similar to that which caused the Mammoth mineralisation.

Despite differences in host rock lithology and ore mineralogy, derivation of the Mammoth mineralisation from underlying ECV via a major fault system is analogous to the genesis of copper mineralisation at Mount Isa proposed by Smith & Walker (1971). The association of Carpentarian sediments and older Eastern Creek Volcanics next to major transgressive faults must be considered prospective for copper mineralisation in the western succession of the Mount Isa Inlier.

Acknowledgements

We wish to acknowledge the encouragement of Gunpowder Copper Limited (GCL) in providing samples and access to company data. I. H. Wilson (Queensland Geological Survey) and G. M. Derrick (Tenneco Oil and Minerals) kindly provided us with a copy of their unpublished data. Discussions with G. P. Moore, J. Rawlins, J. Rowe, and M. J. Hunter (all formerly of GCL), B. L. Gulson (CSIRO), I. H. Wilson and G. M. Derrick are appreciated.

Samples were crushed by W. V. Hutchings and analysed by S. C. Goadby, A. R. Horne, K. Kinealy, A. Martinez, K. J. Mizon, N. C. Morgan and K. W. Riley at the North Ryde laboratories of the CSIRO Institute of Energy and Earth Resources.

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DISTRIBUTION AND GEOCHEMISTRY OF VOLCANIC ROCKS IN THE DUCHESS-URANDANGI REGION, QUEENSLAND

R. J. Bultitude[1] & L. A. I. Wyborn

Recent mapping in the Duchess-Urandangi region, covering most of the southern part of the Mount Isa Inlier, has shown that felsic and mafic volcanics occur in most Precambrian stratigraphic units exposed there. Five distinct geochemical suites of felsic volcanics are recognised, each suite probably having been derived from a chemically unique crustal source region. The Leichhardt suite is distinguished by high Sr, and low Zr, Nb and Y abundances, whereas the Argylla suite has low Sr and very high Zr and Nb concentrations. The Bottletree suite is characterised by high Ba, Sr, Zr, and Nb, the Duchess-Corella suite by low Sr and Zr, and high Nb and Y contents, and the Carters Bore suite by high K_2O and low Al_2O_3, Na_2O, CaO, Pb, Sr, and Ba. Most of the analysed mafic volcanics from the region are chemically similar, and there is no systematic change in composition from west to east. The mafic volcanics are characterised by low incompatible-element contents and are similar chemically to continental tholeiites of the Karroo province of southern Africa. Silica values for the volcanics and their intrusive equivalents show a well-defined bimodal distribution, probably indicating an extensional crustal regime.

Introduction

The Duchess-Urandangi region covers most of the southern part of the Mount Isa Inlier (Geological Survey of Oueensland, 1975; Fig. 1). The inlier is generally considered to consist of a central basement belt flanked on either side by thick sequences of younger rocks, commonly referred to as the western and eastern successions, which consist mainly of Haslingden Group and Mary Kathleen Group rocks, respectively. This interpretation was first put forward by Carter & others (1961) and has been followed by most later workers (e.g., Plumb & Derrick, 1975; Derrick & others, 1977a; Plumb & others, 1980, 1981), but has been challenged by Blake (1980, 1981). Blake suggested that the Haslingden Group predates not only the eastern succession, but part of the basement belt, and that the Corella Formation, the most widespread unit of the Mary Kathleen Group, represents at least two quite separate units, one older than, and one younger than, the Haslingden Group.

Two major northerly trending fault zones, the Wonomo/Mount Annable/Mount Isa Fault system in the west and the Pilgrim Fault Zone to the east divide the Duchess-Urandangi region into three geographical parts: the western, central, and eastern areas (Fig. 1; Blake & others, 1981a). Correlations between these areas are generally uncertain.

The stratigraphy of the Duchess-Urandangi region is summarised in Figure 2 and the distribution of the main rock groupings is shown in Figure 3. Most Precambrian stratigraphic units in the region contain felsic or mafic volcanics (Fig. 3).

Petrographic and geochemical data on the volcanic rocks presented in this paper are based on the examination of several hundred thin sections and 125 chemical analyses. The samples were analysed at AMDEL (Australian Mineral Development Laboratories), Adelaide. Most element abundances were determined by X-ray fluorescence spectrometry; Co, Cr, Cu, Li, Zn, Ni, and V concentrations were determined by atomic absorption spectroscopy. Representative analyses of volcanic rocks from the region are listed in Tables 1 and 2. The complete list of analyses is given in Wyborn (in preparation). Mineral compositions in twenty samples (19 metabasites and one metadacite) were analysed using the TPD energy- dispersive microprobe at the Research School of Earth Sciences, Australian National University, following the methods of Reed & Ware (1975) and Ware (1981). All analysed amphiboles have been classified according to the scheme of Leake (1978).

Of the five felsic volcanic suites recognised in the Duchess-Urandangi region, two, the Leichhardt and Argylla, consist predominantly of felsic volcanic units, which extend to the north, where they have been studied by Wilson (1978). Wilson reported that the two sequences (mapped as Leichhardt Metamorphics and Argylla Formation) were chemically distinct, a conclusion with which we concur after the study of equivalent formations farther south. In contrast, the mafic volcanic rocks analysed from the Duchess-Urandangi region tend to be chemically uniform, and the variation in composition from west to east found by Glikson & others (1976) in equivalent formations to the north, is not apparent in the Duchess-Urandangi region.

Petrography and metamorphism

The volcanic rocks in the region have been regionally metamorphosed to either greenschist or amphibolite grade. The felsic volcanics are generally porphyritic, containing phenocrysts of mainly quartz and feldspar and, less commonly, biotite, hornblende, and opaque minerals in a fine-grained quartzofeldspathic groundmass, which commonly also contains minor biotite, muscovite, or hornblende. Amphibolite-grade rocks are difficult to distinguish, because the most common assemblage in the felsic volcanics is quartz + feldspar + biotite, which remains stable from upper greenschist to at least upper amphibolite grade. Greenschist-grade felsic volcanics contain chlorite, epidote, muscovite, biotite, actinolite, calcite, and plagioclase. The plagioclase grains are mostly albite partly replaced by sericite, muscovite, and epidote/clinozoisite. Some hornblende is generally present in amphibolite-grade felsic volcanics and chlorite, epidote, and actinolite show a decrease in abundance. Plagioclase compositions range from calcic oligoclase to andesine. Sphene, apatite, opaque minerals, allanite, zircon, and monazite are common accessory minerals in both greenschist and amphibolite-grade rocks.

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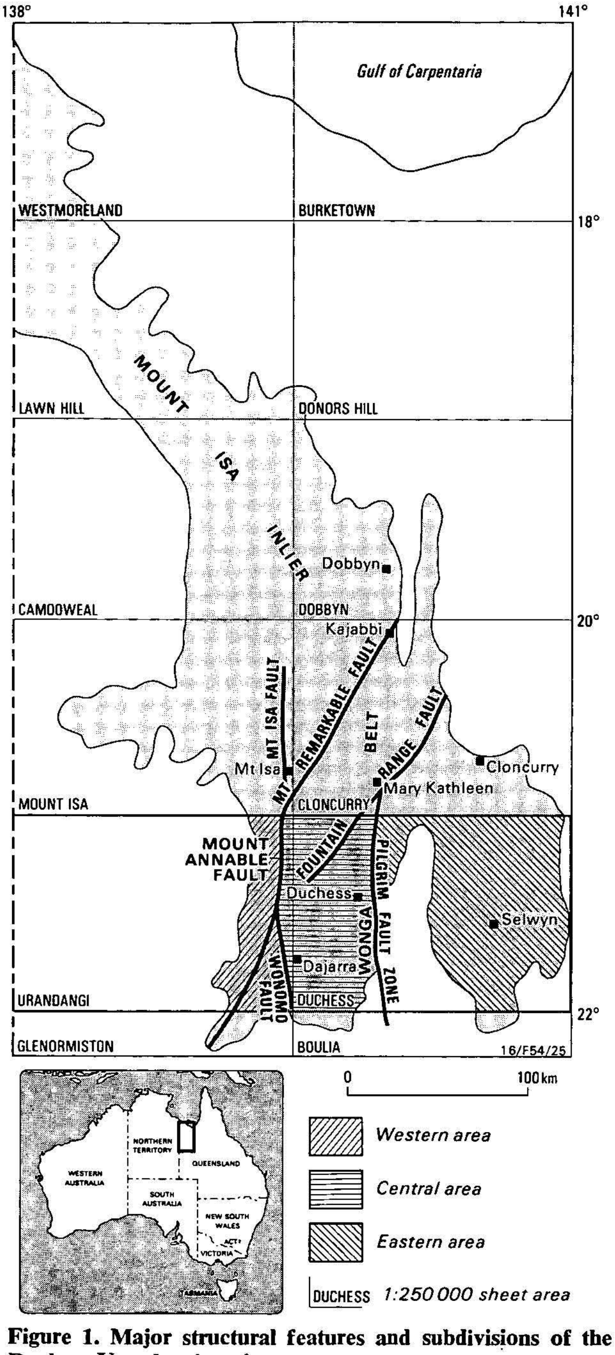

Figure 1. Major structural features and subdivisions of the Duchess-Urandangi region.

Greenschist-grade mafic volcanics contain albite, chlorite, actinolite, epidote/clinozoisite, biotite, quartz, sphene, potassium feldspar, apatite, and calcite. Primary igneous textures are generally preserved and some plagioclase grains have sericitised cores of labradorite and rims of oligoclase-andesine. Primary clinopyroxene is rare. Amphibolite-grade mafic volcanics contain coexisting tschermakitic to magnesiohornblende, or rarely, ferrohornblende and calcic oligoclase or andesine, and some garnet or actinolitic hornblende may also be present. Most primary igneous textures have been obliterated by recrystallisation effects.

Volcanic rocks of the central area

The central area bounded by the Wonomo/Mount Annable/Mount Isa Fault system to the west and the Pilgrim Fault Zone to the east, consists of three main structural divisions: the central Kalkadoon-Leichhardt block, which is flanked by the western succession in the west and the Duchess belt in the east. The Kalkadoon-Leichhardt block consists largely of igneous rocks—felsic and mafic volcanics of the Tewinga Group and granitic intrusives. Most stratigraphic units are dominated by volcanics, with only minor intercalated sediments. The Duchess belt (Bultitude & others, in press) consists mainly of the Corella Formation, a unit of calc-silicate rocks and subordinate felsic and mafic volcanics, but also contains some basement rocks (Plum Mountain Gneiss) and plutons of the Wonga Batholith. The highly deformed western part of the Duchess belt, which includes upper Tewinga Group rocks, is the southern extension of the Wonga belt of Derrick (1980). The western succession unconformably overlies rocks of the Kalkadoon-Leichhardt block and consists mainly of sedimentary and volcanic rocks of the Haslingden Group. The Bottletree Formation, which underlies this group, is also regarded by us as part of the western succession, rather than part of the basement sequence (*cf* Derrick & Wilson, 1981).

The Tewinga Group, as defined by Derrick & others (1976a) comprises three formations, from oldest to youngest, the Leichhardt Metamorphics, Magna Lynn Metabasalt and Argylla Formation. In the Kalkadoon-Leichhardt block, the Leichhardt Metamorphics of earlier workers are mapped partly as Leichhardt Volcanics, a formation of generally little-recrystallised felsic volcanic rocks, and partly as undivided Tewinga Group, which consists mainly of amphibolite-grade felsic gneissic rocks.

The felsic gneisses of the **undivided Tewinga Group** range from banded to massive, and many contain feldspar (mainly microcline) augen or feldspar megacrysts and small mafic inclusions. A few massive units show vague contorted flow banding and are probably meta-rhyolite lavas, but most of the gneisses may be meta-ignimbrites. Mafic volcanics are represented by massive to schistose and commonly amygdaloidal metabasalt (Blake & others, 1982). Four out of seven analysed zircon size fractions separated from a metadacite have yielded a U-Pb zircon age of 1866 ± 5 m.y. (Page, in preparation). Page interpreted this result as most probably representing the initial crystallisation age of the metadacite. The age is similar to that obtained for the Leichhardt Volcanics, and also for the Leichhardt Metamorphics north of the region (Page, 1978, in preparation). Seven samples have been chemically analysed, six felsic gneisses and one metabasalt.

The **Leichhardt Volcanics** (Blake & others, 1981b) consist mainly of massive rhyolitic to dacitic ignimbrites, which contain abundant to sparse phenocrysts (<5 mm) enclosed in a fine-grained quartzofeldspathic groundmass in which eutaxitic and devitrification textures are commonly preserved. Phenocrysts of euhedral sodic plagioclase are more abundant than those of euhedral to partly resorbed quartz and alkali feldspar; rare phenocrysts of biotite and hornblende, now recrystallised and altered, may also be present. The Leichhardt Volcanics also contain minor flow-banded rhyolite lavas, some possible high-level intrusions, and rare basaltic lava flows and clastic sediments (Blake & others, 1982; Bultitude & others, in press). The metamorphic grade appears to be predominantly greenschist; some higher grade areas are indicated by the

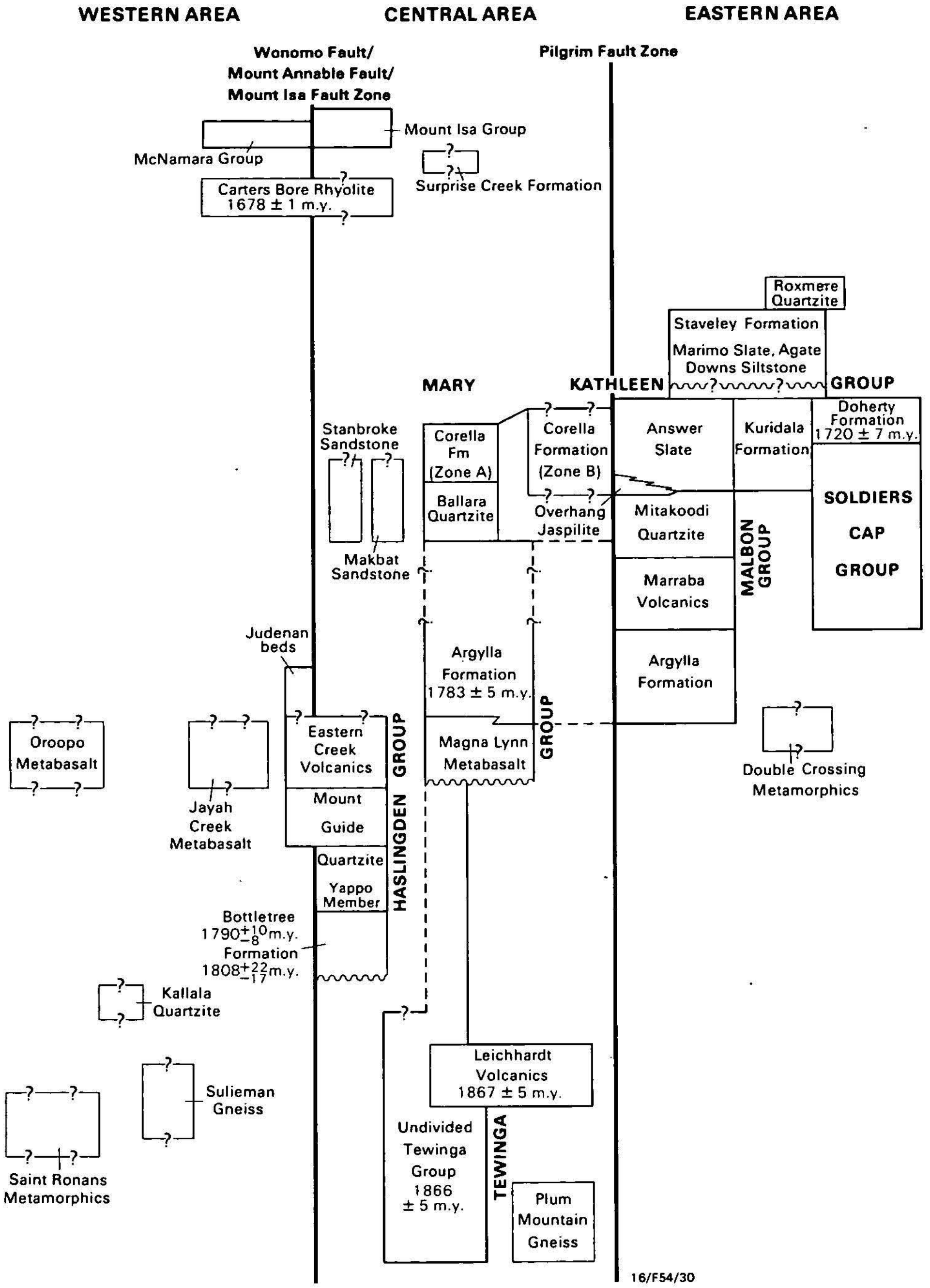

Figure 2. Stratigraphic correlation scheme for the Precambrian of the Duchess-Urandangi region.

presence of amphibolite-grade mafic dykes. A U-Pb zircon age of 1867±5 m.y. has been obtained by pooling data for 19 zircon fractions from the Leichhardt Volcanics and Leichhardt Metamorphics (Page, in preparation). Thirty-four samples from the Leichhardt Volcanics have been analysed.

The **Magna Lynn Metabasalt** (Derrick & others, 1976a) crops out in the northeastern part of the Kalkadoon-Leichhardt block and the Duchess belt. Metabasalt is the main rock type, with some meta-arenite, conglomerate, and minor felsic volcanics. Pillow structures and hyaloclastite structures are rare, suggesting that the basaltic volcanism was mainly subaerial. The Magna Lynn Metabasalt has been regionally metamorphosed, mainly to amphibolite grade, and is extensively recrystallised. A major unconformity (disconformity) representing about 80 m.y. separates the Leichhardt Volcanics from the overlying Magna Lynn Metabasalt and Argylla Formation (Page, 1978, in preparation). Three mafic volcanic samples have been analysed.

The **Argylla Formation** (Carter & others, 1961) crops out in the Kalkadoon-Leichardt block and the western part of the Duchess belt, and also in the western part of the eastern area, east of the Pilgrim Fault Zone. It consists mainly of extensively recrystallised to gneissic rhyolitic to dacitic metavolcanics (massive ignimbrite, together with minor felsic lava, agglomerate, and bedded tuff) and some possible high-level intrusives. The formation also includes interlayered shallow-water clastic metasediments, especially in the eastern area, and scattered mafic lava flows. The felsic volcanic rocks

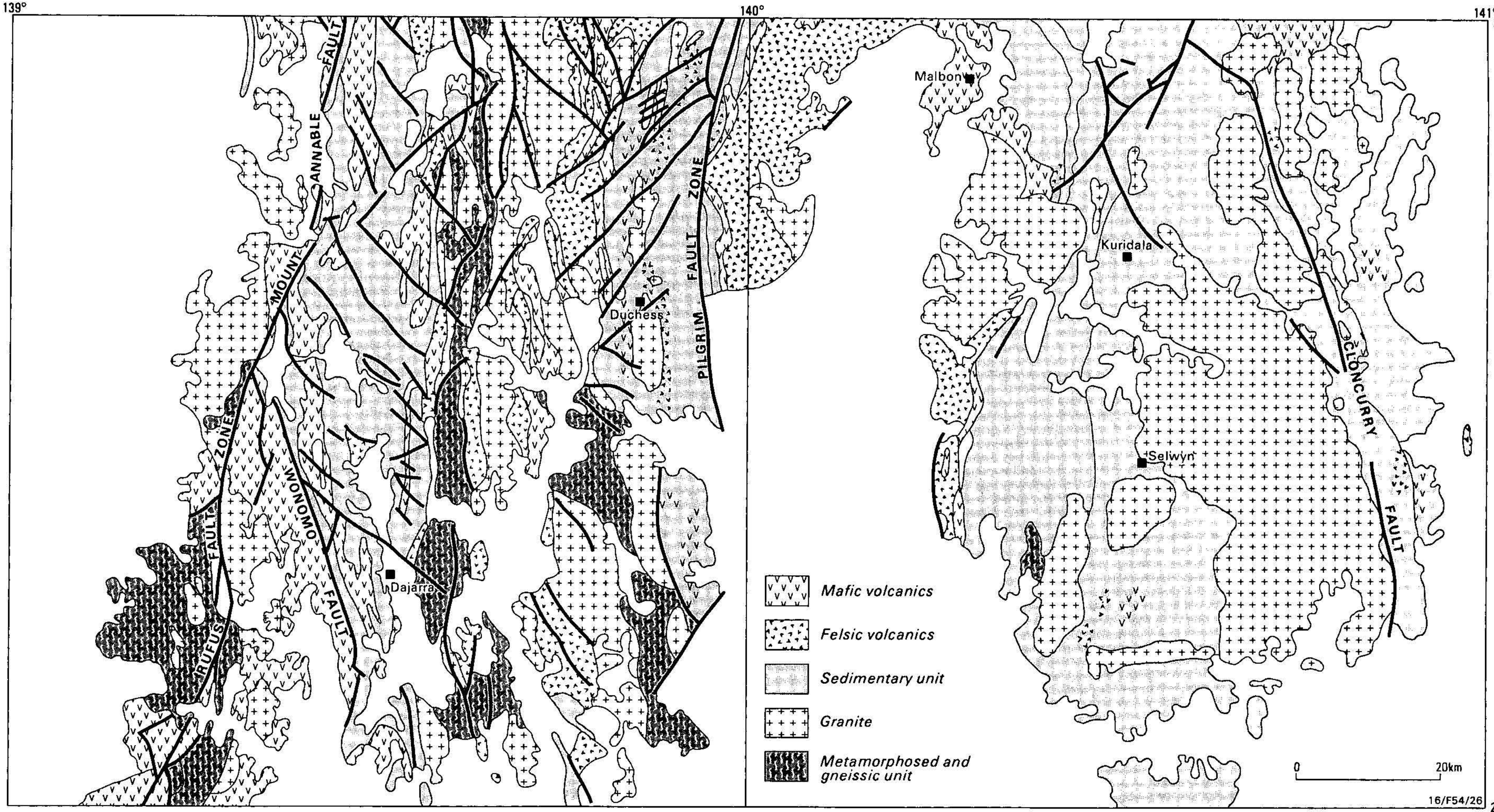

Figure 3. Generalised geological map of the Duchess-Urandangi region, showing the distribution of volcanic-bearing units.

commonly contain phenocrysts of potassium feldspar and subordinate smaller phenocrysts of sodic plagioclase and quartz. The formation has been regionally metamorphosed, mainly to amphibolite grade. Some interfingering of felsic and mafic volcanics at the base of the Argylla Formation and the top of the Magna Lynn Metabasalt indicate that the two formations are essentially the same age. The age of the Argylla Formation volcanism has been determined at 1783±5 m.y. (Page, in preparation). Thirteen samples of felsic volcanics from the Argylla Formation have been analysed.

The **Plum Mountain Gneiss** (Blake & others, 1981b) crops out in the southeastern part of the central area. The predominant rock types are quartzofeldspathic gneiss and augen gneiss, probably representing felsic volcanics and granite that have been regionally metamorphosed to amphibolite grade (Blake & others, 1981b). The non-intrusive quartzofeldspathic gneissic rocks may be correlated with those of the undivided Tewinga Group. Two analyses of Plum Mountain Gneiss have been obtained, but both are probably from intrusive, rather than extrusive units in the sequence.

The **Bottletree Formation** (Blake & others, 1981b), the oldest unit in the western succession, consists mainly of rhyolitic to dacitic lavas and ignimbrites, interlayered pebbly greywacke and greywacke conglomerate, and sheared, schistose and partly amygdaloidal basaltic lava flows (common near the base and top of the formation). In the porphyritic felsic volcanics the phenocrysts are predominantly plagioclase, but in some units potassium feldspar is the most abundant phenocryst; other phenocrysts include quartz, biotite, magnetite, and hornblende. The Bottletree Formation is extensively recrystallised and has been regionally metamorphosed to amphibolite grade. The formation extends northwards into the Mary Kathleen 1:100 000 Sheet area, where it has been mapped as part of the Argylla Formation (Derrick & others, 1977a). Isotopic data indicate that the Bottletree Formation is about the same age as or a few million years older than the Argylla Formation (Page, in preparation). Twenty-one rocks from the Bottletree Formation have been analysed, including two mafic lavas.

The **Eastern Creek Volcanics** (Carter & others, 1961) are part of the Haslingden Group, which conformably overlies the Bottletree Formation. Haslingden Group rocks have also been mapped in the western area (Bultitude & others, in press). Subdivision of the Eastern Creek Volcanics into Cromwell Metabasalt Member (oldest), Lena Quartzite Member, and Pickwick Metabasalt Member (youngest), following the practice of Derrick & others (1976b) in sheet areas to the north of the Duchess-Urandangi region, has not been possible. The Eastern Creek Volcanics consist of a series of predominantly subaerial tholeiitic basalt lava flows and interlayered clastic sediments. The formation has been regionally metamorphosed to greenschist and amphibolite grades. Five mafic rocks have been analysed from this formation.

The **Corella Formation** (Carter & others, 1961) of the Duchess belt is part of the Zone B Corella Formation of Blake (1982). It consists mainly of amphibolite-grade calc-silicate rocks, but includes interlayered felsic and mafic metavolcanic units. Extensively recrystallised, strongly foliated to gneissic felsic volcanics in the north probably represent mainly ignimbritic feldspar porphyry and non-porphyritic metarhyolite and metadacite (Bultitude & others, in press). In the south, medium to coarse quartzofeldspathic granofels may represent metamorphosed felsic tuff or possible arkose. Amphibolitic mafic lavas contain scattered amygdaloidal zones, rare possible pillows and flow-margin breccias, and are commonly closely associated spatially with felsic volcanic units. Traditionally, the Corella Formation has been thought to overlie the Argylla Formation (Plumb & others, 1980) and hence be younger than about 1780 m.y. (Page, 1978, in preparation). However, Blake (1980, 1981, 1982) considers that the Corella Formation in this belt may contain rocks older than 1870 m.y. One metabasite and fifteen felsic volcanics from the Corella Formation have been analysed.

Volcanic rocks of the western area

The **Sulieman Gneiss** (Blake & others, 1981b) crops out in the southern part of the western area between the Wonomo Fault and Rufus Fault Zone (Fig. 3), and consists of amphibolite-grade interlayered quartzofeldspathic gneiss and schist, augen gneiss, amphibolite, hornblende schist, quartzite, and some banded garnetiferous calc-silicate gneiss. Most of the protolith of this unit was probably rhyolitic to dacitic volcanics and interlayered volcaniclastic sediments; some of the augen gneiss may represent granite and/or intrusive feldspar porphyry. The Sulieman Gneiss may correlate with the Saint Ronans Metamorphics, undivided Tewinga Group, Yaringa Metamorphics, or May Downs Gneiss (regarded by Derrick & others, 1976b, as a metamorphosed equivalent of the lower Mount Guide Quartzite). Three samples have been analysed from this unit, including one metabasite.

The **Jayah Creek Metabasalt** (Blake & others, 1981b) also crops out between the Wonomo Fault and the Rufus Fault Zone. It consists of slightly to highly schistose, amphibolite-grade basaltic lava flows and interbedded sediments. Many individual lava flows have well-preserved amygdaloidal zones and marginal breccias. The Jayah Creek Metabasalt, which is thought to overlie the Sulieman Gneiss concordantly, may be equivalent to the Eastern Creek Volcanics. Three mafic volcanics have been analysed from this unit.

The **Saint Ronans Metamorphics** (Blake & others, 1981b), the oldest unit exposed west of the Rufus Fault Zone, is made up of amphibolite-grade arenites and argillites, and interlayered mafic and felsic volcanics. Interfingering of felsic and mafic volcanics occurs locally, indicating contemporaneous mafic and felsic volcanism. Remnant phenocrysts in the felsic volcanics are of feldspar (mainly albite to andesine), quartz and opaque oxide. Only one sample, an amphibolite, was analysed from this formation.

The **Oroopo Metabasalt** (Blake & others, 1981b) crops out west of the Rufus Fault Zone and consists of massive to amygdaloidal mafic lava flows and some interbedded quartzite, arenite, siltstone, and limestone, regionally metamorphosed to greenschist and lower amphibolite grades. The Oroopo Metabasalt, which overlies the Saint Ronans Metamorphics, may correlate with the Eastern Creek Volcanics which it closely resembles. Two metabasalts from the formation have been analysed.

The **Carters Bore Rhyolite** (Derrick & others, 1978) exposed in the northern part of the western area, is a thin sequence of rhyolitic ash-flow tuffs and minor lava flows, which have been regionally metamorphosed to greenschist grade. The volcanics contain phenocrysts of recrystallised quartz and potassium feldspar (mainly microcline) in a fine-grained granoblastic groundmass. Small, scattered outcrops of felsic volcanics in the southwestern part of the central area have also been tentatively assigned to this formation (Blake & others, 1982). The age of the Carters Bore Rhyolite has been determined at 1678±1 m.y. (Page, 1978). Three samples have been chemically analysed.

Volcanic rocks of the eastern area

Volcanic units in the eastern area, east of the Pilgrim Fault Zone, are much less voluminous than in the central and western areas, and most sequences are dominated by clastic metasediments or calc-silicate rocks.

The dominant rock types in the **Double Crossing Metamorphics** (Blake & others, 1981b) are gneiss and schist, which are thought to be mainly metamorphosed quartzofeldspathic sediments; however, the formation also contains some probable felsic and mafic metavolcanics (Blake & others, 1979). These rocks, which have been metamorphosed to amphibolite grade, may represent pre-Argylla Formation basement rocks or lateral equivalents of the Argylla Formation and Malbon Group rocks. One felsic gneiss, a possible metavolcanic has been analysed.

The **Marraba Volcanics** (Carter & others, 1961) the older formation of the Malbon Group (Derrick & others, 1976c), consists predominantly of basaltic lava flows and clastic metasedimentary rocks, but locally includes some felsic volcanics in the upper part (Noon, 1978, 1979). The mafic volcanics range from aphyric to porphyritic and from massive to vesicular and amygdaloidal. The grade of metamorphism increases from greenschist in the north to amphibolite in the south. One mafic volcanic rock has been analysed.

The **Mitakoodi Quartzite** (Carter & others, 1961), the younger formation of the Malbon Group, consists of meta-arenite, minor metasiltstone and limestone, and scattered lenses of felsic and mafic metavolcanics (Noon, 1978; Blake & others, 1979; Donchak & others, 1979). The metamorphic grade increases from greenschist in the north to amphibolite in the south. Two felsic volcanics were analysed.

The **Soldiers Cap Group** (Carter & others, 1961; Derrick & others, 1976d) crops out extensively in the eastern part of the region, mainly east of the Cloncurry Fault. It contains amphibolite-grade mica schist, gneiss, meta-arenite, and amphibolite bodies, which are thought to represent both extrusive lavas and intrusive metadolerites (Blake & others, 1979). Minor felsic volcanics are represented by metarhyolite and possibly garnetiferous quartzofeldspathic gneiss (Donchak & others, 1979). The age of the Soldiers Cap Group is uncertain. Metabasalts within the group have been correlated with the Marraba Volcanics and Eastern Creek Volanics (Plumb & others, 1980), but Blake (1980) suggested that the Eastern Creek Volcanics may be older than some of the volcanics of the Soldiers Cap Group. Three metabasites and one quartzofeldspathic gneiss have been analysed.

The main rock types in the **Kuridala Formation** (Carter & others, 1961), part of the Mary Kathleen Group (Derrick & others, 1977b) are metamorphosed interbedded greywacke, siltstone, and shale. The formation locally includes some metarhyolite containing small phenocrysts of quartz and alkali feldspar, associated agglomerate and bedded tuff, as well as minor basaltic volcanics (Blake & others, 1979; Donchak & others, 1979). Porphyroblastic garnet, andalusite, and staurolite have developed in the metasediments, indicating metamorphism to amphibolite grade. One metabasalt was analysed.

Calc-silicate granofels and massive calc-silicate breccia of the **Doherty Formation** in the eastern area were previously mapped as Corella Formation (*see* Blake & others, 1981b). The formation also contains lensoid bodies of metarhyolite up to 200 m thick and scattered bands of possibly amygdaloidal metabasalt and para-amphibolite (Blake & others, 1981b). The Doherty Formation has been regionally metamorphosed to amphibolite grade. Two metarhyolite samples have been analysed, from separate lenses, as well as two metabasites.

A small body of greenschist-grade metabasalt, not chemically analysed, occurs within the **Staveley Formation** (Blake & others, 1981b), a unit consisting predominantly of calcareous metasedimentary rocks.

Geochemistry

The volcanic rocks of the region have been regionally metamorphosed to either greenschist or amphibolite grade, and are commonly extensively recrystallised; hence element abundances, especially those for the more mobile elements, may be expected to depart significantly from original concentrations, particularly in the more extensively recrystallised rocks. However, the general consistency of element trends on variation diagrams shown by the various suites, some of which include samples from widely scattered locations throughout the Duchess-Urandangi region, suggests that although some remobilisation of elements, especially alkali elements, may have occurred, most analysed specimens are close to their original compositions. Wilson (1978) and Glikson & Derrick (1978), in studies of equivalent volcanic formations to the north of the Duchess-Urandangi region, also concluded that apart from some mobility of alkali elements the chemical compositions of most specimens have been little changed by metamorphism.

Felsic volcanics

Five major chemically distinct cogenetic groups or suites of felsic volcanics have been recognised in the Duchess-Urandangi region. The five suites, named after the main stratigraphic unit in which they are represented are the Leichhardt, Argylla, Bottletree, Duchess-Corella, and Carters Bore. All volcanic rocks of a particular suite are chemically, but not necessarily stratigraphically, related (*see* Chappell, 1979).

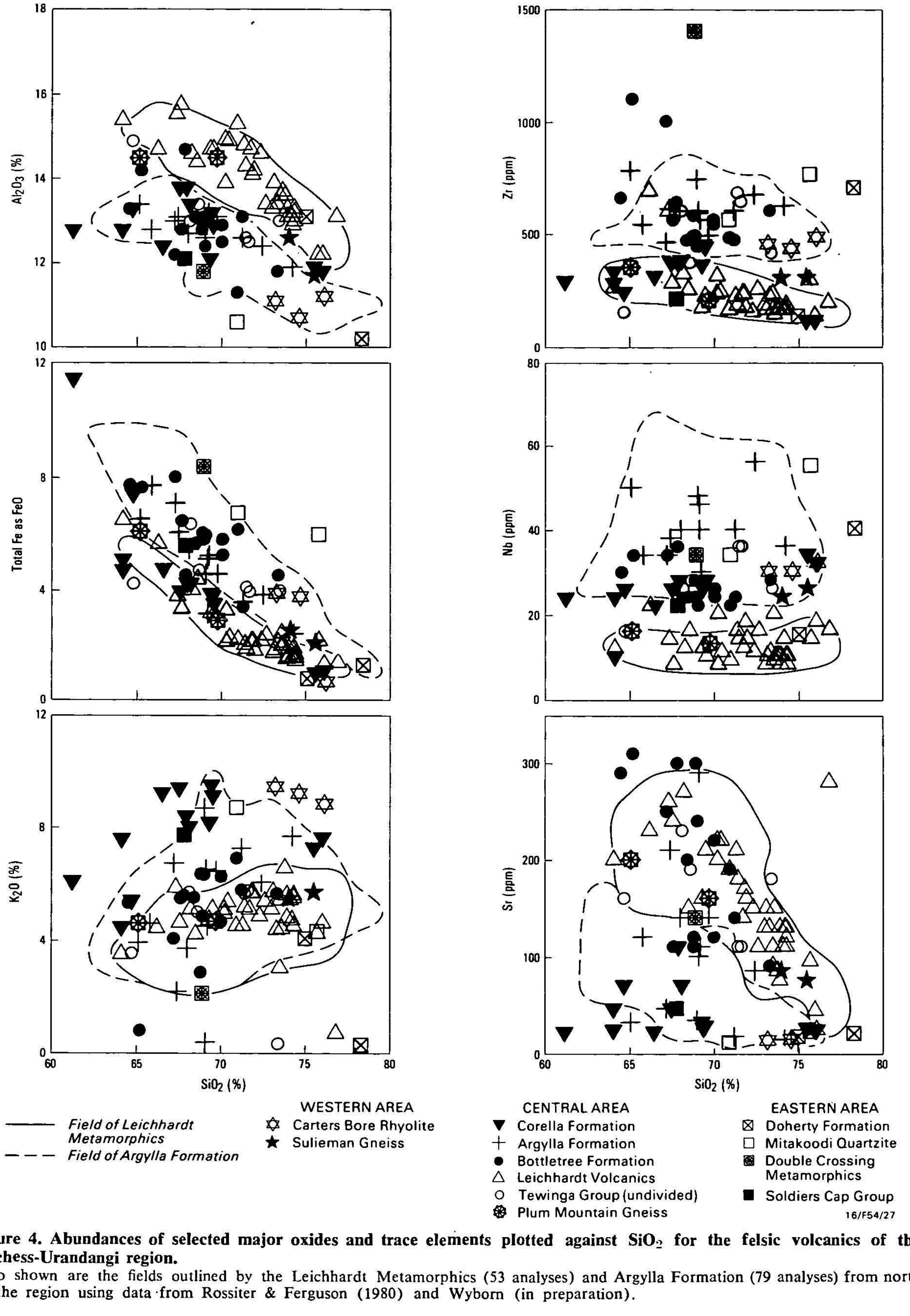

Figure 4. Abundances of selected major oxides and trace elements plotted against SiO_2 for the felsic volcanics of the Duchess-Urandangi region.

Also shown are the fields outlined by the Leichhardt Metamorphics (53 analyses) and Argylla Formation (79 analyses) from north of the region using data from Rossiter & Ferguson (1980) and Wyborn (in preparation).

Table 1. Representative chemical analyses of felsic volcanics from the Duchess-Urandangi region.

	Leichhardt Volcanics		*Argylla Formation*		*Bottletree Formation*		*Corella Formation*		*Carters Bore Rhyolite*		
No. of samples or sample numbers*	34		13		19		15		7653–1143A	7653–1143B	7653–1143C
	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s			
SiO_2	72.36	2.59	69.03	2.52	70.00	3.60	67.40	4.24	76.10	74.60	73.20
TiO_2	0.23	0.11	0.62	0.20	0.64	0.15	0.48	0.24	0.47	0.45	0.44
Al_2O_3	13.84	0.86	12.82	0.38	11.93	2.97	12.88	0.67	11.20	10.70	11.10
Fe_2O_3	1.19	0.50	3.04	1.24	2.71	1.34	3.23	2.13	0.49	3.75	3.88
FeO	1.18	0.86	2.05	0.81	3.19	0.80	1.64	0.95	0.24	0.35	0.35
MnO	0.03	0.02	0.04	0.03	0.06	0.02	0.05	0.08	0.01	0.01	0.01
MgO	0.45	0.31	0.56	0.36	0.45	0.26	0.61	0.28	1.02	0.13	0.13
CaO	1.60	0.64	1.68	1.14	2.43	0.98	1.74	1.13	0.24	0.09	0.09
Na_2O	2.90	0.58	2.55	0.95	2.10	0.81	1.67	1.00	0.20	0.10	0.16
K_2O	4.84	0.96	5.52	1.70	4.76	1.60	7.71	1.58	8.82	9.20	9.44
P_2O_5	0.06	0.03	0.15	0.09	0.14	0.06	0.11	0.06	0.15	0.06	0.07
Ba	817	318	856	503	1483	523	1194	332	210	200	170
Rb	197	53	190	53	175	50	241	64	100	130	140
Sr	152	60	89	58	180	74	40	28	24	14	13
Pb	26	23	7	5	18	10	3	3	5	3	<2
Th	29	6	30	6	26	4	33	14	34	26	30
U	6	2	8	3	5	3	10	6	12	4	10
Zr	212	99	607	86	566	143	311	107	480	430	450
Nb	13	4	41	10	27	5	26	6	32	30	30
Y	27	7	77	17	52	14	50	20	46	50	50
La	64	16	87	21	93	19	62	34	90	90	110
Ce	115	40	172	46	175	28	107	56	180	160	190

Major oxides—wt%; trace elements—ppm.
* Where more than 4 samples from a formation have been analysed the mean ($\bar{x}$) of the analyses and standard deviation (s) are given.
n.a. = not analysed.

Table 2. Representative chemical analyses of mafic volcanics from the Duchess-Urandangi region, and some average analyses of mafic igneous rocks from north of the region.

	Cromwell Metabasalt Member[2]		*Pickwick Metabasalt Member*[3]		*Eastern Creek Volcanics*		*Bottletree Formation*		*Undivided Tewinga Group*	*Magna Lynn Metabasalt*			*Corella Formation*
No. of samples or sample numbers[1]	60		15		5		7653–5071	7653–5100	7753–0836	7753–0452	7753–2310	7753–5077C	7753–0148
	$\bar{x}$	s	$\bar{x}$	s	$\bar{x}$	s							
SiO_2	48.25	2.70	49.54	1.18	50.49	3.07	50.20	50.90	49.70	49.60	53.50	49.90	49.60
TiO_2	2.77	0.68	1.43	0.16	1.30	0.49	1.86	1.21	1.97	1.79	1.29	1.40	1.83
Al_2O_3	13.28	1.00	14.09	0.66	14.47	0.81	15.80	15.40	13.30	14.60	14.00	15.10	12.80
Fe_2O_3	5.22	2.08	3.68	0.82	4.99	0.79	6.12	3.14	4.65	3.11	4.07	3.81	5.52
FeO	9.66	1.99	8.35	0.85	6.71	2.10	6.78	8.55	10.30	10.30	6.69	8.08	9.88
MnO	0.23	0.05	0.19	0.04	0.19	0.01	0.19	0.20	0.24	0.23	0.29	0.35	0.18
MgO	4.75	1.37	6.47	0.90	6.62	1.95	2.62	5.92	5.70	6.04	6.20	7.04	4.40
CaO	7.50	1.66	8.61	1.26	9.51	2.29	11.70	10.80	8.73	10.00	5.99	7.97	8.06
K_2O	1.63	0.93	1.71	0.44	1.04	0.52	0.70	0.33	0.83	0.60	2.21	1.52	1.18
Na_2O	2.44	0.82	2.46	0.61	2.70	0.44	1.35	1.65	1.65	1.94	2.46	3.12	3.68
P_2O_5	0.45	0.22	0.15	0.03	0.13	0.07	0.53	0.20	0.19	0.20	0.18	0.20	0.23
Ba	443	352	314	145	239	109	380	170	310	140	520	330	210
Rb	64	49	55	13	30	23	26	3	22	11	65	70	24
Sr	160	59	187	41	181	55	390	260	130	130	180	160	120
Pb	23	16	14	12	37	33	380	160	38	280	140	75	60
Zr	290	72	119	34	120	63	280	170	140	150	160	180	120
Nb	18	5	6	3	6	4	22	14	14	16	18	18	14
Y	51	12	27	7	26	11	34	26	28	30	32	32	26
La	41	24	32	12	38	25	40	35	15	50	30	30	30
Ce	97	27	47	13	42	19	180	55	30	40	80	70	90

Major oxides—wt%; trace elements—ppm.
1. Where more than 4 samples from a formation or member have been analysed the mean ($\bar{x}$) of the analyses and standard deviation (s) are given.
2. Analyses of the Cromwell Metabasalt Member of the Eastern Creek Volcanics from Glikson & Derrick (1978) and Wyborn (in preparation).
3. Analyses of the Pickwick Metabasalt Member of the Eastern Creek Volcanics from Glikson & Derrick (1978) and Wyborn (in preparation).
4. Analyses of Soldiers Cap Group metabasites from Glikson & Derrick (1978).
n.a. = not analysed.

For total Fe, TiO_2, CaO, K_2O, Al_2O_3, Sr, Pb, Th, U, Zr, Nb, Y, and Zn the distinction between the suites is quite marked at similar SiO_2 values. These differences for selected elements are shown on Harker variation diagrams (Fig. 4). Other plots, not presented here, show that Y has a similar trend to Nb, that TiO_2 follows FeO, that Pb and CaO follow Sr, that Th and U show trends similar to that of K_2O, and that Al_2O_3 and Zn have distinctly different trends, when plotted against SiO_2. The fields defined by samples from the Leichhardt Metamorphics and Argylla Formation collected north of the Duchess-Urandangi region are

Table 1 continued

Plum Mountain Gneiss		*Mitakoodi Quartzite*		*Double Crossing Metamorphics*	*Undivided Tewinga Group*			*Sulieman Gneiss*		*Soldiers Cap Group*	*Doherty Formation*	
7920–5314	7753–2551	8053–0099	8053–2040A	7853–4709	7753–2013	5 $\bar{x}$	s	7753–2364B	7853–2359	7853–1105	7853–0494	7853–0496
65.10	69.70	70.90	75.70	68.90	64.70	70.62	2.22	74.00	75.50	67.80	78.30	75.00
0.79	0.39	0.54	0.50	0.47	0.48	0.54	0.14	0.43	0.28	0.67	0.17	0.13
14.50	14.50	10.60	8.95	11.80	14.90	12.90	0.36	12.60	11.70	12.10	10.20	13.10
0.48	0.17	5.82	4.25	6.18	1.04	2.42	0.43	0.42	0.32	1.65	0.82	0.58
5.65	2.74	1.48	2.10	2.80	3.29	2.41	1.09	2.15	1.78	4.08	0.53	0.28
0.07	0.04	0.01	0.02	0.06	0.06	0.07	0.02	0.04	0.03	0.26	0.02	0.02
1.26	0.94	0.12	0.17	0.71	3.93	0.56	0.43	0.55	0.40	0.53	0.19	0.20
3.25	2.07	0.23	0.50	1.92	3.37	1.78	0.40	1.40	0.88	2.82	1.44	0.60
2.50	2.70	0.32	2.55	3.19	2.85	3.23	1.34	2.90	1.90	0.77	5.66	5.04
4.60	4.66	8.70	4.30	2.10	3.53	4.48	2.35	5.47	5.69	7.72	0.28	4.05
0.19	0.15	0.13	0.09	0.05	0.11	0.23	0.27	0.10	0.07	0.17	0.04	0.05
1300	600	1250	1100	580	450	1042	632	700	880	1100	30	250
170	250	140	55	46	190	200	102	230	210	280	2	90
200	160	11	22	140	160	164	53	85	75	46	20	17
19	19	<2	3	16	28	50	44	13	20	50	<2	<2
24	22	22	42	18	n.a.	31	2	30	42	n.a.	36	36
6	4	8	10	4	8	4	2	<4	4	n.a.	4	<4
350	200	560	760	1400	150	540	141	300	300	210	700	130
16	13	34	55	34	16	30	5	24	26	22	40	15
20	12	36	60	90	7	54	20	36	38	36	120	38
90	50	25	20	90	45	86	21	90	120	30	80	<20
130	92	75	25	200	70	166	47	160	220	60	160	20

Table 2 continued

Oroopo Metabasalt		*Jayah Creek Metabasalt*			*Saint Ronans Meta-morphics*	*Sulieman Gneiss*	*Soldiers Cap Group*[‡]		*Soldiers Cap Group*			*Marraba Vol-canics*	*Kuridala Formation*	*Doherty Formation*	
7853–3020	7953–2376A	7853–2405D	7853–2408A	7853–3035	7953–2034	7953–2477	25 $\bar{x}$	s	7853–0166A	7853–4666	7853–4365	7853–4346A	7853–0821	7853–0065F	7853–0072C
54.50	51.00	52.80	52.40	56.70	51.40	49.60	48.69	2.57	48.30	48.80	49.30	51.10	50.80	49.20	50.10
0.87	0.92	1.02	1.21	1.25	0.92	1.56	1.62	0.61	2.85	1.62	1.43	2.03	1.42	2.23	1.59
13.20	14.40	14.30	14.30	13.90	14.90	15.10	14.04	1.81	12.90	13.70	13.90	12.80	13.70	12.10	12.50
2.51	4.93	3.84	6.43	4.36	3.61	6.65	4.41	1.82	0.48	5.26	0.34	5.95	4.73	6.01	7.55
7.67	6.18	6.67	5.29	7.33	7.43	5.39	9.68	3.02	14.10	10.00	11.20	9.37	7.14	9.02	6.65
0.17	0.14	0.20	0.17	0.14	0.18	0.19	0.23	0.08	0.49	0.21	0.24	0.21	0.47	0.15	0.12
6.61	6.14	6.10	4.60	5.65	6.49	6.80	5.40	1.44	5.85	5.40	6.50	5.14	5.87	4.96	5.20
10.70	9.06	9.48	9.61	3.95	9.55	10.20	10.21	2.96	9.10	8.25	11.20	7.83	8.67	8.78	8.80
0.22	1.48	1.32	0.54	0.85	0.65	0.36	0.82	0.65	1.72	0.61	0.73	0.54	0.49	0.81	1.12
1.51	2.00	1.70	3.34	2.86	2.20	1.88	2.57	1.32	1.03	3.77	2.66	2.20	4.12	3.89	4.90
0.10	0.16	0.14	0.17	0.14	0.13	0.19	0.16	0.07	0.30	0.17	0.15	0.19	0.12	0.19	0.18
55	350	460	360	460	240	170	247	196	200	140	100	150	780	410	150
2	32	34	17	48	22	10	28	28	85	16	20	15	7	26	24
120	230	130	230	110	190	190	186	113	70	60	150	110	300	120	95
65	5	120	60	36	150	13	8	4	5	<2	<2	22	38	36	26
70	130	140	160	130	110	100	137	45	170	120	95	140	80	150	140
8	8	16	16	14	14	16	n.a.		7	5	5	14	12	16	6
17	26	22	26	22	18	24	33	7	38	36	18	36	26	34	28
30	20	60	30	20	30	20	68	12	<20	<20	<20	15	40	25	40
20	30	70	60	50	60	20	n.a.		20	20	20	35	50	60	75

also shown on Figure 4. Representative analyses and average analyses of the various felsic volcanic suites and units are listed in Table 1.

Leichhardt suite. The Leichhardt suite consists of volcanics from the Leichhardt Volcanics in the Duchess-Urandangi region and from the stratigraphically equivalent and chemically indistinguishable Leichhardt Metamorphics to the north. Compared to the other suites the Leichhardt suite is characterised by low Y, Zr, Nb, TiO_2, and total Fe contents, relatively low K_2O, Th, and U abundances, relatively high Al_2O_3, Pb, Sr, Na_2O, and CaO contents, and intermediate Zn values. When plotted against SiO_2, most elements show inverse linear trends that are identical to those shown by the Kalkadoon Granite (Wyborn & Page, in preparation). The two samples from the Plum Mountain Gneiss also plot with the Leichhardt suite. However, it is difficult to distinguish felsic intrusive units from volcanics in the Plum Mountain Gneiss, and the samples analysed may be of granite or intrusive feldspar porphyry. The formation probably contains cogenetic intrusives and extrusives that are the highly metamorphosed equivalents of the Leichhardt Volcanics and Kalkadoon Granite.

Argylla suite. The Argylla suite consists mainly of felsic volcanics from the Argylla Formation. It is distinguished by high Zr, Nb, Y, TiO_2, and total Fe values, relatively high K_2O, Th, and U values and low Na_2O, Al_2O_3, Pb, Sr, and Zn contents. The Argylla suite includes the two analysed samples of felsic volcanics from the Mitakoodi Quartzite, as well as Argylla Formation volcanics from north of the Duchess-Urandangi region. The sample of Double Crossing Metamorphics plots with the Argylla suite except for TiO_2 values, which are relatively low, and Sr and Pb values, which are relatively high.

Bottletree suite. This suite is represented by felsic volcanics of the Bottletree Formation. Like the Argylla suite, it has high Zr, Nb, Y, TiO_2, and total Fe contents, relatively high K_2O, Th, and U values, and low Al_2O_3 contents. However, CaO, Sr, and Pb contents are significantly higher in the Bottletree suite, and are similar to those for the Leichhardt suite. Zn values are also distinctly high.

Duchess-Corella suite. This suite consists of volcanics from the Corella Formation of the Duchess belt. Nb and Y contents are high, as in the Argylla and Bottletree suites, but TiO_2, Zr, and total Fe contents are low and comparable to values for the Leichhardt suite. Sr, CaO, Na_2O, and Al_2O_3 contents are also low, and Pb is exceptionally low, whereas K_2O, Th, and U values are relatively high. This suite is spatially associated with the Wonga Batholith, which is made up of numerous chemically distinct plutons, but there are insufficient data available to establish a cogenetic relationship between these volcanics and any plutons of the Wonga Batholith.

Carters Bore suite. This suite contains the volcanics of the Carters Bore Rhyolite. The three rocks analysed have SiO_2 contents ranging from 73.2 to 76.1 per cent, and are characterised by very high K_2O and low Al_2O_3, Ba, Pb, Sr, Na_2O, and CaO contents; TiO_2 and MgO contents are also anomously high for such siliceous rocks. Although of minor occurrence in the Duchess-Urandangi region, the Carters Bore Rhyolite is probably a correlative of the Fiery Creek Volcanics (Hutton & others, 1981), which contain chemically similar felsic volcanic rocks (*see* analyses listed in Wyborn, in preparation).

Other felsic volcanic compositions

Undivided Tewinga Group (central area). Of the six analysed samples from the undivided Tewinga Group, one, that of a metadacite (77532013, Table 1) from an age-determination site (Page, in preparation), is indistinguishable both in age and chemistry from felsic volcanics of the Leichhardt suite. The remaining five analyses (Table 1) are unlike either the Leichhardt or Argylla suites: their high TiO_2, Zr, Nb, and Y, and low Al_2O_3 contents distinguish them from the Leichhardt suite, and their Pb, Sr and CaO contents are too high for the Argylla suite. Instead, they are closer to the Bottletree suite, although their CaO and total Fe contents are slightly lower.

Sulieman Gneiss (western area). The two analyses of Sulieman Gneiss plot close to the limits of the field for the Leichhardt suite except for their anomalously high Nb values. TiO_2, CaO, Zr, Y, and Ce plot close to the upper limits of the field defined by the Leichhardt suite.

Soldiers Cap Group (eastern area). The analysed sample of quartzofeldspathic gneiss from the Soldiers Cap Group has low Sr, Y, Zr, and Al_2O_3 and high TiO_2, total Fe, and K_2O contents and does not fit into any of the five main suites recognised.

Doherty Formation (eastern area). One (the age-determination sample) of the two analysed samples of metarhyolite from the Doherty Formation is enriched, and the other significantly depleted in incompatible elements. No clear genetic relationship has been discerned between these metarhyolites and plutons of the adjacent Williams Batholith, or the five major suites of felsic volcanics in the Duchess-Urandangi region.

Mafic volcanics

The mafic volcanics of the region have been less thoroughly sampled than the felsic volcanic units. Most analysed samples plot in the subalkaline field on an alkalies vs silica diagram (Irvine & Baragar, 1971), and show a trend of iron enrichment on an AFM diagram. In Figure 5, selected oxides and trace elements (after the analyses had been recalculated to 100 per cent free of volatiles) are plotted against M′ number, where $M' = 100\ Mg/Mg{+}0.85\ (Fe^{2+}{+}Fe^{3+})$ atomic (after Cox, 1980). Decreasing values of M' reflect fractionation of liquidus or near-liquidus phases. Differentiation Index (D. I., Thornton & Tuttle, 1960), which sums the (CIPW) normative salic components, was not used, because most of the lower-grade mafic volcanics contain abundant albite ± biotite, indicating probable mobilisation of the alkali elements and spurious D. I. values. The fields defined in Figure 4 by mafic volcanic rocks from north of the Duchess-Urandangi region are based on data obtained from Glikson & Derrick (1978) and Wyborn (in preparation). These data indicate that the Cromwell Metabasalt Member of the Eastern Creek Volcanics is characterised by significantly higher concentrations of TiO_2, P_2O_5, Zr and Y than the Pickwick Metabasalt Member, and that their respective fields are essentially mutually exclusive when these oxides and trace elements are plotted against M' (Fig. 5). The Soldiers Cap metabasites show compositional overlap with the Pickwick Metabasalt Member, but include some more highly fractionated variants. Average and representative analyses of mafic volcanic rocks from the Duchess-Urandangi region and the region to the north are listed in Table 2.

Central area. Analysed samples of metabasalt from the Eastern Creek Volcanics, Magna Lynn Metabasalt, Bottletree Formation and Corella Formation from the central area plot within the fields defined by analyses of Pickwick Metabasalt Member and Soldiers Cap Group from north of the Duchess-Urandangi region, except for one sample from the Bottletree Formation, which has anomously high P_2O_5 and Zr contents.

Western area. Mafic volcanic samples from the Jayah Creek Metabasalt, Oroopo Metabasalt, Saint Ronans Metamorphics, and Sulieman Gneiss are chemically similar to those of the central area, and hence to the Pickwick Metabasalt Member.

Eastern area. Analysed mafic volcanics from the Doherty Formation, Kuridala Formation, and Soldiers

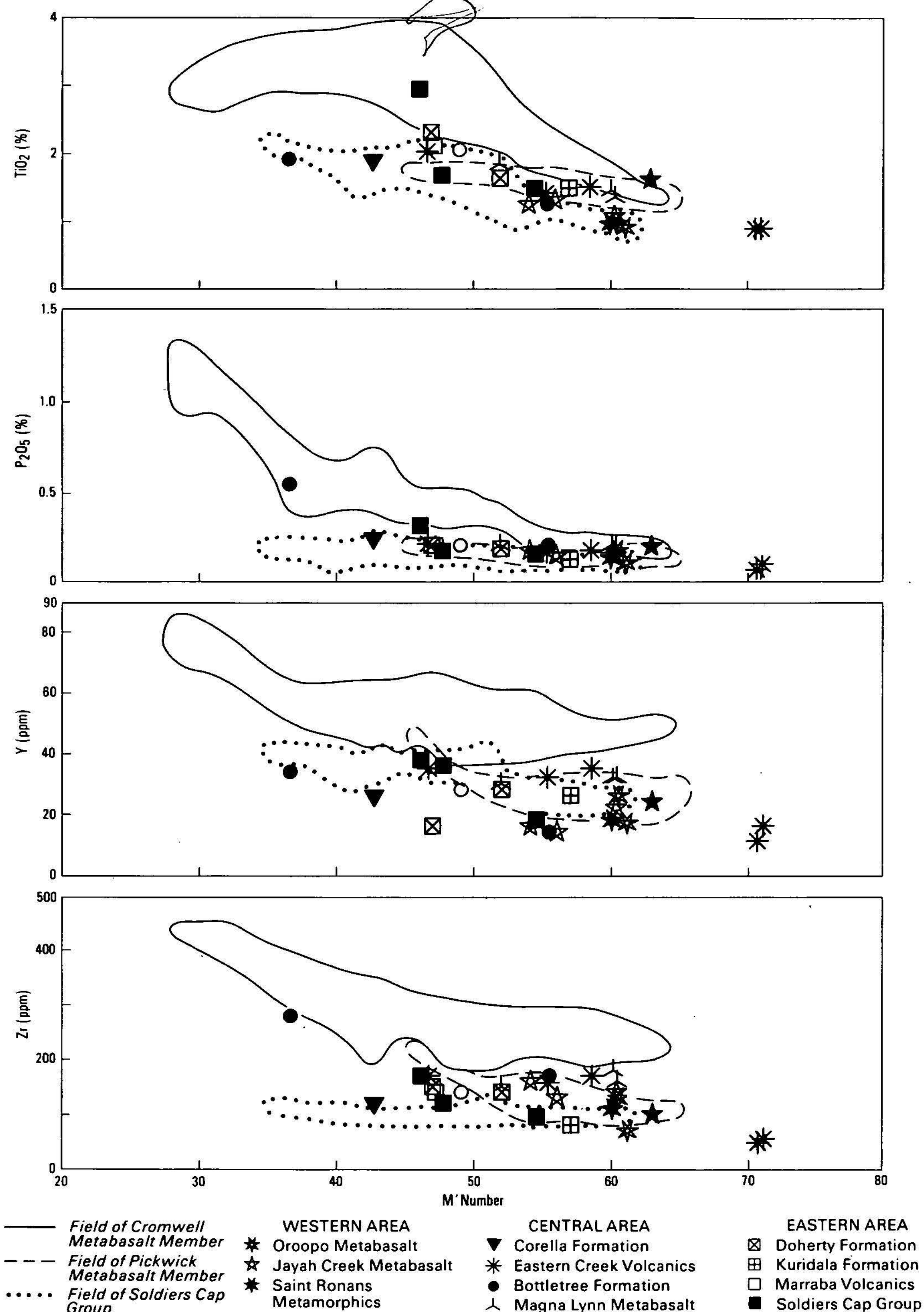

Figure 5. Abundances of selected major oxides and trace elements plotted against M' for the mafic volcanics of the Duchess-Urandangi region.
Also shown are the fields defined by the Cromwell Metabasalt Member (55 analyses) and Pickwick Metabasalt Member (14 analyses), based on data from Glikson & Derrick (1978) and Wyborn (in preparation).

Cap Group are virtually indistinguishable from one another, and are similar to most of the other mafic volcanics of the Duchess-Urandangi region. One sample (78530166, Table 2) from the Soldiers Cap Group has a relatively high TiO_2 content, but the other samples have element concentrations similar to those of the Soldiers Cap Group metabasites analysed by Glikson & Derrick (1978).

Discussion

Felsic volcanics

Source region composition and extent of partial melting are most likely to be the main factors controlling the chemistry of the felsic volcanic suites (*see* Chappell, 1979). According to van der Molen & Paterson (1979) about 30-35 per cent by volume of a source region must melt before the melt fraction separates from the refractory residue. The extraction of such volumes of material will extensively modify the composition of the source region, particularly as the first partial melt contains most of the available minimum-melt component, unless the source region is very extensive, both laterally and vertically. Hence, successive partial melting events involving the same source region are unlikely to repeatedly produce felsic volcanics of similar composition. Consequently, chemically similar felsic volcanics cropping out in the same general area are likely to be similar in age, and may be used in establishing stratigraphic relationships.

Thus, the occurrence of Argylla-suite volcanics in the Mitakoodi Quartzite, and in the Ballara Quartzite to the north of the Duchess-Urandangi region (*see* analyses listed in Wyborn, in preparation) may indicate that there was no major time break between the eruption of the Argylla Formation volcanics and the deposition of the two predominantly sedimentary suites (*see* Blake, 1980, 1981; also Derrick & Wilson, 1981 for some alternative interpretations), or that the Ballara and Mitakoodi Quartzites are possibly even laterally equivalent to parts of the Argylla Formation.

The close similarity in chemical composition of some quartzofeldspathic gneissic rocks to less-metamorphosed felsic volcanic rocks may indicate that the gneissic rocks are the more extensively deformed equivalents of the felsic volcanics, rather than part of a much older unrelated sequence. In this regard, five of the six analysed samples of felsic gneiss from the undivided Tewinga Group are chemically similar to the Bottletree suite and hence may be of similar age, rather than part of a much older sequence, as favoured by Blake (1980).

However, not all felsic volcanic units of similar age necessarily come from the same source region, especially if they are exposed in geographically separate areas. It is highly likely that the composition of the source regions will change, at least slightly, from one area to another. Thus, although the Bottletree and Argylla Formations are closely similar in age, the felsic volcanics of the Bottletree Formation are mainly dacites and relatively enriched in Pb, Ca, Sr, FeO, and Zn, compared with those (mainly rhyolites) of the Argylla Formation. These differences indicate that the source region for the Bottletree Formation felsic volcanics was more feldspar-rich and possibly more reduced than that for the Argylla Formation.

Mafic volcanics

Although only a few analyses from each formation are available, it does appear that the mafic volcanics of the region are chemically very similar to one another. They are characterised by low and uniform contents of most incompatible elements (Ti, P, Zr, and Y), and in this respect are similar to many of the basaltic lava flows (continental tholeiites) of the Karroo province, southern Africa (Cox & Hornung, 1966; le Roex & Reid, 1978). However, in one part of the Karroo province, the Nuanetsi border zone, the lavas have relatively high K, Ti, P, Ba, and Sr contents (Cox & others, 1965; Manton, 1968); these occur in a region where volcanism was coincident with strong downwarping (Carmichael & others, 1974).

The eastward progression from rocks of continental tholeiitic affinities characterised by high values of Ti P, K, Zr and Y to rocks of ocean-floor tholeiitic affinities, characterised by low values of these elements, as recorded by Glikson & others (1976) and Glikson & Derrick (1978) in the Mount Isa region, is not apparent in the Duchess-Urandangi region. Basalts of the Cromwell Metabasalt, the basal member of the Eastern Creek Volcanics in the Mount Isa region, have relatively high incompatible-element contents, and like the chemically similar basalts of the Nuanetsi border zone, Karroo province, may have been generated during a strong downwarping event. The apparent absence of this member in the Duchess-Urandangi region may indicate that the downwarping was less intense in the south than farther north.

Tectonic implications

Silica values for the volcanic rocks and their intrusive equivalents in the Duchess-Urandangi region show a well-defined bimodal distribution (Fig. 6). Igneous rocks of intermediate composition, typically the predominant rock types produced above subduction zones at convergent plate boundaries, are rare. A bimodal distribution is generally considered to be a product of extensional tectonics (e.g., Christiansen & Lipman, 1972; Martin & Piwinski, 1972) and implies that the dominant tectonic regime in the Duchess-Urandangi region was a tensional one, which probably resulted in crustal thinning, rifting and high heat flow. The favoured interpretation, that of an extensional tectonic regime, conflicts with the view of Wilson (1978) who stated that the Tewinga Group contains volcanic rocks typical of convergent plate margins.

Conclusions

- Volcanic rocks of felsic and/or mafic composition are present in most Precambrian stratigraphic units in the Duchess-Urandangi region.
- The volcanics have been regionally metamorphosed to amphibolite or greenschist grade.
- The volcanics form a distinctly bimodal suite, indicating that they probably evolved in a tensional tectonic regime.
- Five felsic volcanic suites have been identified. These may be useful time-markers.

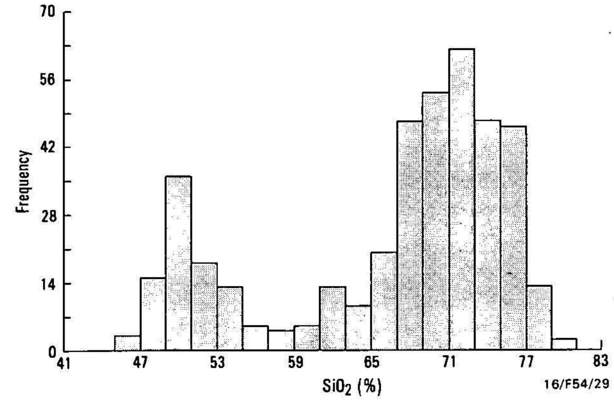

Figure 6. Absolute frequency distribution diagram for SiO_2 based on 412 analyses of igneous rocks from the Duchess-Urandangi region.
Data from Wyborn (in preparation).

- Some felsic rocks from relatively high-grade metamorphic sequences in the region are chemically similar to and may be the more deformed and recrystallised equivalents of felsic volcanics in lower-grade units, and not parts of much older 'basement' sequences.
- The analysed mafic volcanic rocks in the region appear to be chemically uniform and similar to continental tholeiites of the Karroo province of southern Africa. The compositional changes from west to east reported by Glikson & others (1976) and Glikson & Derrick (1978) to the north, are not apparent in the Duchess-Urandangi region.

Acknowledgements

We gratefully acknowledge helpful discussions with J. Knutson, P. J. T. Donchak, D. Wyborn, A. L. Jaques, and in particular, D. H. Blake. Some of the analyses used in this study were of samples collected by D. H. Blake, A. L. Jaques, I. H. Wilson, and G. M. Derrick. R. W. Page kindly provided a preprint and M. Owen wrote the computer programmes used in assessing and plotting the data. R. J. Bultitude publishes with the permission of the Director-General, Department of Mines, Queensland.

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A REVIEW OF THE CORELLA FORMATION, MOUNT ISA INLIER, QUEENSLAND

D. H. Blake

As mapped by previous workers, the Corella Formation is the most extensively exposed formation in the eastern succession of the Proterozoic Mount Isa Inlier. Outcrops consist partly or predominantly of thin-bedded calcareous metasediments, many of which are scapolitic, and occur in three zones. The Corella rocks in the westernmost zone, Zone A, form a well-defined stratigraphic unit overlying felsic volcanics dated at about 1780 m.y., and it is suggested that they be asssigned to a new formation. Those in the central zone, Zone B, probably belong to at least two separate units, one more than 1740 m.y. old and possibly older than 1870 m.y., and one about 1600 m.y. old, 70 m.y. younger than the Mount Isa Group. Zone B contains the type section for the Corella Formation, but this defines neither the top nor the base of the formation, its location is uncertain, and stratigraphic relations of rock types within it are largely unknown. The suggestion is made that, for the present, the Corella Formation in Zone B be downgraded to Corella beds. The Corella rocks in Zone C, to the southeast, can be assigned to two units—the Doherty Formation, which contains rhyolite dated at about 1720 m.y., and the less-metamorphosed and probably younger Staveley Formation.

Introduction

The status of the Corella Formation, a unit of mainly calcareous metasediments, especially calc-silicate rocks, has recently become a contentious issue in interpretations of the Proterozoic geological history of the Mount Isa Inlier. The problem is whether the formation represents a single unit with a restricted time range, as favoured by Derrick and co-workers (e.g., Derrick & Wilson, 1981), or two or more stratigraphic units of widely different ages, as suggested by Blake (1980, 1981).

According to Carter & others (1961) and most later workers (e.g., Plumb & Derrick, 1975; Derrick & others, 1977a; Plumb & others, 1980, 1981), the Mount Isa Inlier (Orogen) consists of a northerly trending belt of mainly igneous basement rocks flanked on either side by stratigraphically equivalent younger cover rocks, which are generally known as the western and eastern successions (see Blake, 1980, for an alternative view). The Corella Formation is confined to the eastern succession.

The Corella Formation was defined by Carter & others (1961), following a broad reconnaissance survey of the Mount Isa region in the 1950s by geologists from the Bureau of Mineral Resources (BMR) and the Geological Survey of Queensland (GSQ). The original definition was retained, with a few minor modifications, in a recent revision of the Corella Formation by Derrick & others (1977a). In this revision, one of the results of the more detailed survey of the Mount Isa region carried out by BMR and GSQ geologists from 1969 to 1980, the main change was the replacement of part of the Corella Formation west and southwest of Cloncurry by a new formation, the Overhang Jaspilite.

As mapped by Carter & others (1961) and Derrick and co-workers, the Corella Formation is the most extensive formation exposed in the Mount Isa Inlier. It includes almost all the calcareous rocks and calc-silicate rocks found in the eastern succession in the southern part of the Inlier, and has an outcrop area of nearly 5000 km^2. Outcrops of the formation occur in three broad north-south-trending zones: a western zone, here termed Zone A, which lies mainly west of the highly deformed Wonga Belt; a central zone, Zone B, which includes most of the Wonga Belt, as well as a large area to the east; and an eastern zone, Zone C, to the east of the Duck Creek Anticline (Fig. 1). The type section designated by Carter & others (1961) for the formation is in Zone B, and two reference sections selected by Derrick & others (1977a) are in Zone A.

The Corella Formation is currently correlated by Derrick and co-workers with the Quilalar Formation of the western succession (Plumb & others, 1980; Derrick & others, 1980), a unit which is conformable or disconformable on the Haslingden Group and separated from the overlying Mount Isa Group by a regional unconformity. It has also been correlated with the Mount Isa Group (Plumb & Derrick, 1975; Derrick & others, 1977b), and with the Myally Beds (Carter & others, 1961), now the Myally Subgroup of the Haslingden Group.

Corella Formation in Zone A

In Zone A the Corella Formation is exposed in a series of mainly tight, upright, major synclines and half-synclines (one limb removed by faulting parallel to the axial plane), where it consists predominantly of grey calcareous and now scapolitic sedimentary rocks that have been regionally metamorphosed to greenschist and amphibolite grades; the metamorphism shows a general increase in grade eastward towards the Wonga Belt. The Corella Formation in this zone is readily divisible into three conformable unnamed members: a lower mainly pelitic member, a middle mainly arenaceous member, and an upper mainly pelitic member (Derrick & others, 1977a; Wilson & others, 1977). In PROSPECTOR*, but not in MARY KATHLEEN to the south, minor metabasalt is present at the top of the upper member.

The maximum thickness of the Corella Formation in Zone A is about 1260 m, and stratigraphic sections in which thicknesses of more than 1000 m are present are believed by Derrick & others (1977a) to be nearly complete; i.e., in these sections there has been little post-depositional erosion of the Corella Formation. The three unnamed members of the formation show considerable variations in thickness, and this is attributed to lateral facies changes (e.g., Wilson & others, 1977).

* Names of 1:100 000 Geological Sheet areas are given in capitals.

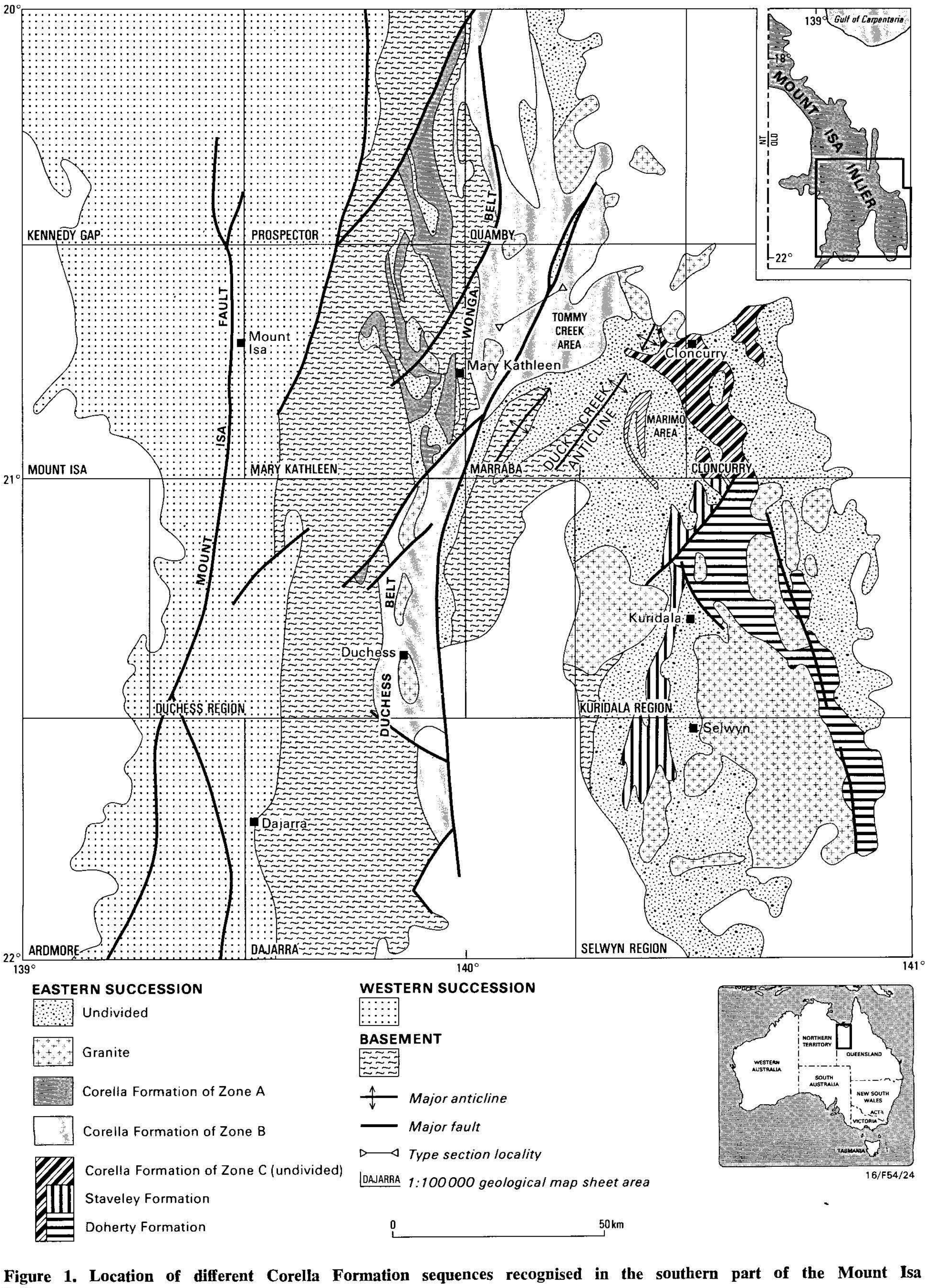

Figure 1. Location of different Corella Formation sequences recognised in the southern part of the Mount Isa Inlier.

The Corella Formation of Zone A corresponds to the 'young' Corella Formation of Blake (1980), and may be a correlative of the Quilalar Formation to the west, as suggested by Derrick & others (1980). It overlies the Ballara Quartzite conformably and is overlain disconformably and locally with angular unconformity by the Deighton Quartzite. As it has a distinctive lithology and mappable upper and lower contacts, it is a well-defined stratigraphic unit.

The Zone A Corella Formation postdates felsic volcanics of the Argylla Formation, dated at about 1780 m.y. (Page, 1978, in prep.), which underlie the Ballara Quartzite and are generally considered to be part of the basement underlying the eastern and western successions (e.g., Plumb & others, 1980). It is probably older than the Mount Isa Group, dated at about 1670 m.y. (Page, 1981), as this group is disconformable on the Surprise Creek Formation, a unit that overlies the Quilalar Formation and is considered by Derrick & others (1980) to be a correlative of the Deighton Quartzite. Several igneous bodies (Hardway Granite, dolerite sills) intrude the Corella Formation in Zone A, but the ages of these have yet to be determined.

The general concordance (parallelism of bedding) and absence of metamorphic unconformities in the sequence Argylla Formation/Ballara Quartzite/Corella Formation/Deighton Quartzite in Zone A, and similarly in the sequence Haslingden Group/Quilalar Formation/Surprise Creek Formation/Mount Isa Group of the western succession to the west, in the southern part of the Mount Isa Inlier, indicate that the regional metamorphism and tight folding affecting all these units probably took place some time *after* the deposition of the Mount Isa Group. There is no evidence to suggest that a major tectonic event involving greenschist to amphibolite grade regional metamorphism occurred in this part of the Mount Isa Inlier during the period from 1780 m.y. ago, the age of the Argylla Formation, or even from about 1870 m.y. ago, the age of felsic volcanics (Leichhardt Metamorphics/Volcanics) underlying the Argylla Formation, to about 1670 m.y. ago, when the Mount Isa Group was deposited (Blake, 1981).

Corella Formation in Zone B

The Corella Formation, as mapped in Zone B, forms a belt up to 35 km wide, consisting mainly of banded and brecciated calc-silicate rocks, quartzite and other meta-arenites, felsic and mafic metavolcanics, mica schist, marble, and carbonaceous metasiltstone. It differs from that in Zone A in the following respects:

- It is much thicker: a *minimum* thickness of 2000 m near Mary Kathleen (Derrick & Wilson, 1981) and a possible maximum thickness of more than 4000 m (Derrick, 1980) contrasts with a *maximum* thickness of about 1260 m for the Corella Formation in Zone A.
- It contains abundant felsic and mafic volcanics: these are widespread in DUCHESS REGION (Bultitude & others, in prep.) and DAJARRA (Blake & others, 1981c), and also in MARRABA (Derrick, 1980), where, in my view, much of the unit mapped as intrusive Tommy Creek Microgranite is metamorphosed felsic volcanics that are interlayered with calcareous metasediments (see also Derrick, 1980, p. 14) and many of the amphibolite and metadolerite bodies within the Corella Formation are extrusive rather than intrusive.
- The metasediments are generally more calcareous (Derrick & Wilson, 1981).
- The formation is not readily divisible into lower and upper pelitic members and a middle arenaceous member (Derrick, 1980), and comprises a complex of lithologic units rather than stratigraphic members—as is evident on MARRABA (Derrick, 1980) and QUAMBY (BMR, 1980) geological maps. Relations between these lithologic units are often uncertain.
- It is generally more deformed and metamorphosed.
- Its stratigraphic relations are not clearly defined, and the presence in Zone B of correlatives of the Ballara and Deighton Quartzites, which stratigraphically bound the Corella Formation in Zone A, is open to doubt. Within the Wonga and Duchess Belts in the west of Zone B some discontinuous bands and lenses of quartzite occur at or close to concordant contacts between the Corella Formation and felsic gneisses to the west, and those in the Wonga Belt have been assigned to the Ballara Quartzite by Derrick (1980) and Derrick & Wilson (1981); however, this correlation is questioned by Blake (1980, 1981). According to Derrick & Wilson (1981), facing evidence indicates that the Corella rocks overlie the felsic gneisses, but such evidence may be of doubtful reliability where the rocks are intensely deformed and metamorphosed. To the east, in the southern part of MARRABA (Derrick, 1980), the Corella Formation is reported to overlie, either conformably or disconformably, the Overhang Jaspilite, a formation consisting largely of thin-bedded calcareous metasediments, like the Corella Formation, but contacts between these two units in Zone B are invariably marked by breccia, possibly of tectonic origin. In the north, in QUAMBY, Corella rocks are reported to be overlain, probably conformably, by the Knapdale Quartzite, a possible correlative of the Deighton Quartzite (Derrick & others, 1977c; Wilson & others, 1979), but this formation is not exposed to the south.

Clearly, the Corella Formation in Zone B is not such a well-defined stratigraphic unit as the Corella Formation of Zone A, and the possibility that two or more sequences of significantly different ages are represented should not be discounted. This possibility is supported by U-Pb zircon age data obtained by Page (1978, 1979, 1981, in prep.) on spatially associated intrusive and extrusive igneous rocks: in Zone B the Corella Formation is intruded by several granitic bodies, including the Burstall Granite, northeast of Mary Kathleen, dated at 1720–1740 m.y., and the Tommy Creek Microgranite further east, which is dated at about 1600 m.y.; in the Tommy Creek area the formation also includes felsic metavolcanics dated at about 1600 m.y. Hence some Corella rocks in Zone B are probably about 1600 m.y. old, 70 m.y. younger than the Mount Isa Group, and some are probably more than 1740 m.y. old. The older Corella rocks appear to have been deformed and metamorphosed both before and after being intruded by the Burstall Granite and similar granites to the south (e.g. Derrick, 1980; Plumb & others, 1980; Bultitude & others, in prep.), as these granites and probably related pegmatite veins cutting folded Corella rocks are themselves deformed and recrystallised. The later tectonism may be equivalent to that affecting the Corella Formation and underlying Argylla and Leichhardt rocks in Zone A, but the earlier tectonism possibly predates the 1870 m.y. old, Leichhardt rocks, as suggested by Blake (1980, 1981).

In addition to containing relatively old and young rocks, the Zone B Corella Formation may also include rocks of intermediate age, such as correlatives of the Zone A Corella Formation. Distinguishing the potentially different sequences of lithologically similar rocks may be a problem, because of the generally intense deformation and metamorphism in Zone B, and will require additional work in the area. One possible contact between different sequences of Corella rocks is exposed 23 km east of Mary Kathleen, about one hundred metres north of the Barkly Highway. Here, a zone a few metres wide, consisting of angular fragments of calc-silicate rocks, separates tightly folded, thin-bedded calc-silicate rocks to the south from a northerly dipping sequence of interbanded biotite schist, bedded calc-silicate rocks, felsic and mafic metavolcanics, and black slate to the north. The tightly folded sequence is intruded by Burstall-type granite and may be part of the pre-1740 m.y. old Corella Formation (the 'old' Corella Formation of Blake, 1980), whereas the northern sequence includes the felsic volcanics dated at about 1600 m.y. by Page (in prep.). The fragmentary zone separating the two sequences may represent either a major unconformity or a faulted contact.

Type section of the Corella Formation

The type section is the specifically designated sequence of rocks that constitutes the standard for the definition and recognition of a stratigraphic unit; in order to be recognised away from its type section, a unit must have essentially the same lithology and relative stratigraphic position as in its type section (Hedberg, 1976). Hence, the type section is critical in the definition of a stratigraphic unit.

The type section for the Corella Formation selected by Carter & others (1961) 'cuts obliquely across strike, and extends from a point half a mile (0.8 km) east of the Federal copper mine, on the Cloncurry-Mount Isa road about 23 miles (37 km) from Cloncurry, thence westerly along the road 2–3 miles (about 5 km) to the old Mary Kathleen mine road, which is then followed for about ten miles (16 km) to an outcrop of Wonga Granite'. The Cloncurry-Mount Isa road is the former main road, in use before the sealed Barkly Highway was completed in the mid-1960s, but the old Mary Kathleen mine road cannot be identified with certainty (Wilson & Hutton, 1980). Hence, the location of the western and central parts of the type section is not clear. As noted by Carter & others (1961) and Derrick & others (1977a), the type section contains many faults, intricate folding, and probable repetitions and absences of strata. Derrick & others (1977a) considered the top of the formation was not defined in the type section and the lower part was poorly represented. However, they proposed that the type section of Carter & others be retained except for about 3 km at its western end, which, they stated, consists of recrystallised felsic volcanics assigned to the Argylla Formation. The type section area contains good exposures of laminated calc-silicate rocks and calc-silicate breccia, and also a variety of other rock types, including mica schist, phyllite, metabasalt, quartzite, metagreywacke, black slate, albitite, and intrusive granite, pegmatite, and metadolerite. However, because of a general lack of sedimentary facing evidence, together with structural complexities, a stratigraphic sequence has yet to be established in this area.

The obvious conclusion is that the type section of the Corella Formation has too many deficiencies to be considered a suitable standard for the definition and recognition of a formation: it defines neither the top nor the base of the unit, its exact location is uncertain, and stratigraphic relations of rock types in it are largely unknown.

The Corella Formation in Zone C

This zone includes the outcrops of Corella-type rocks in the Marimo area of southeast MARRABA (Derrick, 1980), in CLONCURRY to the east (Glikson & Derrick, 1970), and in KURIDALA REGION (Donchak & others, in prep.) and SELWYN REGION (Blake & others, in prep.) to the south (Fig. 1). Two sequences of rocks previously mapped as Corella Formation can be distinguished here, but neither can be correlated with reasonable assurance with the Corella Formation of the type section area in Zone B.

The more extensive of the two sequences crops out in the eastern part of the zone, and in the KURIDALA REGION and SELWYN REGION is now named the Doherty Formation (Blake & others, 1981a, 1981b). It is probably several thousands of metres thick, and consists predominantly of thin-banded calc-silicate rocks (metasediments) and calc-silicate breccia, but it includes small amounts of schist, carbonaceous metasiltstone, metabasalt, and also metarhyolite which is thought to be extrusive and has been dated by the U-Pb zircon method at 1720 ± 7 m.y. (Page, in prep.). These rocks are moderately to tightly folded and have been regionally metamorphosed to amphibolite grade. The Doherty Formation is in contact with other Proterozoic stratigraphic units, none of which are obvious correlatives of any units exposed in Zones A and B. However, it is generally bounded by faults and breccia zones, and its stratigraphic position relative to adjacent units is uncertain. At present, the Doherty Formation is thought to overlie, perhaps conformably, the Soldiers Cap Group, which includes some interbedded calc-silicate rocks, and it may be a correlative of the Kuridala Formation.

The other sequence previously mapped as Corella Formation in Zone C crops out west of the Doherty Formation, and, in the KURIDALA REGION and SELWYN REGION is now assigned to the Staveley Formation, a unit defined by Carter & others (1961) and revised by Blake & others (1981a, 1981b). It consists predominantly of bedded and brecciated sandy and silty sediments, which are commonly calcareous, and includes some limestone and calc-silicate rocks. In general, these rocks have been regionally metamorphosed to greenschist grade only. Delicate sedimentary structures are preserved in many places, and halite casts are present at a few localities. The formation may have a maximum thickness of 2000 m or more, but this is uncertain because of faulting, tight folding, and a lack of marker beds.

The Staveley Formation overlies the Overhang Jaspilite and Answer Slate to the west, either conformably or disconformably, and is overlain, apparently conformably, by the Agate Downs Siltstone, Marimo Slate (with which it also appears to interfinger), and sandstone mapped as possible Roxmere Quartzite (Blake & others, 1981a). Contacts with the Overhang Jaspilite are generally marked by iron and manganese-rich breccia, which may be part of a regolith representing a significant erosional unconformity. North of Kuridala the Staveley Formation is faulted against higher grade metamorphic rocks of the Doherty Formation, and, therefore, is probably the younger unit, although the possibility that the two formations are lateral equivalents cannot be completely discounted. Southwest of Selwyn the Staveley Formation appears to be unconformable on the Kuridala Formation (Blake & others, in prep.). In the Marimo area, in southeast MARRABA, the Marimo Slate sequence includes some calcareous bands, assigned to the Corella Formation (Derrick, 1980), which are probably correlatives of the Staveley Formation: these bands are similar in lithology and relative stratigraphic position to calcareous bands in the Staveley Formation to the south.

In general, the Staveley Formation is more sandy, less calcareous, and less metamorphosed than the Doherty Formation, and its stratigraphic relations are better defined. Both formations are intruded by granites (undated) of the Williams Batholith and by metadolerite and dolerite.

The age of the Staveley Formation is uncertain. If it is disconformable on the Overhang Jaspilite and younger than the Doherty Formation, as is thought likely, it is probably younger than 1720 m.y., and could be similar in age to the Corella sequence dated at about 1600 m.y. in the Tommy Creek area of Zone B—the two sequences occupy similar synclinoria situated on opposite sides of the Duck Creek Anticline.

Conclusions

All the sequences mapped as Corella Formation by Carter & others (1961) and Derrick and co-workers contain calcareous sediments that have been regionally metamorphosed to greenschist and amphibolite grades, and many of these metamorphic rocks are scapolitic. This lithologic similarity appears to have been the main reason for assigning the sequences in Zones A, B, and C to a single formation, the implication being that, in the eastern succession, carbonate deposition took place during a single period of relatively short duration. In contrast, calcareous and especially dolomitic sediments occur at more than one stratigraphic level in the western succession: they are common, for example, in the upper part of the Myally Subgroup (Wilson & others, 1977) and in the overlying Quilalar Formation (Derrick & others, 1980; Derrick & Wilson, 1981), and also in the much younger Mount Isa and McNamara Groups (Hill & others, 1975; Hutton & others, 1981). The stratigraphy of the Mount Isa Inlier, in fact, is characterised by the repetition, at different stratigraphic levels, of similar rock types, such as quartz sandstones, mafic volcanics, felsic volcanics, and calcareous sediments (e.g., Blake, 1980; Plumb & others, 1980, 1981). Consequently, lithology by itself is not a reliable correlation factor.

The other main criteria for correlating geographically separated sequences—stratigraphic relations and similarity in age—do not support the view that the Corella Formation is a single stratigraphic unit. The Corella sequences in the different zones are not in contact with the same units, and U-Pb zircon data indicate that the sequences include rocks ranging in age from pre-1740 m.y. to about 1600 m.y.

The Corella Formation in Zone A is a well-defined stratigraphic unit. Unlike that in the other zones, it comprises three readily identifiable members, it is clearly conformable on the Ballara Quartzite, which overlies the 1780 m.y. old Argylla Formation, and it is overlain by the Deighton Quartzite disconformably and, locally, with angular unconformity. The Zone A Corella sequence may be correlated with the Quilalar Formation of the western succession, and is probably older than the 1670 m.y. old Mount Isa Group. It cannot be correlated with any certainty with the sequence exposed in the type section area of the Corella Formation in Zone B. I suggest, therefore, that this sequence be defined as a new formation, using one of the reference sections proposed by Derrick & others (1977a) as its type section.

The Corella Formation of Zone B is not a well-defined stratigraphic unit. It probably contains two sequences of quite different ages, one older than 1740 m.y. and perhaps older than 1870 m.y. and one about 1600 m.y. old. It may also include other sequences of intermediate age. The type section of the Corella Formation, which is situated in this zone, is not a suitable standard for defining and recognising a stratigraphic unit. Because of these factors, I suggest that the Corella Formation in Zone B be down-graded in status to *Corella beds* until the different sequences within it can be defined as separate formations or until the unit, at least in its type section area, can be shown to be a legitimate formation according to the International Stratigraphic Guide (Hedberg, 1976).

In Zone C the Corella Formation, as mapped previously, comprises two lithologically and stratigraphically distinct sequences. In the KURIDALA REGION and SELWYN REGION these are now assigned to the Doherty Formation, which is probably about 1720 m.y. old, and the Staveley Formation, which is probably somewhat younger, perhaps similar in age to the 1600 m.y. old Corella sequence in the Tommy Creek area of Zone B. I suggest that the Corella rocks of Zone C in MARRABA and CLONCURRY should also be assigned to one or other of these two new formations or, if this is not possible at present, they should be mapped temporarily as Corella beds.

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THE ROLE OF PRE-EXISTING SULPHIDES IN COPPER-ORE FORMATION AT MOUNT ISA, QUEENSLAND

C. W. Robertson[1]

The sulphide deposit at Mount Isa, northwest Queensland, is a siltstone-shale sequence that has been metamorphosed to lower greenschist facies and variously altered by hydrothermal events. Galena and sphalerite, forming the lead-zinc-silver orebodies, and fine-grained pyrite are interbedded with the sediments, but chalcopyrite mineralisation appears to have overprinted these. In the largest copper orebody, the 1100 Orebody, a massive high-grade core of chalcopyrite is developed at the same stratigraphic level as rich pyrite mineralisation; with a reduction in the concentration of pyrite in this core. Cobalt is strongly associated with the copper ores and shows this same relationship. Sulphur isotope values for the chalcopyrite and pyrite are in the same range, indicating a common sulphur source. Sulphur abundances in the pyritic horizons do not increase with increasing copper grade. These factors support the view that sulphur needed for the formation of chalcopyrite and cobalt-rich sulphides was derived from the pre-existing sequence. Those sulphur sources controlled the copper, silica, and cobalt deposition from the mineralising solutions, and provide the link in explaining the spatial relationship of the copper to the lead-zinc-silver ores.

Introduction

The Isa Mine base-metal deposit at Mount Isa, Queensland, is contained in the Urquhart Shales, a sequence of dolomitic shales and siltstones of Middle Proterozoic (Carpentarian) age that has undergone structural deformation and metamorphism to lower greenschist facies. Major folding, with axial plane trends varying from northwest-southeast to north-south, has rotated the whole sequence into a westerly dipping attitude.

Neudert & Russell (1981) have described the depositional environment of the sediments as being shallow water, with intermittent hypersaline and emergent conditions, and they suggested a modern analogue in the lake complex of the Dead Sea graben, including the associated continental sabkhas. McClay & Carlile (1978) found pseudomorphed sulphate evaporites in the dolomite and laminated cherts, and interpreted them as being originally gypsum and anhydrite that crystallised in the sediments prior to compaction.

The basin in which the carbonate-rich sediments were deposited periodically became anoxic, when syngenetic or very early diagenetic fine-grained framboidal pyrite was formed. This fine-grained pyrite is now finely interbedded with the carbonate-rich sediments and faithfully follows the bedding.

The galena and sphalerite-rich beds forming the lead-zinc-silver orebodies are interbedded with the siltstones, shales, and pyritic shales, and are conformable except in those areas where folding has caused redistribution. The relation of the lead-zinc ores to the enclosing and conformable sediments has been well documented by various workers, (Bennett, 1965; Mathias & Clark, 1976), and a syngenetic or very early diagenetic deposition is well established.

A 'silica-dolomite' (Fig. 1) sequence and associated chalcopyrite forming the copper orebodies overprints this sequence and, therefore, pyritic shales, siltstones, and shales are included in the 'silica-dolomite' (Fig. 2). The occurrence of galena and sphalerite in the zone is rare, and would indicate that there was none present originally or that it has been remobilised in the alteration process. The significant features of the 'silica-dolomite' are: a coarsening of the dolomite grain size forming recrystallised dolomitic shale, production of

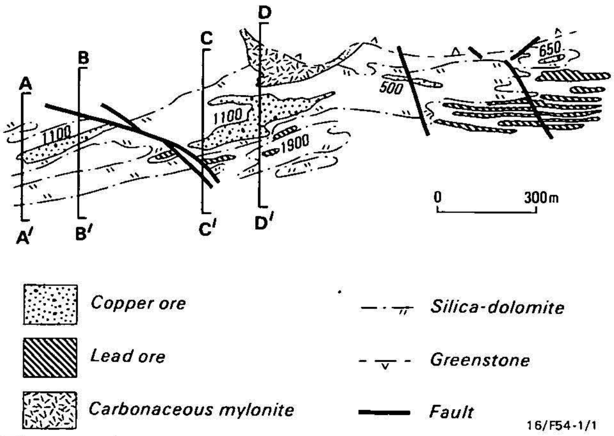

Figure 1. Geological plan of No. 15 Level, Isa Mine.

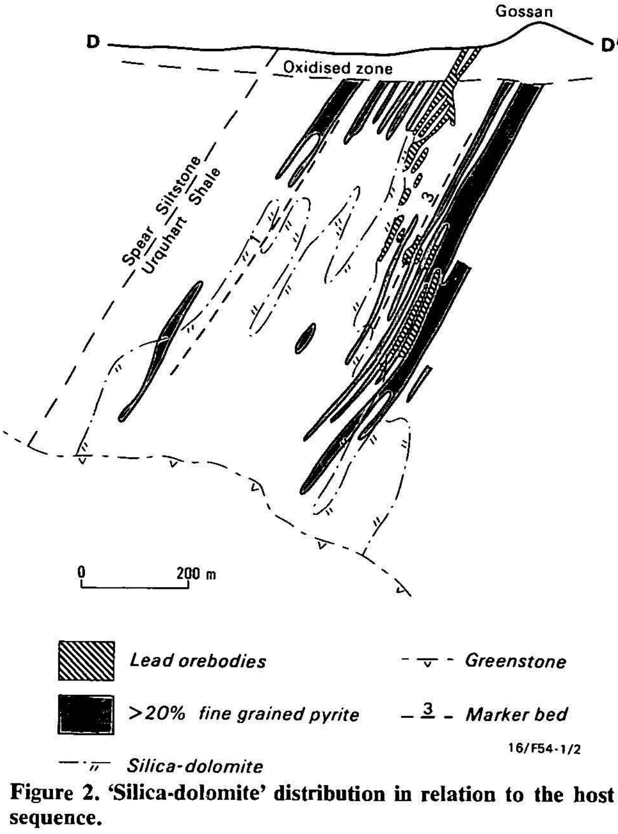

Figure 2. 'Silica-dolomite' distribution in relation to the host sequence.

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dolomite masses with enclosed shale fragments, and, in parts, silicification and brecciation of the shales and siltstones. Full descriptions of the 'silica-dolomite' rock types are presented by Mathias & Clark (1976).

The whole of the Urquhart Shale is truncated at depth by major faulting, which has caused juxtaposition of a greenschist complex, locally termed greenstone, and the Urquhart Shales. The greenstone has been correlated with the Pickwick Metabasalt Member of the Eastern Creek Volcanics by Gulson & others (1981a). The 'silica-dolomite' is widest at the junction of the shales and the greenstone (Fig. 2), interdigitating up dip and along strike with the normal sequence. This geometry indicates that the formation of the 'silica-dolomite' was intimately associated with the fault as the feeder source. The relation of the greenstone to the ore has been complicated by later movements along the fault zone.

A major fine-grained pyrite zone occurs stratigraphically below the lead-zinc sequence (Fig. 3), interdigitating southwards with the 'silica-dolomite' and the cupriferous sequence, and a further fine-grained pyrite zone is intimately associated with the upper lead-zinc-silver orebodies, but is not present southwards.

Thus at Mount Isa, at least three stages of mineralisation occurred: the fine-grained pyrite, the conformable galena and sphalerite, and the overprinting chalcopyrite mineralisation. The timing of the total mineralisation has been variously described. Mathias & Clark (1976) proposed a totally syngenetic origin for all the ores, with a physico-chemical separation of the metals in the basin. Finlow-Bates & Stumpfl (1979) argued for sub-surface deposition of chalcopyrite in a pre-ore breccia, with syngenetic deposition of galena, sphalerite, and pyrite, all from the same ore solution. Gulson & others (1981b) have taken the opposing stance of no relation between the galena-sphalerite and the chalcopyrite.

Trace lead isotope investigations conducted by Gulson & others (1981b) revealed that the isotopic arrays for copper mineralisation intersect the average lead-zinc

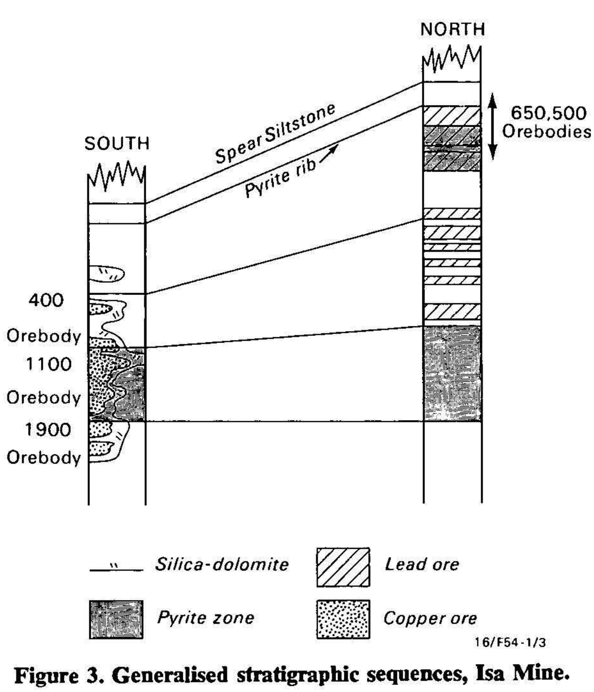

Figure 3. Generalised stratigraphic sequences, Isa Mine.

ore value, and probably represent a variable component inherited from the originally pyritic host shales. The genetic model they presented involved a structural, hydraulic fracturing process or a ductility contrast between the invaded host and the underlying greenstone to develop a fracture zone into which the chalcopyrite was deposited. They concurred with the syngenetic model for the lead-zine-silver ores, but they concluded the copper ore was introduced from brine solutions generated during major regional deformation and metamorphism.

Any genetic model for the Mount Isa deposit has to explain the occurrence of two discrete but spatially close ore types. The geometric arrangement suggests a common bond between the copper and the lead-zinc-silver ores. In consideration of the structural model, the greenstone basement extends well beyond the pre-existing deposit, structural conditions seem similar, and yet, to date, known major copper mineralisation is confined to the same stratigraphic sequence as the lead, zinc, and silver. Lambert (1976) suggested there has to be a reason for the restriction, and he suggested the presence of pyrite would probably be essential for 'fixing' the copper ores.

Investigations into gangue/chalcopyrite relations in the southern 1100 Orebody illustrated the significant influence fine-grained bedded pyrite had on the distribution of copper ore in that area (Robertson, 1975). To establish the significance of this factor in regard to the total copper mineralisation, the gross characteristics of the major copper orebodies have been reviewed and the most significant orebody selected and analysed with respect to copper ore and fine-grained pyrite relationships.

The copper ores

The major copper orebodies described by Mathias & Clark (1976) can be classified simply by dominant host rock lithology, ore disposition, and significant ore mineral associates (Fig. 4). Their sizes may be represented by their percentages of the total known copper reserves. These characteristics show that the orebodies can readily be divided into two types:

Dolomitic disseminated ores

The dolomitic disseminated ores are associated with recrystallised dolomitic shales and dolomitic breccia. The chalcopyrite is generally disseminated amongst the dolomite grains or present as small discontinuous veins. The 650 and 500 Orebodies are included in this type, but being confined by sheared hangingwall and footwall limits, they cannot be related to their adjacent environments.

Pyritic and siliceous massive veined ores

These ores are associated with the original fine-grained pyrite-rich shales and barren shales that have been silicified and brecciated. The chalcopyrite is present in irregular veins grading upwards into massive chalcopyrite. Significantly, this group has a cobalt-copper ore association not seen elsewhere in the sequence, the major cobalt mineral now being cobaltite. This is the most important type of copper ore in the Mount Isa deposit, but the dolomitic type ores have a greater areal distribution.

Number	% known copper resource	HOST SHALE				ORE		Ore associates
		Recrys-tallised	Pyritic	Dolomite breccia	Siliceous breccia	Massive vein	Dissemin-ated	
650, 500		▲		▲		▲	▲	
400		▲		△			▲	
1100 H/W		▲		▲			▲	
1100 F/W		△	▲	△	▲	▲		Cobalt
1900		△	▲	△	▲	▲		Cobalt
3000		△			▲	▲		Cobalt
3500		△	▲		▲	▲		Cobalt

▲ *Major component* △ *Minor component*

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Figure 4. Characterisation of the major copper orebodies.

1100 Orebody

The major ore zone, the 1100 Orebody comprises both types of ore, and is well documented from drill holes and underground excavations. Therefore, it should provide representative information on the copper ore/pyrite relations, and constitute a model for the other copper orebodies.

Four cross-sections have been studied through this ore zone, its attendant 'silica-dolomite' halo and the unaltered sequence (Fig. 1). The copper grade distribution within the 'silica-dolomite' has been established by using variograms to estimate the copper continuity, and from the geostatistically derived grade estimates, a grade mesh was calculated and contoured (Fig. 5). In the shales, sulphur-rich areas in the form of lead-zinc orebodies and zones of fine-grained pyrite have been plotted (Fig. 5). The value of 20% by volume was used to delineate the fine-grained pyrite, as zones containing this amount of pyrite are recorded in normal mining operations. The tuff beds described by Croxford (1964) have been used as marker beds to compare the position of the copper accumulation with the sulphides in the pre-existing sequence (Fig. 5, 6, 7, 8).

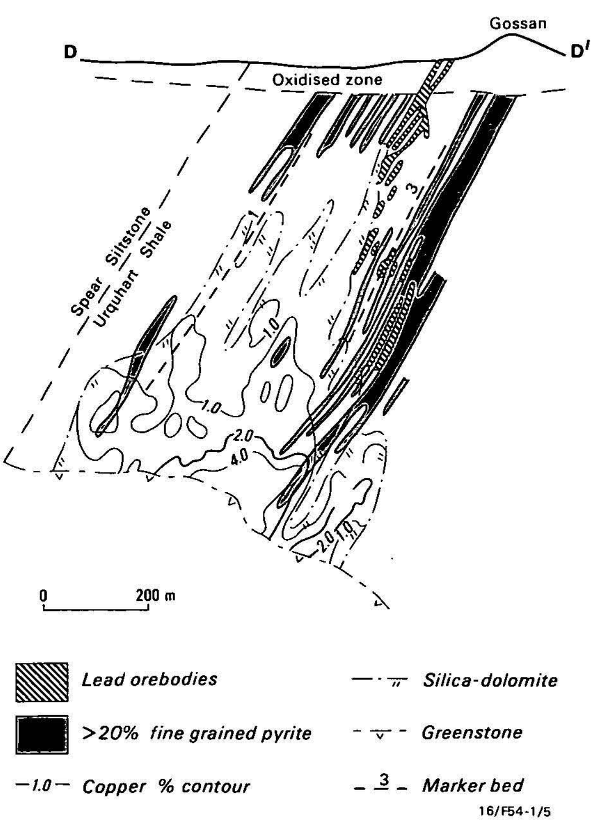

Figure 5. 'Silica-dolomite' and copper distribution in relation to the host sequence, section D-D'.

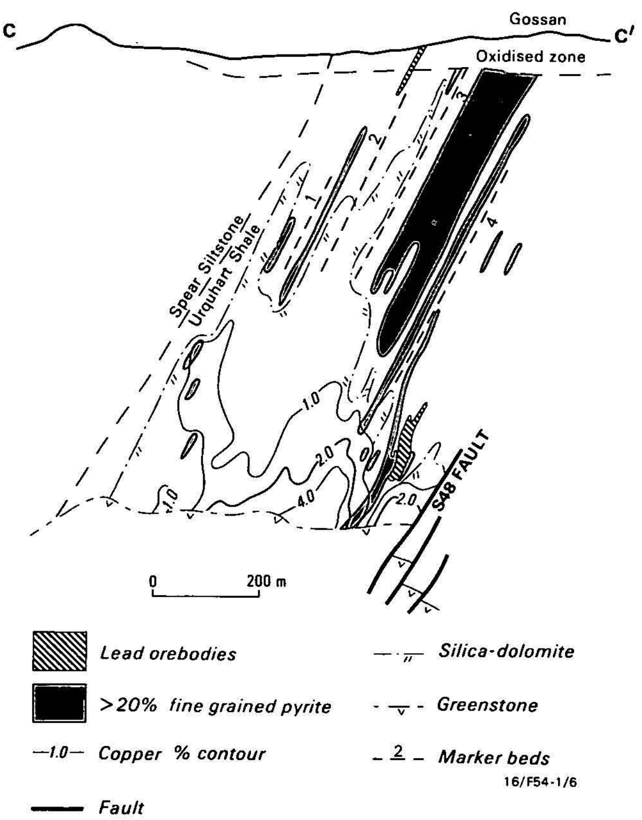

Figure 6. 'Silica-dolomite' and copper distribution in relation to the host sequence, section C-C'.

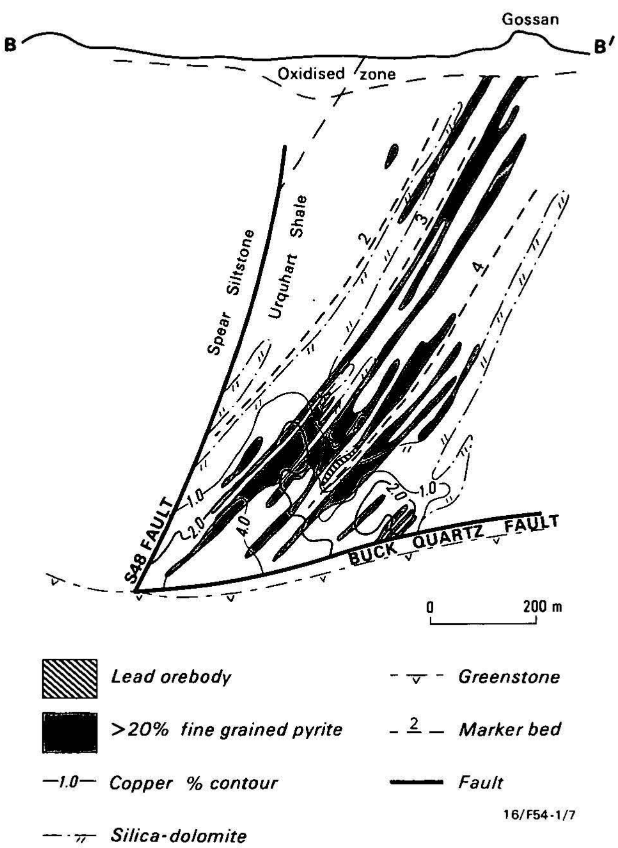

Figure 7. 'Silica-dolomite' and copper distribution in relation to the host sequence, section B-B′.

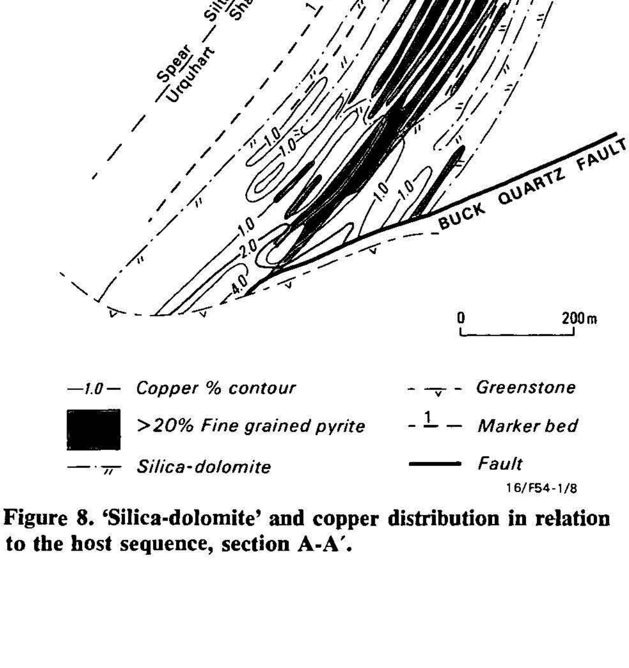

Figure 8. 'Silica-dolomite' and copper distribution in relation to the host sequence, section A-A′.

From the study of the cross-sections a number of conclusions can be drawn:

- The reduction in the abundance of fine-grained pyrite in the high-grade core areas (Robertson, 1975) is common throughout the 1100 Orebody. In the areas equivalent to the 1900 Orebody (Fig. 1, Sections C-C′ and D-D′) there are insufficient data in the up-dip sequence for any similar conclusion or otherwise to be made.

- The highest-grade copper zones are stratigraphically equivalent to the zones of abundant, fine-grained pyrite.

- Over the 1.3 km represented by the cross-sections, the fine-grained pyrite and the copper concentrations maintain a similar stratigraphic relation to the marker horizons. This is particularly illustrated by horizon 3, which sits above the pyrite zone, and horizon 4, which sits below the pyrite zone and the projection of that zone down dip into the cupriferous body. A number of attempts to trace the tuff beds into the 'silica-dolomite' have met with little success and, therefore, perfect correlation can not be made.

- The lower-grade ores are more irregularly distributed and in some sections (Fig. 5 and 6) have different trends to the core zone. The core zone is conformable with the orientation of the host sequence. The lower-grade zones have a more steeply dipping trend and their distribution is asymmetric to the core zone. The trend of these lower grade zones could be a result of redistribution by later structural events.

In the original characterisation (Fig. 4), it was noted that the pyritic ores are also siliceous, and, from the rock-type distributions presented in Mathias & Clark (1976) and the grade distribution (Fig. 9), it can be seen that the high-grade core is contained in the siliceous rock types, and the lower-grade, more irregularly distributed ores are in the coarsely crystalline dolomitic zones.

Within the high-grade copper zone, fragments of fine-grained pyritic shales are common, and in the more 'bedded' ores of the 1900 Orebody fine-grained pyrite is in places interlayered with chalcopyrite. Replacement textures with chalcopyrite replacing fine-grained pyrite are rare, but have been seen in all the orebodies containing the pyritic siliceous ores. Knights (1981) illustrated such textures occurring in the 3500 Orebody.

Sulphur isotopes

The hypothesis that can be put forward is a chemical reaction between the pre-existing sulphur-rich horizons, particularly where massive accumulations are present, and the invading cupriferous solution, resulting in deposition of copper and silica. The dissolution and replacement of the fine-grained pyrite would release sulphur, which could be used in the chalcopyrite formation.

The limited isotope data (Fig. 10) derived from Solomon (1965), Solomon & Jensen (1965), and Smith & others (1978) show a spread of $\delta^{34}S$ values for the fine-grained pyrite of between +5‰ and +29‰. The very limited chalcopyrite data show a narrower spread within the fine-grained pyrite range. In comparison, the

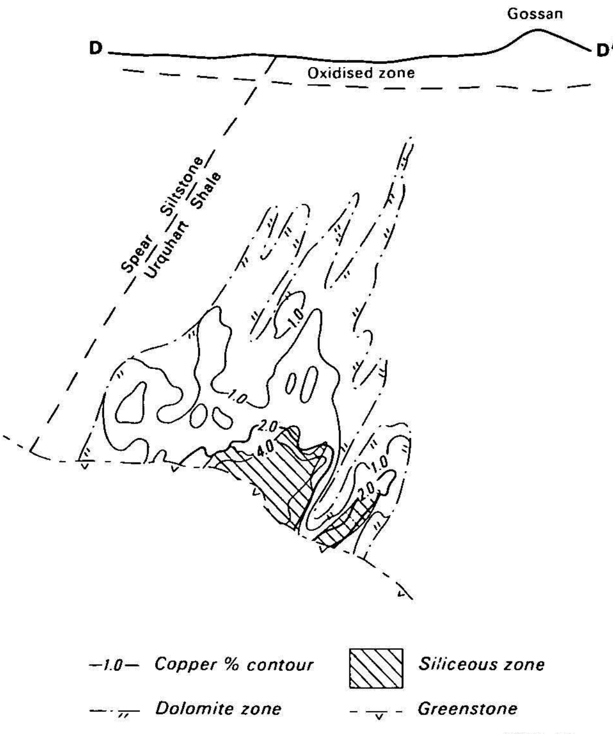

Figure 9. Dolomite and silica distribution in relation to the copper contours, section D-D′.

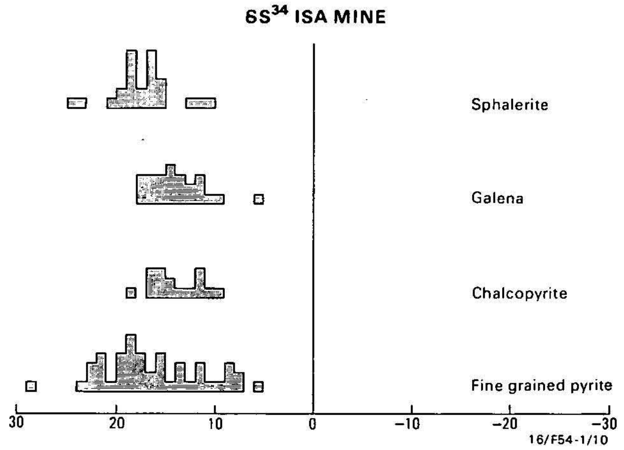

Figure 10. Sulphur isotope histograms—Mount Isa.
Values of $\delta^{34}S$ in parts per thousand.

more comprehensive galena data show a range similar to the chalcopyrite, whereas the sphalerite data show a wider range, comparable with the fine-grained pyrite. These data lead to two possible conclusions:

- The chalcopyrite could have used sulphur and iron from the pyrite in the sediments in its formation. A decrease in the range of the sulphur isotope values could be due to homogenisation during the dissolution and replacement process.

- The chalcopyrite could have a sulphur source similar to that of the other sulphides in the deposit.

If sulphur accompanied the copper in solution, this would be in addition to the sulphur already in the sequence, and if a reasonable continuity of the fine-grained pyrite horizon is assumed, this should result in an increase of sulphur with copper grade. The 80 m wide zone of fine-grained pyritic shale below No. 3 tuff marker horizon (Fig. 7), outside the 'silica-dolomite' halo, contains by volume 0.01% Cu, 22.7% S. The same horizon within the 2% Cu contour contains 2.3% Cu, and 17.8% S, and within the 4% Cu contour it contains 5.1% Cu, 17.3% S. These figures imply, in fact, that sulphur has been reduced in this horizon during the copper mineralisation phase, and most probably redistributed to the adjacent 'silica-dolomite'.

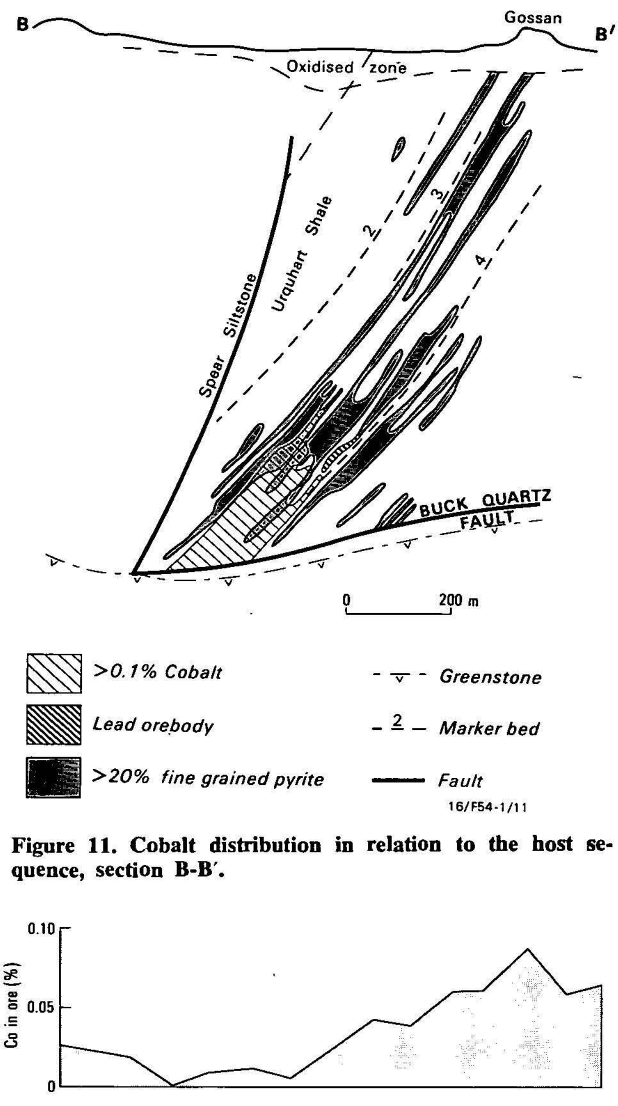

Figure 11. Cobalt distribution in relation to the host sequence, section B-B′.

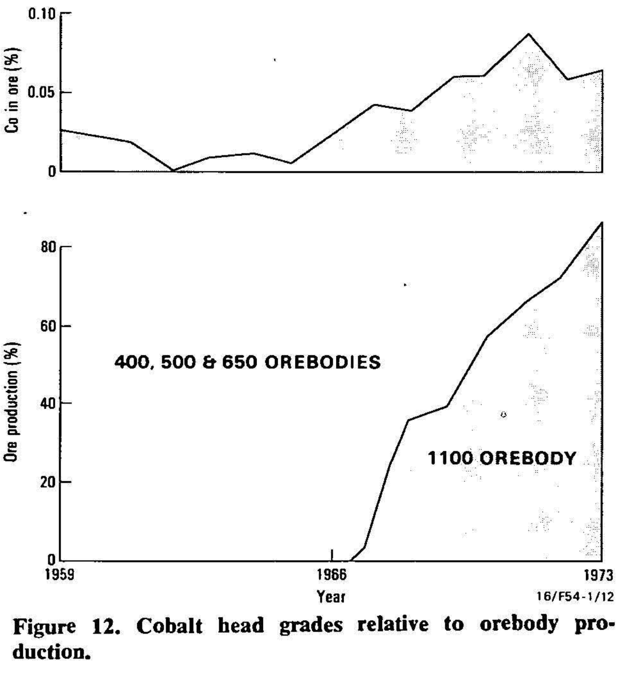

Figure 12. Cobalt head grades relative to orebody production.

Copper ore associates

Other than variable amounts of coarse-grained pyrite and pyrrhotite, which could have formed as a residue to the fine-grained pyrite/chalcopyrite dissolution and replacement process, the other significant sulphide present with the copper ore is cobaltite. Cobalt in various forms described by Croxford (1974) is common in the 1100, 1900, 3000, and 3500 Orebodies. It is closely associated with the copper mineralisation and has its greatest concentrations in the areas where there has been a reduction in the amount of fine-grained pyrite (Fig. 11). Croxford (1974) concluded that alloclasite had been deposited at the same time as the fine-grained pyrite. This conclusion is based on similar zonal growth features occurring both in the alloclasite and the fine-grained pyrite. Cobaltite is now the dominant mineral and has been interpreted as a metamorphic regeneration from the original cobalt mineralisation. Commonly, it contains cores of rounded to euhedral fine-grained pyrite (Croxford, 1974).

No significant cobalt accumulations have been found outside the copper ores. The non-random distribution of cobalt within the copper orebodies (Fig. 12) further supports a hypothesis involving depositional control by the sedimentary sequence.

Conclusions

The mineralising solutions that formed the copper orebodies at Mount Isa contained copper, silica, and cobalt in variable proportions, whose deposition was controlled by the sulphur-rich species present in the Urquhart Shale. The significance of sulphates described by McClay & Carlile (1978) in the chalcopyrite deposition can only be surmised. These minerals have been pseudomorphed by quartz and dolomite and therefore sulphur has been released. In a reducing environment, the sulphur could have been used in sulphide formation. The most significant and evident control is the pyrite. In the areas of massive fine-grained pyrite accumulations next to the solution feeder zone, the pyrite underwent dissolution and replacement, and the released sulphur and iron were used in the formation of the chalcopyrite. Similarly, these areas of pyrite concentration formed a suitable environment for silica and cobalt deposition.

Acknowledgements

I am indebted to the management of Mount Isa Mines Limited for permission to present and publish these data. I thank L. Payne for drafting the original figures and J. Isaacson for the manuscript preparation. I also acknowledge the helpful discussion received from past and present members of the geological staff of Mount Isa Mines Limited.

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GEOLOGICAL EVOLUTION, TECTONIC STYLE, & ECONOMIC POTENTIAL OF THE LAWN HILL PLATFORM COVER, NORTHWEST QUEENSLAND

L. J. Hutton[1] & I. P. Sweet

The Lawn Hill Platform Cover comprises a sequence of mildly deformed Proterozoic sediments and volcanics that crop out northwest of Mount Isa. Three subdivisions are recognised in the sequence: basal coarse clastics and acid and basic volcanics—the Bigie Formation and Fiery Creek Volcanics. They are overlain unconformably by fine to coarse fluvial and shallow marine clastics (the Surprise Creek Formation). The third, uppermost, and major subdivision of the platform cover, the McNamara Group, overlies the Surprise Creek Formation with minor unconformity. It consists of basal clastics, a thick sequence of carbonates, and an upper deep-water clastic sequence. The Lawn Hill Platform Cover is deformed into basins and domes, commonly intersected by major northeast and northwest-trending faults. Economic Cu, Pb and Zn sulphide deposits within the Lawn Hill Platform Cover are concentrated at two main stratigraphic horizons in the lower middle McNamara Group. The main deposits are associated with carbonaceous shales or laminated algal dolomite, suggesting that they may be formed by reduction of base metal rich solutions at an early diagenetic stage by the action of decaying algal material.

Introduction

The Middle Proterozoic Lawn Hill Platform can be subdivided into: older basement, which comprises mainly Haslingden Group rocks and equivalents, Quilalar Formation, and granitic intrusions; and a younger, less-deformed sequence, the platform cover (part of the North Australian Platform Cover of Plumb, 1979).

The Lawn Hill Platform Cover comprises up to 8500 m of mildly deformed sediments that extend from the Murphy Tectonic Ridge in the north to west of Mount Isa in the south, and from the Mount Gordon-Hero Fault zone in the southeast to the Carrara Range region in the west (Fig. 1). It is overlain by sediments of the South Nicholson Group in the northwest, by sediments of the Georgina Basin (Central Australian Platform Cover of Plumb, 1979) in the south and west, and by Cainozoic sediments in the northeast.

A maximum age for the Lawn Hill Platform Cover is provided by a 1678 m.y. age for the Carters Bore Rhyolite in the southern part of the platform (Page, 1978). Although a minimum age of the sequence is provided by a date of 1470–1490 m.y. for the final metamorphic and tectonic event that deformed these rocks (Page, 1978), it is unlikely that sedimentation continued for more than a few tens of millions of years after 1680 m.y.

The thickest development of the Lawn Hill Platform Cover is in the area between Lawn Hill homestead and the Kamarga Dome, where 8500 m of sediments is exposed (Fig. 2). It thins to between 4800 and 5000 m in KENNEDY GAP* and MOUNT OXIDE and to about 3800 m in the Carrara Range region (Sweet & Mond, 1980). Where the sequence laps onto the Murphy Tectonic Ridge, it thins to about 2500 m.

The platform sequence can be broken up into three subdivisions: the Bigie Formation and Fiery Creek Volcanics and equivalents (Hutton & others, 1981), the Surprise Creek Formation (Derrick & others, 1980), and the McNamara Group (Hutton & others, 1981) and equivalents. The stratigraphic nomenclature and correlations between several sections in the Lawn Hill Platform are shown in Figure 3.

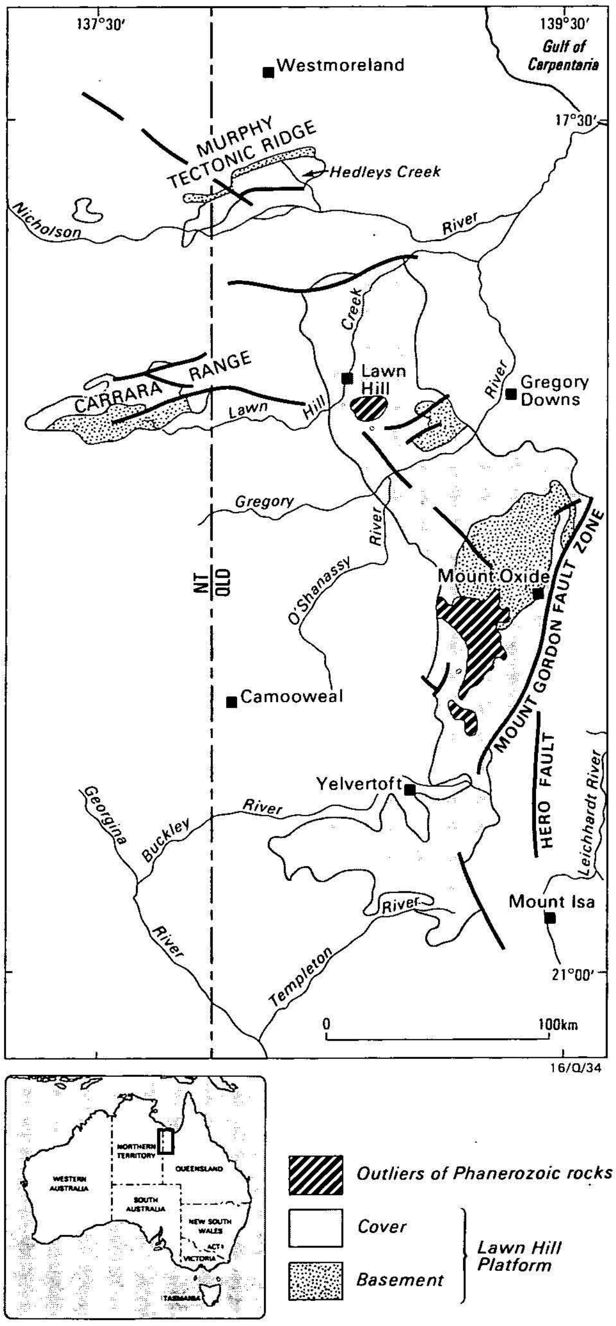

Figure 1. General outline of the Lawn Hill Platform.

[1] Geological Survey of Queensland, G.P.O. Box 194, Brisbane, Queensland 4001

* Names of 1:100 000 Geological Sheet areas are given in capital letters.

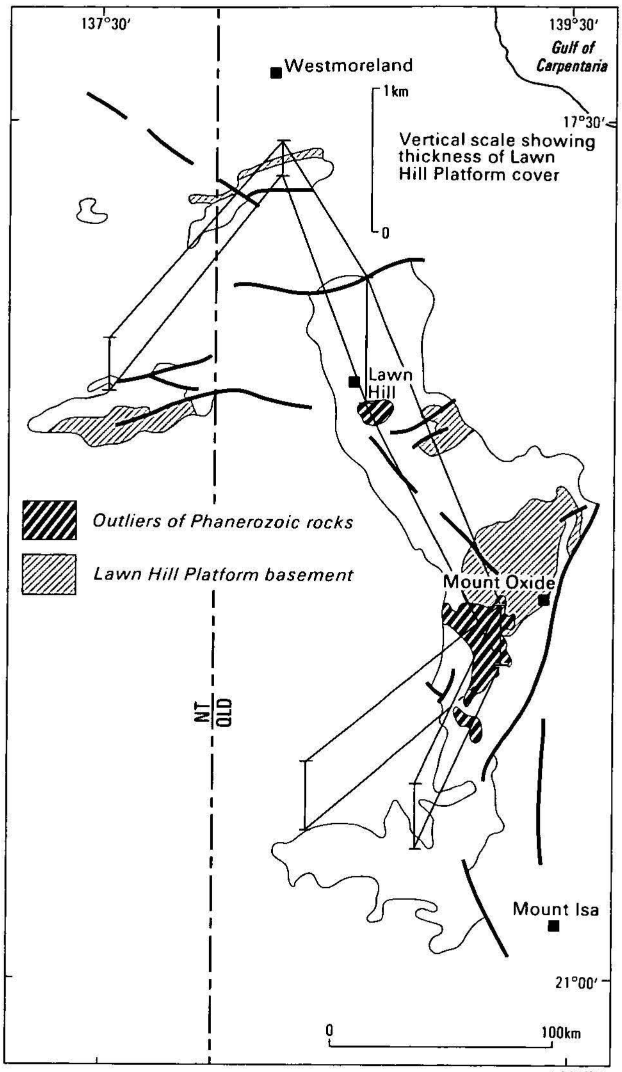

Figure 2. Thickness variations of the Lawn Hill Platform cover across the Lawn Hill Platform.

Bigie Formation—Fiery Creek Volcanics and equivalents

The geological history of the Lawn Hill Platform Cover began with deposition of coarse clastic sediments of the Bigie Formation on an uplifted and dissected land surface. The sediments comprise mainly redbed sandstone, pebbly sandstone and conglomerate, commonly made up of extremely well-rounded and spherical clasts in a hematitic sandy matrix, and minor shale and siltstone. Sedimentary structures include ripples, migrating channels, and cross stratification with dominant tabular foreset beds, and indicate moderately high-energy fluvial deposition, such as channel lag, point bar, and braided stream deposits. Bands of coarser conglomerate occur in the area to the north of Alhambra Station (19°09′S, 139°25′E) and these may represent more proximal deposits.

The abundance of hematite in the Bigie Formation could be due to alteration of detrital iron minerals in the sediments by saline, alkaline, and oxidising groundwaters, probably under hot, dry conditions in a sabhka or playa lake environment, as deduced for Canadian redbeds by Chandler (1980).

Acid and mafic volcanism (Fiery Creek Volcanics and equivalents) followed this phase of alluvial sedimentation. The lack of marine features in the pile indicates that the volcanics may have been erupted onto a land surface. Several periods of volcanicity are indicated by the interlayering of flow-banded rhyolite, rhyolitic agglomerate, amygdaloidal trachybasalt, and sandstone and conglomerate. The best development of acid volcanics is in the Alhambra area in MOUNT OXIDE, where thick acid agglomerates probably indicate eruptive centres nearby.

The conditions that altered the Bigie Formation may have persisted during deposition of the Fiery Creek Volcanics, as these contain hematite and sanidine, which could be the result of chemical alteration of plagioclase. Turner (1980) recorded authigenic sanidine in many redbed sequences (e.g. Permo-Triassic sandstones of northern Europe), sometimes as replacement for plagioclase.

This phase of sedimentation and volcanism was widespread throughout the Lawn Hill Platform, being represented in the south by the Carters Bore Rhyolite, in the east by the Bigie Formation and the Fiery Creek Volcanics, in the north by the Peters Creek Volcanics, and in the Carrara Range region by the Top Rocky Rhyolite. The episode ended with a period of minor tectonism and uplift.

Surprise Creek Formation

The basal conglomerate and sandstone facies of the Surprise Creek Formation was deposited on a deeply dissected land surface, following the uplift that mildly deformed the Fiery Creek Volcanics and their equivalents. Thick accumulations of poorly sorted conglomerate in channels and great thickness variation in conglomerate beds indicate proximal alluvial deposition from high-energy currents in braided streams and alluvial fans (Derrick & others, 1980).

Erosion and infilling of the highly dissected terrain resulted in lower-energy alluvial deposition (Derrick & others, 1980), probably becoming increasingly distal, as indicated by the occurrence of isolated well-rounded pebbles in the sandstone. This part of the Surprise Creek Formation probably also records a marine transgression of unknown extent. In MAMMOTH MINES inliers of Surprise Creek Formation consist of sheets of well-sorted sandstone containing large-scale sets of high-angle cross-bedding. These may be aeolian beach deposits adjacent to more pebbly, cross-bedded, and ripple-marked shallow marine sands. Towards the upper part of the Surprise Creek Formation the sediments become much finer and probably represent shallow marine silts and sands. Occasional quartz sandstone lenses may represent beach or barrier island deposits. A distinctive hematitic marker bed in this upper sequence represents a period of redbed development. Minor tectonism and uplift ended this phase of sedimentation.

The Surprise Creek Formation is best developed in the eastern part of the Lawn Hill Platform in the Alhambra area, with inliers to the west of Gunpowder. No correlatives have been found in the Westmoreland or Carrara Range regions.

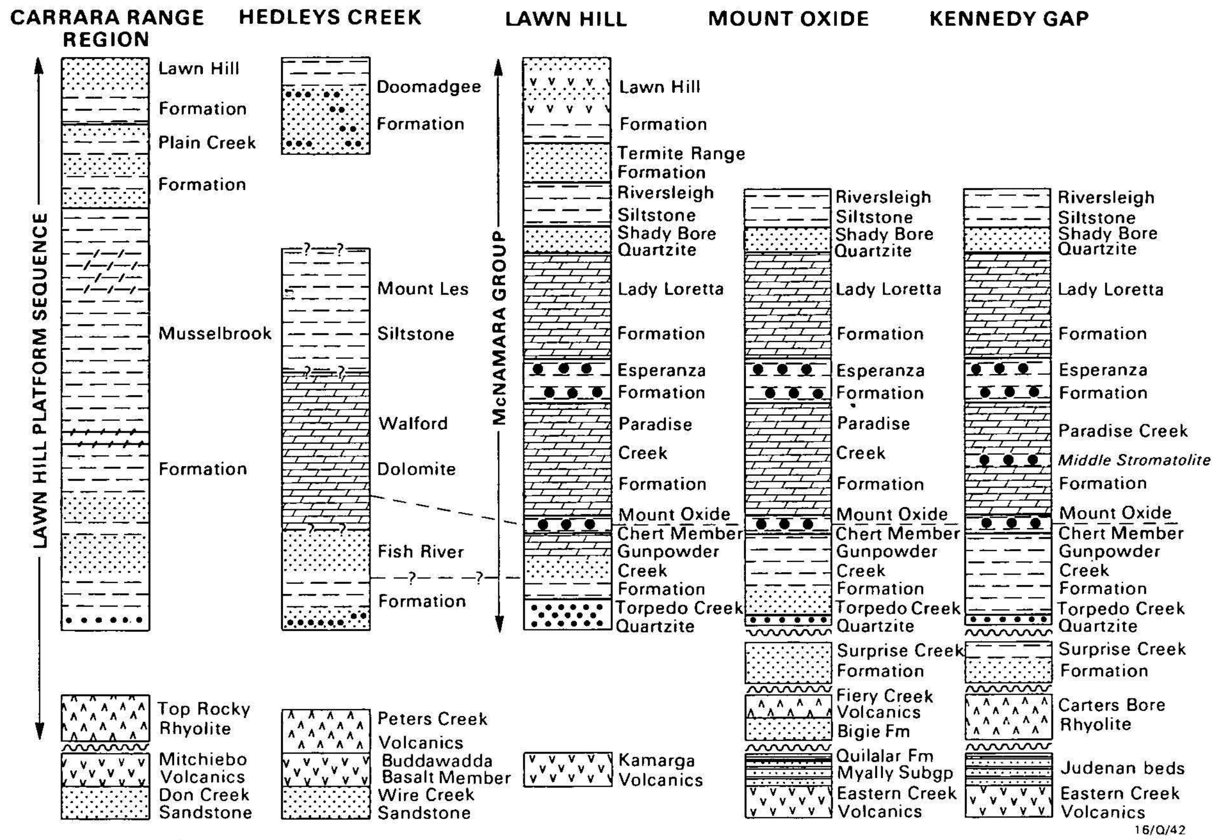

Figure 3. Correlations across the Lawn Hill Platform. Names refer to 1:100 000 Sheet areas.

McNamara Group

Torpedo Creek Quartzite

McNamara Group sedimentation began with a period of alluvial sedimentation on a dissected land surface. Initial high-energy deposition formed poorly sorted conglomerate, derived from underlying sediments, across the Lawn Hill Platform (Fig. 4). Brecciated beds, probably regoliths, mark areas of weathering on the dissected surface. The basal conglomerate-regolith facies is discontinuous and in many places the overlying sediments rest on basement. These well-bedded, ripple-marked, cross-bedded sands represent a phase of distal alluvial, marginal marine, and shallow marine sedimentation, and record a widespread marine transgression. Lenticular gypsum crystals and the well-sorted sands suggest deposition in a high-energy marine shoreline environment (Walter, 1978).

This phase of sedimentation is also preserved in the Hedleys Creek area (Fish River Formation), and in the Carrara Range region (lower part of the Musselbrook Formation). Sweet & Slater (1975) suggested that the source of sediment in the Fish River Formation was to the south, while Wilson & others (1979) suggested a source in the east for the Torpedo Creek Quartzite of KENNEDY GAP. These observations suggest that at least two drainage systems, one flowing north from the centre of the platform and one flowing west in the south, existed at this time. The sediments in the Kamarga Dome area in LAWN HILL were probably locally derived.

Gunpowder Creek Formation

The marine transgression during upper Torpedo Creek Quartzite time formed a shallow epicontinental sea, which covered the Lawn Hill Platform. Structureless feldspathic sandstone at the base of the Gunpowder Creek Formation represents this phase.

Shallowing of the sea led to the deposition of laminated siltstone, fine sandstone, and minor shale and dolomite under very low energy conditions. Depositional slopes were steep enough to cause slumping in fine sandstone and siltstone beds, and some sediments were deposited in tidal and semi-emergent environments characterised by wave scours, low-angle cross-bedding and some desiccation cracks. Following this long period of shallow-water deposition, starvation of siliciclastic sediment supply resulted in precipitation of laminated dolomite, probably in a marginal marine environment. Subsequently, carbonaceous shales and siltstones were deposited. These fine clastics are widespread throughout the outcrop area of the Gunpowder Creek Formation, suggesting deposition in a subtidal, euxinic deeper-water environment rather than a paludal environment. The Gunpowder Creek Formation thins toward the Mount Gordon Fault zone in the east, suggesting that this may have been a high area during this time (Derrick, 1979).

Near the Kamarga Dome, 30–40 km southeast of Lawn Hill homestead, the marine transgression peaked with the deposition of carbonaceous shale and marine shelf sands (Hutton, in preparation). Regression subsequently caused these sediments to emerge in a sabkha

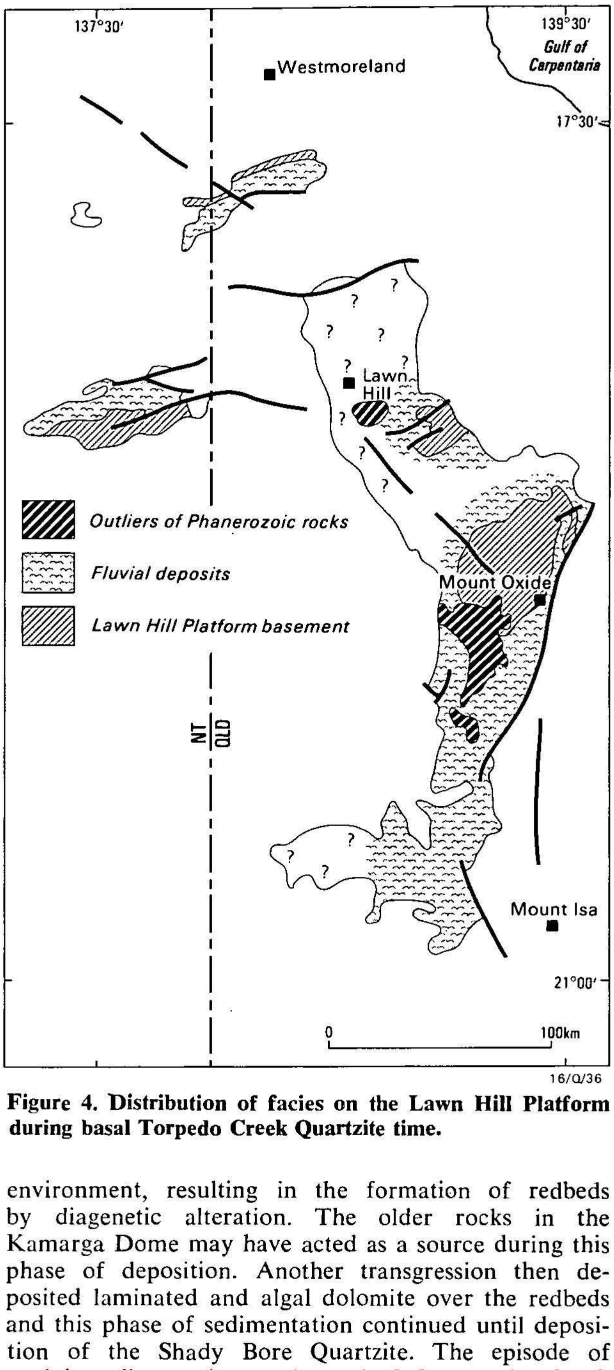

Figure 4. Distribution of facies on the Lawn Hill Platform during basal Torpedo Creek Quartzite time.

environment, resulting in the formation of redbeds by diagenetic alteration. The older rocks in the Kamarga Dome may have acted as a source during this phase of deposition. Another transgression then deposited laminated and algal dolomite over the redbeds and this phase of sedimentation continued until deposition of the Shady Bore Quartzite. The episode of euxinic sedimentation at the end of Gunpowder Creek Formation time is represented here by a band of carbonaceous siltstone and shale in the middle of the algal dolomites. Thus, the upper part of the Gunpowder Creek Formation in the Lawn Hill area is richer in carbonate than the area to the south (Fig. 5). Carbonates are also common in the equivalent rocks in the Hedleys Creek area, where the Walford Dolomite lies conformably on coarse clastics of the Fish River Formation (Sweet & Slater, 1975). The middle and upper parts of the Fish River Formation may be correlatives of the lower part of the Gunpowder Creek Formation in the Kamarga Dome and the lower part of the Walford Dolomite may be a correlative of the overlying dolomites in the dome (Fig. 3). In the Carrara Range region, the rocks are extremely altered, and only broad-scale correlation of the basal part of the Musselbrook Formation with the Gunpowder Creek Formation can be made.

Mount Oxide Chert Member

The Mount Oxide Chert Member is a laminated chert that overlies the carbonaceous shale facies of the Gunpowder Creek Formation in the southern part of the Lawn Hill Platform. It is recognised only in isolated patches in the Kamarga Dome and not at all in the Hedleys Creek area.

Walter (1978) suggested that the member contains features of pervasive diagenetic alteration, and that it may be a silicified algal laminated dolomite. The chert is continuous at depth and therefore not a product of post-deformational surface silicification. Cavaney (1975) suggested that the bed marks the onset of volcanism that deposited felsic tuff beds during middle McNamara Group time and caused a sudden and widespread influx of silica into the environment. This theory is supported by the lack of the Mount Oxide Chert Member in the north, where tuff beds absent.

Paradise Creek Formation

The Paradise Creek Formation began with the deposition of thin-bedded siltstone, shale, chert, and, possibly, limestone in a subtidal marine environment. A high-energy stromatolitic dolomite facies, comprising

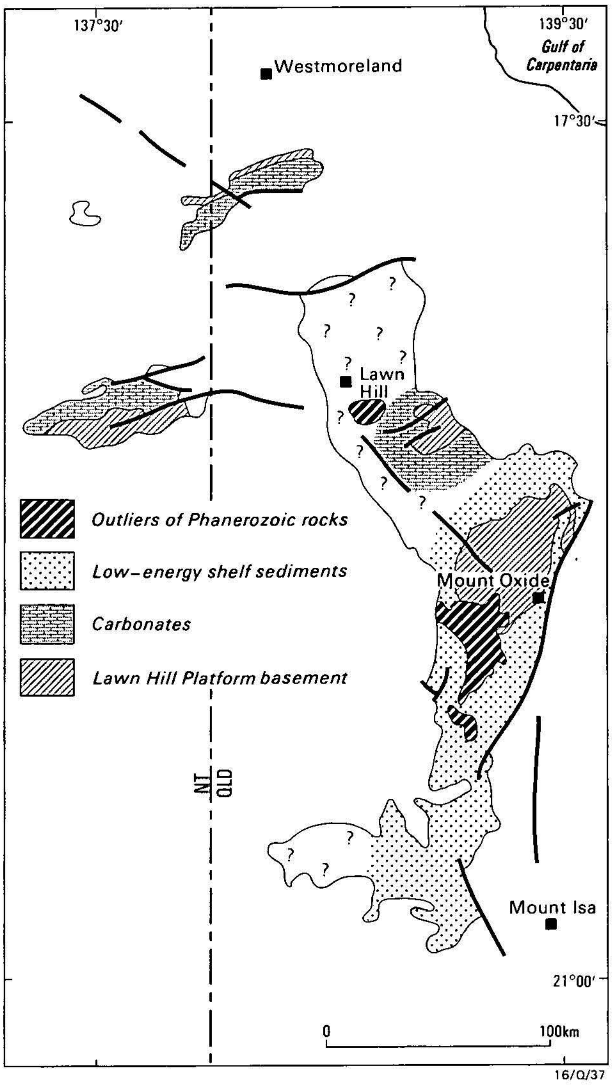

Figure 5. Distribution of facies on the Lawn Hill Platform during upper Gunpowder Creek Formation time.

columnar and pseudocolumnar stromatolites, channels filled with intraclast grainstone, ripple cross-laminated siltstone, and sandstone with rare pseudomorphs after anhydrite (cauliflower cherts) (Chowns & Elkin, 1974), and deposited in a marine intertidal to supratidal environment, overlies the lower laminated facies. This sequence, with increasing numbers of evaporite-derived pseudomorphs towards the top of the unit, forms much of the outcrop area of the Paradise Creek Formation. Much of the dolomite is very fine-grained and may be a primary precipitate. A period of subtidal deposition in the middle of the intertidal to supratidal sequence resulted in the formation of a biostrome of contiguous bioherms containing radially distributed columnar stromatolites, which have been subsequently silicified. A well-sorted quartzose sandstone that crops out to the west of the stromatolitic chert is probably a marine shoreline sand facies (Fig. 6). During this period of sedimentation, the sediment was derived from a land mass to the west.

The Paradise Creek Formation is best developed in the southern and eastern parts of the Lawn Hill Platform. In the north of the platform the Walford Dolomite was probably deposited about this time, as was the middle

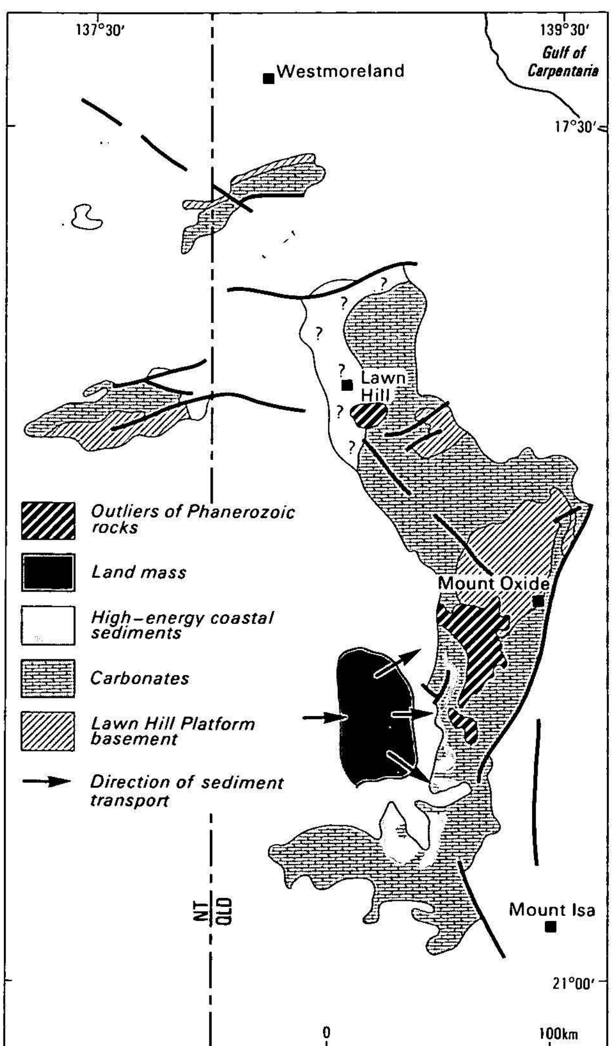

Figure 6. Distribution of facies on the Lawn Hill Platform during the Paradise Creek Formation, Esperanza Formation, and Lady Loretta Formation time.

Musselbrook Formation in the west. However, both of these sequences are much thinner than the Paradise Creek Formation in the southeast.

Esperanza Formation

A period of subtidal deposition, at times several metres below wave base, is indicated by the high-relief domal bioherms, subsequently silicified, that make up the Esperanza Formation. In the Paradise Creek area, in the south of the platform, three such stromatolitic chert bands are interbedded with intertidal sequences. The uppermost of these three cherts grades up from high-relief domal bioherms, through smaller domal stromatolites to high-spired *Conophyton*. This is a prograding sequence, representing a change in environment from deeper water subtidal to lagoonal. In western MOUNT OXIDE this upper band is only partly silicified, indicating that the silicification is diagenetic. A similar prograding sequence in stromatolitic dolomite has been mapped in the basal part of the Lady Loretta Formation on MOUNT OXIDE, and may be an unsilicified equivalent of the uppermost sequence of the Esperanza Formation at Paradise Creek. South of the Kamarga Dome a medium-grained sandstone facies equivalent to the stromatolitic cherts may represent higher-energy river channels or barrier islands within this deeper water environment. The massive stromatolitic cherts are not as well developed at Hedleys Creek, and are probably restricted to the southern part of the platform.

Lady Loretta Formation

The Lady Loretta Formation represents gradation from subtidal to supratidal sedimentation after the deeper water deposition of the Esperanza Formation. The basal Lady Loretta Formation consists of a cyclic sequence of *Conophyton*, locally with up to 2 m relief, interbedded with laminated dolomite, which probably represents a period of subtidal lagoonal deposition and is an extension of the environments found in the upper parts of the Esperanza Formation. At many localities the sequence is brecciated and ferruginised, and the true nature of the basal Lady Loretta Formation cannot be determined.

The remainder of the Lady Loretta Formation was deposited in an energetic intertidal and supratidal environment, and comprises laminated and algal dolomite and bands of intraclast dolomite. A local euxinic facies developed in a small basin in the southern part of the platform and this sequence is host to the Lady Loretta polymetallic ore body. The Lady Loretta Formation may in part be equivalent to the Walford Dolomite and Mount Les Siltstone in the Hedleys Creek area and the Musselbrook Formation in the Carrara Range region.

Shady Bore Quartzite and Lower Riversleigh Siltstone

During late Lady Loretta Formation time, marine regression resulted in emergence of a land mass southwest of the platform, in the area that is now the Undilla Basin. Massive orthoquartzite, sandstone, siltstone and dolomite were deposited in marine shoreline and lagoonal environments in an arc around the margins of this landmass (Fig. 7). These deposits now make up the Shady Bore Quartzite (Sweet & Hutton, 1980; Wilson & others, 1981).

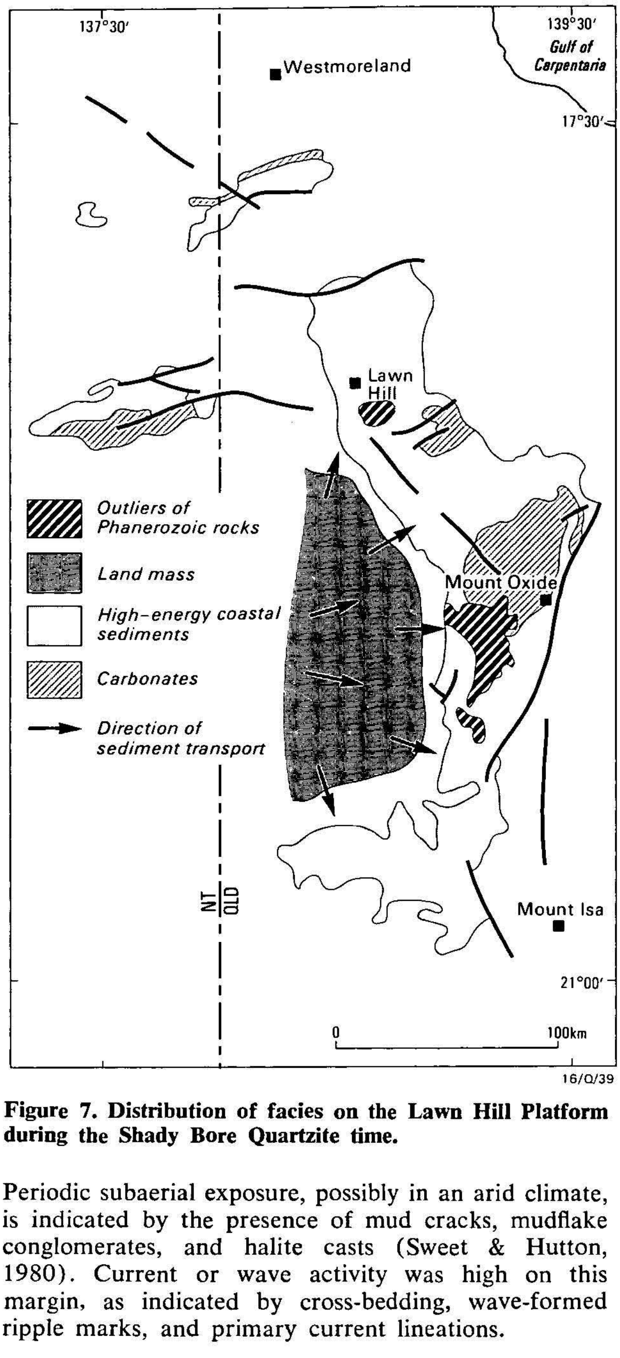

Figure 7. Distribution of facies on the Lawn Hill Platform during the Shady Bore Quartzite time.

Periodic subaerial exposure, possibly in an arid climate, is indicated by the presence of mud cracks, mudflake conglomerates, and halite casts (Sweet & Hutton, 1980). Current or wave activity was high on this margin, as indicated by cross-bedding, wave-formed ripple marks, and primary current lineations.

The medium-grained quartzites are overlain by siliceous and dolomitic siltstone, sandstone, and dolomite, which make up the basal beds of the Riversleigh Siltstone. These show wavy and lenticular lamination, ripple marks, flute casts, and mudcracks, and were probably deposited in peritidal environments, similar to those of the Shady Bore Quartzite. Sandstone bodies, best developed to the south of Lawn Hill, are probably tidal flat or channel deposits in the finer-grained sediments. During upper Riversleigh Siltstone time the locus of deposition shifted to the Lawn Hill area and further north and west. Sedimentation may have continued on the southern part of the Lawn Hill Platform during upper Riversleigh Siltstone, Termite Range Formation, and Lawn Hill Formation time; however, the deeper water and turbidite facies (see below) appear to be restricted to the Lawn Hill area. A maximum of 2500 m of siltstone and minor sandstone overlies the Shady Bore Quartzite in the Yelvertoft Sheet area in the southwestern part of the platform cover compared with over 6500 m of siltstone, carbonaceous shale, sandstone, greywacke, and tuff in the Lawn Hill area, to the north.

Upper Riversleigh Siltstone and Termite Range Formation

The sediments deposited during late Riversleigh Siltstone time are much more carbonaceous than the dolomitic and terrigenous sediments laid down during early Riversleigh Siltstone time (Sweet & Hutton, 1980). Although carbon-rich rocks can form in shallow-water reducing environments, the absence of other shallow-water facies and the presence of overlying deep-water deposits suggest that the upper part of the Riversleigh Siltstone was deposited in a deep-water euxinic environment. Subsidence during Riversleigh Siltstone time caused a change from shallow-water high-energy environments to deeper-water low-energy environments in a pronounced trough. The best development of Riversleigh Siltstone is about 10 km north of Riversleigh homestead (19°09′S, 138°44′E). The upper, carbonaceous facies does not crop out south of this area, and was probably not deposited there. North of this area, the carbonaceous facies and sandstone lenses are thinner, and this may indicate the basin here was starved of sediment.

During Termite Range Formation time, uplift of the source of sediment caused rapid deposition of coarse terrigenous material in the developing trough. The sequence contains only rare sedimentary structures and individual sandstone and greywacke beds are of constant thickness over several kilometres. Sweet & Hutton (1980) suggested that the sandstone beds were deposited from turbidity currents. Complete Bouma cycles of graded, parallel-laminated and rippled sand or silt grading up into finer sediment (Bouma, 1962) have not been recognised, although parts of the Bouma cycle have. Walker (1967) discussed deposition from 'traction carpets' in some turbidity currents, resulting in deposition of non-graded beds with sharp tops and bases, similar to those observed in the Termite Range Formation.

The Termite Range Formation is best developed in a northeast-trending belt up to 50 km wide that stretches from the Gregory River in the south, through Lawn Hill Station to Elizabeth Creek in the north. The formation has not been recognised outside this belt, which probably corresponds to the extent of the trough that developed during this time (Fig. 8).

A source area for sediment during late Termite Range Formation time may have been the Murphy Tectonic Ridge. Fresh microcline is common in sandstone and greywacke of the upper part of the Termite Range Formation, suggesting that a granite body, such as part of the Nicholson Granite Complex, may have been unroofed and supplying sediments during this time. Sweet & Slater (1975) recorded the presence of fresh microcline in the Doomadgee Formation on HEDLEYS CREEK, and suggested that it may have been derived from the nearby Murphy Tectonic Ridge. The lower part of the Doomadgee Formation was deposited by fluvial processes after a period of uplift, and may be a non-marine equivalent of the Termite Range Formation.

Lawn Hill Formation

Continuing deep-water conditions led to the formation of a euxinic environment and deposition of a carbonaceous shale sequence during lower Lawn Hill Formation time, and a contemporary period of volcanicity supplied ash to the basin both as tuff and mixed with terrigenous sediment.

The Bulmung Sandstone Member represents a final pulse of turbidite deposition in the basin. This turbidite unit lenses out eastwards, indicating a sediment source to the west. In the Carrara Range region the lower part of the Lawn Hill Formation consists of about 1000 m of intertidal, high-energy shelf deposits, suggesting that it was nearer the margin of the basin than was the Lawn Hill region.

By mid-Lawn Hill Formation time the depositional environment shallowed as the trough filled. Tuff and tuffaceous sediments still made up a large proportion of the sequence, but the percentage of silt was greater. Laminated, crystalline dolomite beds occur at this level, with the proportion of dolomite increasing northwards.

A crossbedded, ripple-marked, rarely glauconitic sandstone containing mudflake conglomerates marks a phase

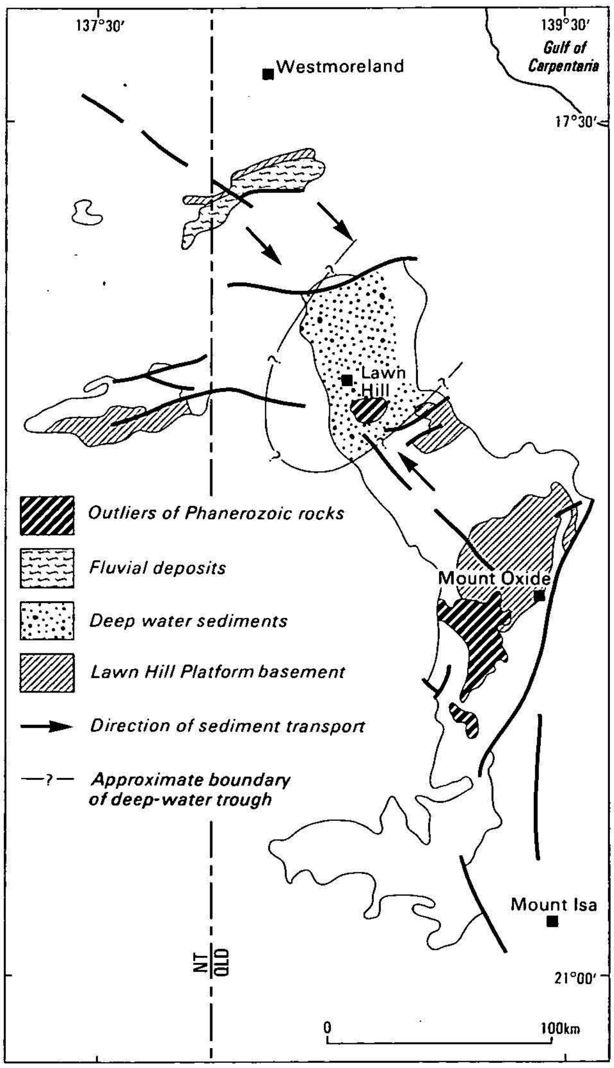

Figure 8. Distribution of facies on the Lawn Hill Platform during the Termite Range Formation time.

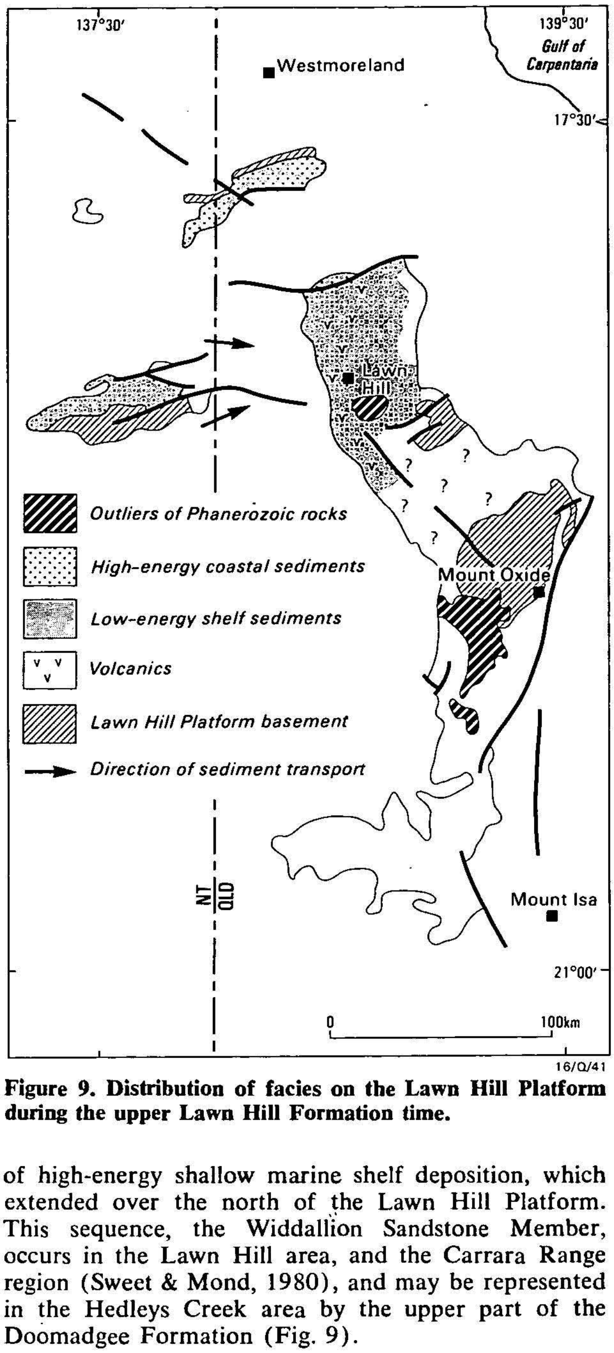

Figure 9. Distribution of facies on the Lawn Hill Platform during the upper Lawn Hill Formation time.

of high-energy shallow marine shelf deposition, which extended over the north of the Lawn Hill Platform. This sequence, the Widdallion Sandstone Member, occurs in the Lawn Hill area, and the Carrara Range region (Sweet & Mond, 1980), and may be represented in the Hedleys Creek area by the upper part of the Doomadgee Formation (Fig. 9).

A fine-grained siltstone, present in a few places immediately below the unconformity with the South Nicholson Group and Cambrian rocks, represents a phase of shallow marine sedimentation; it is the youngest preserved unit of the Lawn Hill Platform Cover.

Tectonic style of the rocks of the Lawn Hill Platform Cover

The rocks of the Lawn Hill Platform have undergone at least one major deformation, and Lee (1972) showed that around the Lady Loretta deposit one earlier episode and two later episodes of deformation can also be recognised. The age of the major episode is in doubt, but it is probably synchronous with the first of three deformations recognised in the Mount Isa area by Wilson (1973). These events must have postdated

1670 m.y., the age of tuff beds in the Mount Isa Group (Page, 1981), and most probably occurred early in the interval 1620–1490 m.y., the period during which the Mount Isa Group was metamorphosed (Page, 1978).

The Lawn Hill Platform Cover is characterised by basin and dome-type folding with associated longitudinal and cross faulting, commonly intersected by major northeast and northwest-trending faults. Several large domes occur on the Lawn Hill Platform, notably the 30-km diameter Kamarga Dome, east of Lawn Hill station. A similar sized, but less clearly defined, dome in central MAMMOTH MINES is a much deeper-seated structure with only the younger beds exposed.

The style and complexity of basin and dome folding is similar in the basement rocks of the Lawn Hill Platform (Myally Subgroup, Quilalar Formation) to the overlying cover rocks, at least in the northwestern part of the platform, suggesting that the metamorphic event that preceded the deposition of the Lawn Hill Platform Cover in that area was not generally associated with major deformation and only produced intense deformation locally.

Basin and dome folding on the Lawn Hill Platform is probably an embryonic stage of fold development. An alternative hypothesis for the development of this style of folding is the emplacement of diapiric bodies, but there is no evidence of diapiric bodies on the Lawn Hill Platform.

To the south of Lawn Hill station the long axes of ellipse-shaped domes are oriented north-south, suggesting that the direction of principal compression was east-west. However, north of Lawn Hill station the long axes are oriented northeast and east-northeast. This probably reflects a change in the orientation of basement structures from north-trending south of Lawn Hill to northeast-trending north of Lawn Hill.

A north-trending zone of strong deformation, fault-bounded and containing strongly cleaved sediments, extends from the south of the platform near Lady Annie mine for 75 km to the north. A belt of steeply dipping Myally Subgroup and Quilalar Formation, overlain by flat-lying Fiery Creek Volcanics, lies immediately to its east. Elsewhere, the unconformity with the basement rocks is low-angled, and, therefore, it appears that this belt was strongly folded before the Lawn Hill Platform cover was deposited.

The zone may also correspond to a topographic high during deposition of the Myally Subgroup. In the core of an anticline north of Lady Annie, mafic volcanics that have strong affinities with the Eastern Creek Volcanics (R. Russell. Mount Isa Mines, pers. comm. 1978) are overlain by Surprise Creek Formation, with the Myally Subgroup either very thin or absent. Southeast and northeast of this area, thick sequences of Myally Subgroup and Judenan Beds are present.

Several major faults cut the Lawn Hill Plaform Cover. The Termite Range Fault is a large northwesterly striking fault that extends from just south of Lawn Hill station for 100 km southeast. The sense of movement on the fault is vertical (Sweet & Hutton, 1980) and variable in magnitude. Several smaller northeasterly striking faults terminate against the Termite Range Fault, but Hutton & Sweet (1980) considered these and the Termite Range Fault to be synchronous with the major folding episode in the region.

The Mount Gordon Fault Zone forms the southeastern margin of the Lawn Hill Platform. It comprises numerous northeasterly striking faults, whose overall sense of movement has not been determined. The fault zone corresponds to the Mount Gordon Arch (Derrick, 1979), a topographic high in early McNamara Group time, onto which lower McNamara Group units thin. This arch may have acted as a barrier between Mount Isa Group sediments and their correlatives in the McNamara Group.

Economic geology and potential of the Lawn Hill Platform Cover

Economic mineral deposits in the Lawn Hill Platform Cover occur at Mount Oxide, Lady Annie, Lady Loretta, and Lawn Hill, and numerous smaller mines and prospects occur at several stratigraphic levels throughout the sequence. Apart from persistent but minor malachite staining in the Torpedo Creek Quartzite, the stratigraphically lowest significant mineralisation occurs in the Gunpowder Creek Formation.

Lead-zinc mineralisation in the lower McNamara Group

The largest deposit of lead-zinc sulphides occurs at Lady Loretta in MAMMOTH MINES within the upper part of the Lady Loretta Formation. The ore comprises finely banded galena, sphalerite, and pyrite, with minor chalcopyrite and tetrahedrite. Loudon & others (1975) proposed that this deposit formed by an exhalative-sedimentary process similar to that envisaged for present-day Red Sea metal accumulations. Cavaney (1975) correlated the ore horizon with the host rocks of similar banded sphalerite-galena ores at Mount Isa and MacArthur River. If this correlation is correct, the ore deposition at Lady Loretta may have been part of a widespread episode of exhalative sulphide accumulation at that time. However, Sweet (1980) suggested that the Lady Loretta Formation may be younger than the Urquhart Shale at Mount Isa, and, therefore, the period of accumulation of exhalative suphides may have been longer than previously envisaged.

The ore body at Lady Loretta lies within a zone of more intense folding than is found elsewhere on the Lawn Hill Platform, and it is possible that it lies in a belt of deep-seated fractures that acted as conduits for hot, ore-carrying solutions.

Lead-zinc sulphide mineralisation also occurs in the upper part of the Gunpowder Creek Formation, at Kamarga in eastern LAWN HILL. Here, the mineralisation occurs as disseminated sulphides or void fillings and veinlets in an algal dolomite and dolarenite adjacent to a major fault. This mineralisation may have been emplaced during an exhalative phase similar to that which formed the ores at Lady Loretta. It is possible that the lead and zinc were channelled along a fault plane, but did not reach the sediment-water interface. Instead, the metal ions in the solutions were precipitated as sulphides at a reducing layer in the sequence below the surface. Alternatively, the exhalative processes may have been active over a long time.

An alternative mechanism for the mineralisation at Kamarga is precipitation from acidic solutions generated in a sabkha environment. Renfro (1974) described a common association of iron, lead, zinc, and copper sulphides in evaporite-bearing dolomites overlying redbed sandstone sequences; such an association is present at Kamarga. He proposed a mechanism in which acidic terrestrial groundwaters scavenge metal ions from underlying rocks and deposit them as sulphides in the reducing environment produced by rotting algal material in a shallow marine environment.

Information on the mineralisation at Kamarga was obtained from the results of exploration in that area by geologists from Newmont, CRA, and ICI.

Lead-zinc mineralisation in the upper McNamara Group

Stratabound vein-type silver-lead-zinc mineralisation occurs in tuff and siltstone of the Lawn Hill Formation south of Lawn Hill station. It occurs in veins with quartz and sideritic gangue in northeast-striking faults. Almost all the mineralisation is in an 80 m thick tuff and siltstone unit that is capped by a resistant sandstone bed. Lead isotopes from galena in the ores at Lawn Hill are different from those in the main lead orebodies at Mount Isa and McArthur River (Richards, 1975). It is possible that the ores at Lawn Hill represent a later phase of lead-zinc mineralisation than the bedded ores at Mount Isa, and may be related to the tuffaceous volcanism during Lawn Hill Formation time.

Copper mineralisation in the McNamara Group

Copper deposits are found at several stratigraphic levels in the Lawn Hill Platform Cover:

- Copper mineralisation in the Torpedo Creek Quartzite is minor and generally shows as malachite staining. In the Kamarga area on LAWN HILL the copper occurs as disseminated chalcopyrite in a probable redbed association. Grades are very low and not economic.

- Copper mineralisation tends to be concentrated near the top of the Gunpowder Creek Formation or in the overlying Mount Oxide Chert Member at the top of the sequence. The main ore body at this level is at Mount Oxide and comprises mainly bedded chalcocite and framboidal pyrite in a strongly carbonaceous shale (Cavaney, 1975). Many smaller deposits occur at or about this stratigraphic level. Some, such as at McLeod Hill and Mount Kelly, consist of malachite and chrysocolla in brecciated rocks closely associated with major faults, and probably formed by reduction of acidic ore-bearing solutions in the strongly carbonaceous shales during diagenesis. As many of these deposits are related to major faults, it is possible that the faults acted as conduits for ore-bearing solutions, which may have resulted from the onset of volcanism at about Mount Oxide Chert Member time.

- Copper mineralisation in the Paradise Creek Formation and younger units is closely associated with faults and shears. The main deposit is at Lady Annie, where chalcopyrite and pyrite occur in a breccia of coarse-grained carbonate in a dolomitic matrix. Copper minerals in the oxidised zone include cuprite, native copper, bornite, and malachite (Cavaney, 1975). Minor mineralisation occurs in fractured dolomites in several small prospects on MAMMOTH MINES. The Esperanza Mine is in fractured chert and siltstone of the Esperanza Formation, in the Mount Gordon Fault Zone.

Economic potential of the Lawn Hill Platform

Two broad types of mineralisation occur on the Lawn Hill Platform. The first is an exhalative-sedimentary type, of which the Lady Loretta lead-zinc deposit is the best example. It is possible that a similar process was responsible for smaller lead-zinc deposits in older rocks, as at Kamarga, when metal-carrying solutions did not reach the sediment-water interface, but were precipitated when they intersected highly reducing environments. The orebody at Lady Loretta is located in a structurally anomalous zone, which may be coincident with older faulting. It is possible that any other deposits of this type would be associated with major pre-existing faults, which would have acted as conduits for the ore-bearing solutions. The strongly deformed zone north of Lady Annie and the faulted limb of the Ploughed Mountain Anticline (in LAWN HILL), where carbonate-rich and carbonaceous rocks are closely associated, would appear to be areas worthy of further exploration. The potential of the Carrara Range region is virtually untested. However, major faults are present, and the probable presence of dolomite and shale in the Musselbrook and Lawn Hill Formations led Sweet & Mond (1980) to recommend that further exploration be undertaken.

The second type is the copper mineralisation that is common in the lower units of the McNamara Group. In most cases, this is also associated with major faults, and the interval in which it mostly occurs, i.e. from just below the Mount Oxide Chert Member to the lower Lady Loretta Formation, also corresponds to the maximum development of felsic tuff in the sequence. It is probable that the mineralisation in many of these cases is a result of scavenging of metals from older units by solutions generated during the volcanic episode.

Acknowledgements

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PROTEROZOIC INTRUSIVE BRECCIA BODIES NEAR DUCHESS, NORTHWESTERN QUEENSLAND

D. H. Blake, R. J. Bultitude[1], & P. J. T. Donchak[1]

Several breccia bodies consisting of randomly oriented angular to rounded fragments of locally derived amphibolite-grade metamorphic rocks dispersed in an igneous-textured pink matrix occur in the southern part of the Proterozoic Mount Isa Inlier, where they have been mapped as Mount Philp Breccia. The fragments in the breccia can be matched with rocks in the adjacent Corella Formation, a unit of mainly calc-silicate rocks. The breccia matrix contains stubby phenocrysts of tremolite and small miarolitic cavities set in a groundmass of interlocking albite laths. The breccia bodies postdate the deformation and metamorphism of the enclosing Corella Formation, and are thought to fill pipes and fissures formed by explosive releases of pressure during intrusion of magma into calc-silicate rocks at depth.

Introduction

Bodies of breccia, consisting of randomly oriented angular to rounded fragments of banded and foliated metamorphosed rocks dispersed (i.e. not touching) in a non-foliated pink to red igneous-textured matrix, crop out at several localities near Duchess, in the southern part of the Mount Isa Inlier (Fig. 1). The largest and most northerly body was previously mapped as Mount Philp Agglomerate (Carter & others, 1961; Derrick & others, 1977a, 1977b), but this name has now been revised to Mount Philp Breccia (Blake & others, 1981). Several similar but smaller bodies of breccia were found to the south in 1977 (Bultitude & others, 1978, and in press). None of the breccia bodies has been studied in detail.

Geological setting

The Mount Philp Breccia bodies form part of the Precambrian Mount Isa Inlier (Geological Survey of Queensland, 1975), an area of complexly folded, faulted, and regionally metamorphosed volcanic, sedimentary, and intrusive rocks. They are situated in a north-trending belt of Corella Formation, which consists predominantly of banded calc-silicate and carbonate rocks, but also includes felsic and mafic metavolcanics, quartzite, and other metasediments. These rocks show small-scale and large-scale tight folding about steep to vertical axial planes, and are intruded by numerous mafic bodies and several granite plutons.

Near Duchess (Bultitude & others, 1978, and in press) the belt of Corella Formation is bounded to the east by the Pilgrim Fault, and to the west by concordant gneissic and schistose rocks, in part representing mafic and felsic volcanics mapped as Magna Lynn Metabasalt and Argylla Formation. According to Carter & others (1961) and Derrick and co-workers (e.g. Derrick & others, 1977b; Plumb & others, 1980; Derrick, 1980; Derrick & Wilson, 1981) the Corella Formation here is part of the Proterozoic cover sequence, and belongs to the 'eastern succession', but Blake (1980, 1981, 1982) has suggested that it may belong to the basement underlying the 'eastern succession'. It predates the 1720–1740 m.y.-old Burstall Granite and associated rhyolite dykes (isotopically dated, U-Pb zircon method, by Page, 1979, 1981), which intrude it to the north. The presence of clinopyroxene in most calc-silicate rocks, sillimanite in locally associated schistose metapelites, and green hornblende+oligoclase/andesine in interlayered mafic metavolcanics and also in many intrusive mafic bodies indicates that the Corella Formation has been regionally metamorphosed to amphibolite grade.

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Features of the Mount Philp Breccia

The distribution of the Mount Philp Breccia bodies is shown in Figure 1. The outcrops are generally elongate, parallel to the regional northerly trend of the enclosing Corella Formation. Contacts, where exposed, are highly irregular in detail, and veins and apophyses of breccia material commonly penetrate outwards for several metres. The large outcrops may represent groups of closely spaced or coalescing breccia bodies. Neither the present nor the original attitudes of any of the breccia bodies have been determined. Some of the bodies occur adjacent to faults.

Breccia fragments

The breccia fragments range in size from less than 1 cm to several tens of metres across, and in shape from equant to elongate, tabular, or irregular, and from angular to rounded (Figs. 2, 3). Even where closely packed, they are invariably separated from one another by matrix, contacts with which generally appear sharp and clear-cut. Some fragments, especially at their margins, show alteration to 'red rock' in which the feldspathic constituents are impregnated with very fine hematitic 'dust', giving them a red or deep pink colour.

Most fragments in the breccia bodies can be matched with rock types in the adjacent Corella Formation. They include various types of banded to massive, amphibolite-grade calc-silicate rocks, together with massive and foliated amphibolite, para-amphibolite, amygdaloidal amphibolitic metabasalt, quartzite, albitite, and mica schist. In addition, fragments of quartz-feldspar pegmatite (well-displayed at Pelican Waterhole) and metadolerite are present locally. The calc-silicate rock fragments are variously amphibolitic, diopsidic, opaque-rich, feldspathic, quartzose, carbonate-rich, and scapolitic, and range in colour from almost white to shades of pink, green, and grey. Amphibolite and metabasalt fragments are commonly scapolitic. Some banded fragments show small-scale folding.

The fragments form a heterogeneous, polymictic mixture enclosed in, and in places veined by, the pink to red matrix. Clearly, they were transported during breccia formation. Those of banded, folded, and foliated rocks are randomly oriented, indicating that

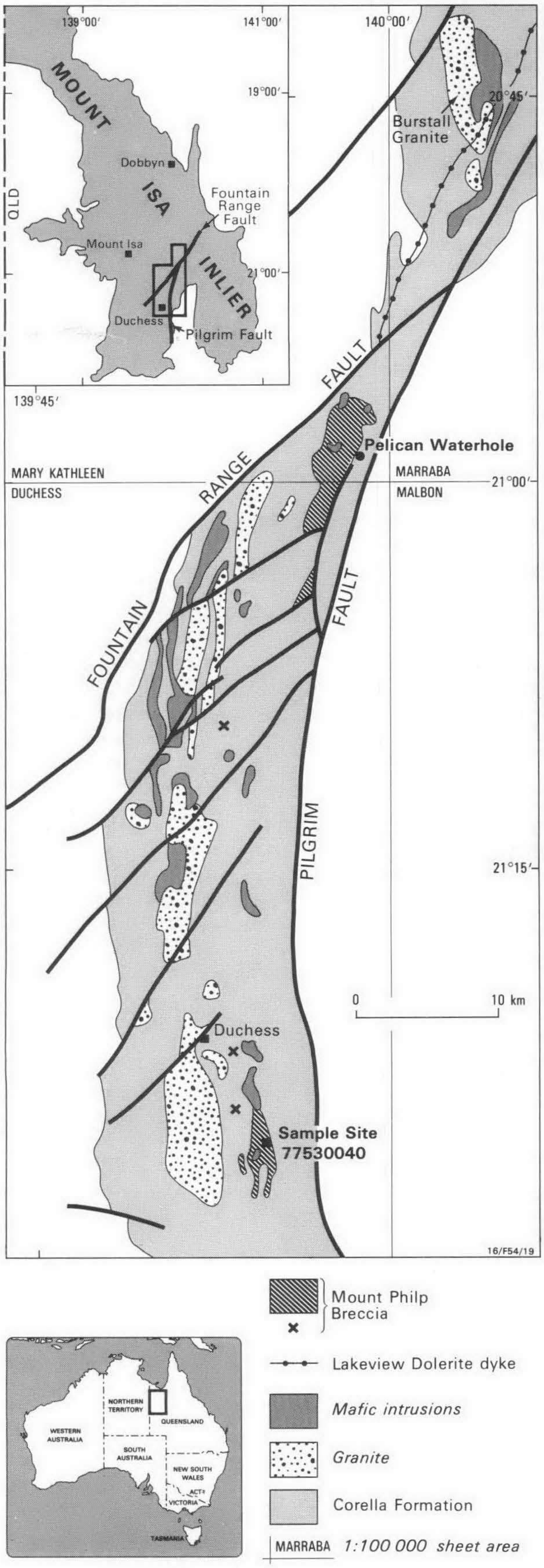

Figure 1. Locality map.

the brecciation took place after these rocks had been lithified, deformed, and metamorphosed. Many of the fragments, especially the larger ones, may not be far removed from their pre-brecciation positions, but no stratigraphic ordering of fragments like that found in some intrusive breccias (e.g., the Redbank breccia pipes described by Knutson & others, 1979) has been recognised.

Although most contacts between fragments and matrix are sharp and clear-cut megascopically, many are microscopically irregular to diffuse, and in some cases the felsic component of the outer part of the fragment consists of albite similar in texture to that of the matrix. In one sample examined, for example, coarse aggregates of pale green amphibole forming the bulk of a small mafic fragment poikilitically enclose small pools of groundmass-type albite.

Breccia matrix

The matrix enclosing the fragments (Figs. 4–9) is characterised by the presence of euhedral to subhedral, stubby crystals of green amphibole, commonly 2–3 mm long and 1–2 mm wide, set in a reddish fine and even-

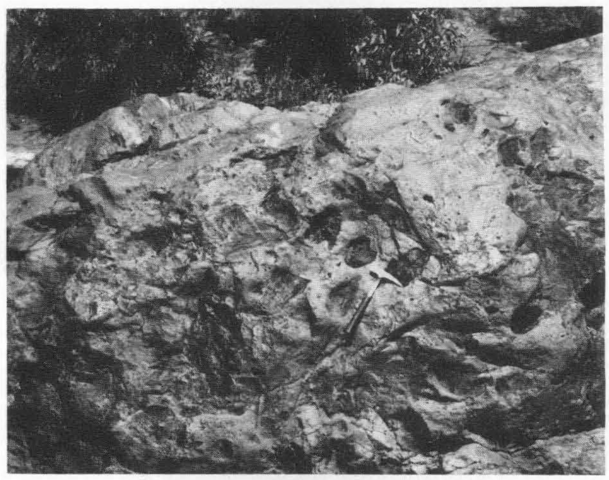

Figure 2. Angular to rounded fragments of calc-silicate rocks enclosed in a fine-grained matrix, Mount Philp Breccia at Pelican Waterhole.

Figure 3. Large fragment, cut by veins of felsic matrix material, alongside smaller irregular fragments in Mount Philp Breccia, Pelican Waterhole.

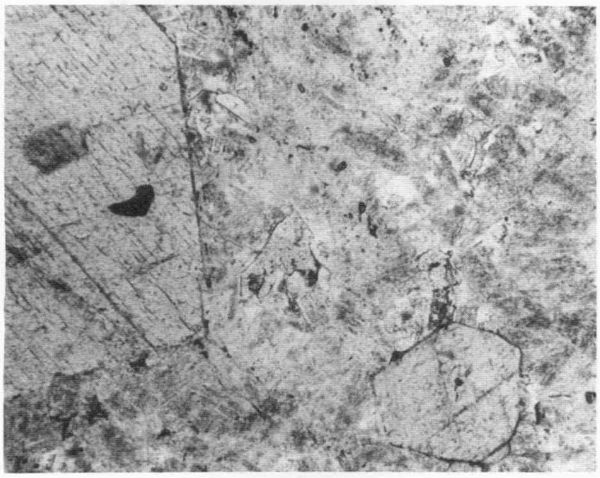

Figure 4. Matrix of Mount Philp Breccia.
Stubby euhedral crystals of tremolite in groundmass of albite laths. Ordinary light, sample 77530040. Width of field approx. 2 mm.

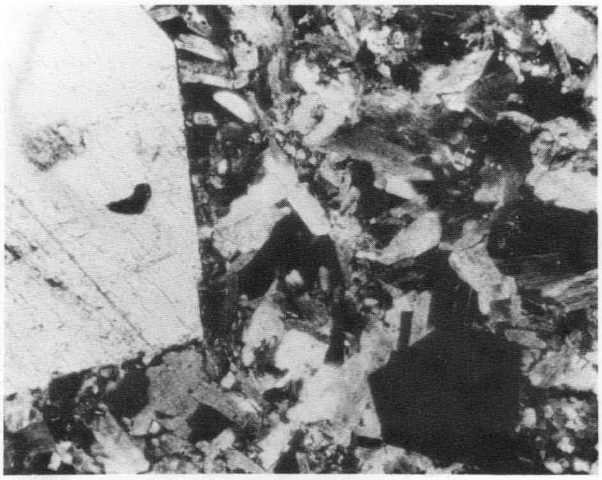

Figure 5. As above, crossed polarisers.

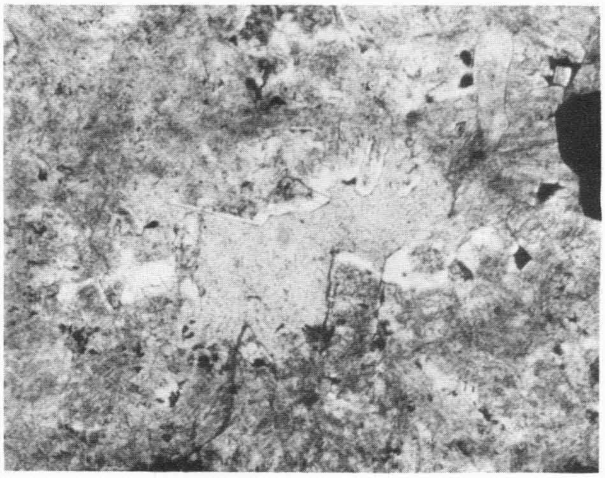

Figure 6. Matrix of Mount Philp Breccia.
Small irregular cavity lined with euhedral albite crystals. Ordinary light, sample 77530040. Width of field approx. 1.4 mm.

Figure 7. As above, crossed polarisers.

grained groundmass of interlocking, subhedral laths of albite impregnated with hematite dust. The amphibole crystals, which are pale green to almost colourless in thin section, typically make up between 10 and 15 percent of the matrix. Small irregular cavities lined with inwardly projecting albite crystals and partly filled with carbonate or clear albite are also generally present, as are magnetite euhedra, opaque granules and irregular clots, fine to coarse ragged grains of pale green amphibole and clinopyroxene, and small calc-silicate aggregates. In some samples the matrix contains a stilpnomelane-like mineral, mainly in small cavities. The well-shaped amphibole crystals differ from the irregular amphibole grains in being weakly colour-zoned and clean rather than full of minute inclusions or with prominent cleavages, although some contain a few small inclusions of clinopyroxene and other minerals. Some of the amphibole euhedra in the matrix of breccia southeast of Duchess have thin rims and small acicular overgrowths of darker amphibole (Figs. 8, 9), and many of those in the breccia matrix at Pelican Waterhole have minute patches of dark blue-green amphibole developed along cracks and cleavage traces. The albite crystals lining the irregular cavities are generally less turbid than the albite laths elsewhere in the matrix, and they commonly have clear outer margins (Fig. 6).

Representative chemical analyses of the main mineral components in the breccia matrix are given in Table 1. From the classification of Leake (1978), the amphibole euhedra consist mainly of tremolite, but some have rims of actinolite, and some in a sample from Pelican Waterhole contain minute patches of ferrowinchite and riebeckite. Clinopyroxene grains analysed consist of salite.

The textural features of the breccia matrix resemble those of typical high-level, felsic, igneous intrusions, and are taken to indicate crystallisation from a melt. The amphibole euhedra are, therefore, interpreted as phenocrysts rather than porphyroblasts, and the small irregular cavities are considered to be miarolites; the ragged grains and aggregates of amphibole, clinopyroxene, and opaque minerals are regarded as partly digested xenocrysts and xenoliths derived from the calc-silicate country rocks. The igneous-type textures distinguish the matrix of the Mount Philp Breccia bodies from that of tectonic breccias within the Corella Formation, which, although commonly consisting mainly of tremolite/actinolte and albite, have relatively coarse and more irregular textures and acicular rather than stubby amphibole crystals.

The matrix of the Mount Philp Breccia appears to vary little either locally or regionally, and its composition

Table 1. Representative analyses of albite, amphibole, pyroxene, and magnetite in matrix of Mount Philp Breccia.

	Albite			*Amphibole*						
				actinolite	*tremolite*					*Tremolitic hornblende*
	dusted 1a	clear 1b	dusted 2c	1Rd	1Cd	1Re	1Ce	2Rf	2Cf	1Cg
SiO_2	67.20	67.18	67.66	54.81	54.74	54.49	54.06	54.74	55.50	53.31
TiO_2	—	—	—	0.28	—	0.19	0.34	0.19	0.12	0.41
Al_2O_3	19.94	20.22	20.28	1.92	2.07	1.69	2.28	1.69	1.37	2.59
V_2O_3	—	—	—	—	—	—	—	—	—	—
Cr_2O_3	—	—	—	—	—	—	—	—	—	—
FeO*	0.50	—	—	9.49	9.86	9.02	10.19	7.17	6.85	10.03
Fe_2O_3**				6.00	7.89	7.44	8.72	7.76	8.58	7.15
FeO**				4.09	2.76	2.33	2.34	0.19	0.87	3.59
MnO	—	—	—	—	—	—	—	—	—	—
MgO	—	—	—	18.78	19.01	19.57	18.77	20.81	21.60	18.53
CaO	—	—	—	11.05	10.90	11.32	10.61	11.21	11.14	11.12
Na_2O	11.87	11.61	11.98	1.20	1.22	1.01	1.27	1.19	1.28	1.21
K_2O	0.06	—	0.08	0.11	0.07	—	0.11	0.14	0.10	0.17
Cl	—	—	—	0.06	0.05	0.13	0.14	—	—	0.17
Total***	99.57	99.01	100.00	97.70	97.92	97.42	97.77	97.14	97.96	97.54

* Total Fe as FeO

** Fe_2O_3 and FeO calculated from total-Fe values on the basis AB_2O_4 spinel and ABO_3 ilmenite stoichiometry in the case of magnetite; and from total-Fe values by varying the Fe^{2+}/Fe^{3+} ratios such that total cations, excluding Ca + Na + K. = 13 (Leake, 1978) in the case of amphibole.

*** Total includes FeO*, but not Fe_2O_3** and FeO** for amphibole. and includes Fe_2O_3** and FeO**, but not FeO* for magnetite.

In sample designation the number refers to the rock sample (1 = 7756005—from grid reference 933792, Pelican Waterhole. Mary Kathleen 1:100 000 Sheet area; 2 = 77530040—from grid reference 877306, Duchess 1:100 000 Sheet area); R = rim, C = core, P = small patch in amphibole euhedra; small letters indicate individual grains.

Analyses were made on the TPD electron microprobe at the Research School of Earth Sciences, Australian National University, following analytical procedures of Reed & Ware (1975).

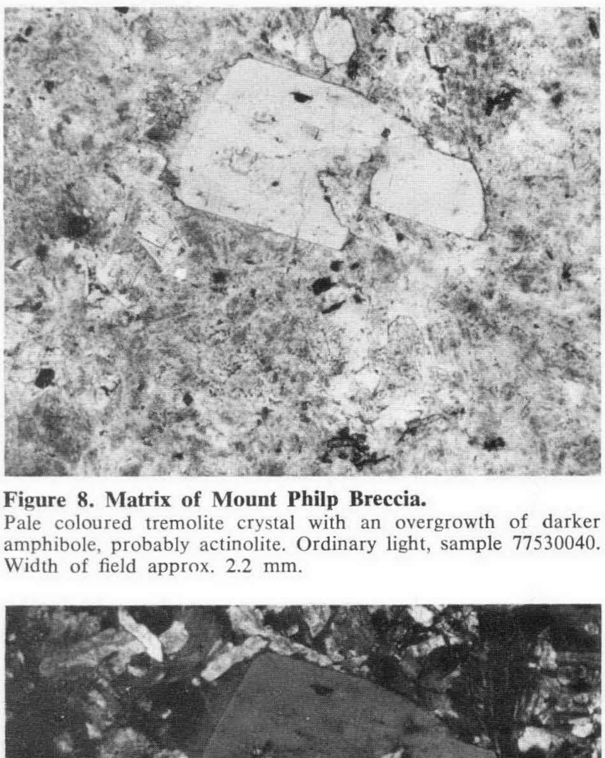

Figure 8. Matrix of Mount Philp Breccia.
Pale coloured tremolite crystal with an overgrowth of darker amphibole, probably actinolite. Ordinary light, sample 77530040. Width of field approx. 2.2 mm.

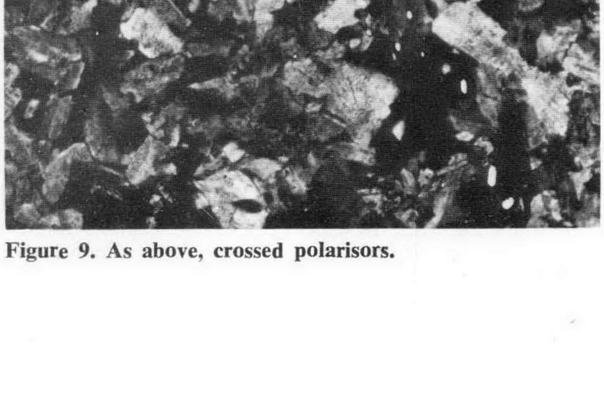

Figure 9. As above, crossed polarisors.

does not appear to be related to the proportion of matrix to fragments or to the composition of the locally predominant fragment type. Two whole-rock chemical analyses of the breccia matrix are given in Table 2; one of the samples analysed comes from Pelican Waterhole and the other from 9 km southeast of Duchess (sample site 77530040, Fig. 1) nearly 50 km to the south. Both samples contain about 60 percent SiO_2, and are characterised by high Na_2O and very low K_2O contents. Even if small amounts of xenolithic material are allowed for them, their chemical composition is quite unlike that of any unaltered igneous rock known to us. Similarly, no normal igneous rock consists predominantly of tremolite + albite, although this is a common metamorphic assemblage.

Origin of the Mount Philp Breccia

Any theory for the origin of the Mount Philp Breccia needs to take account of the following factors:

(1) The breccia crops out at widely separated localities, but is confined to a north-trending belt of the Corella Formation, a unit of mainly calc-silicate rocks.

(2) The fragments in the breccia are angular to rounded and consist of amphibolite-grade sedimentary, volcanic, and intrusive rocks, similar to those in the adjacent Corella Formation, which were regionally metamorphosed before being brecciated.

(3) The breccia is polymictic, and fragments within it are haphazardly arranged.

(4) Individual fragments in the breccia are separated from one another by matrix material: rarely, if ever, is one fragment seen to touch another. Hence the matrix was probably emplaced at the same time as the enclosed fragments.

(5) The matrix of the breccia has an igneous-type texture, and, unlike the enclosed fragments, does not appear to have been recrystallised to any marked degree or deformed.

(6) The composition of the breccia matrix appears to vary little from place to place, and is not obviously related to the proportion of matrix to rock fragments

	Amphibole				*Pyroxene*	*Magnetite*	
	Ferro-winchite		*Riebeckite*		*Salite*		
	1Ph	1Pi	1Pj	1Pk	1l	1m	2n
	53.05	51.68	53.19	52.52	53.08	0.31	0.00
	—	—	0.21	0.20	—	0.21	0.11
	0.81	1.28	0.74	0.93	0.63	0.25	0.24
	0.22	0.11	—	—	—	0.29	0.39
	—	—	—	—	—	0.14	0.19
	26.48	29.11	26.54	29.41	8.34	92.64	94.21
	10.44	10.92	10.63	10.64		67.52	69.59
	17.09	19.29	17.00	19.84		31.89	31.59
	0.26	—	—	—	—	—	—
	7.45	5.76	7.37	5.38	14.15	—	0.21
	4.35	4.44	3.23	2.33	21.56	—	—
	4.99	4.72	5.80	6.54	1.55	—	—
	—	—	—	—	—	—	—
	0.07	—	—	—	—	—	—
	97.68	97.10	97.08	97.31	99.31	100.61	102.32

or to the bulk composition of the enclosed fragments. It is not like that of any known unaltered igneous rock in the Mount Isa Inlier or elsewhere. However, in mineralogy and perhaps in overall chemistry, although not in texture, the matrix is similar to that of some tectonic calc-silicate breccias in the Mount Isa Inlier.

Factors 2, 3 and 5 indicate that the bodies of Mount Philp Breccia were formed after the surrounding Corella Formation had been deformed and regionally metamorphosed to amphibolite grade, so they cannot be contemporaneous with any volcanics in the Corella Formation, the interpretation favoured by Carter & others (1961) and Derrick & others (1977a, 1977b). The heterogeneous, polymictic, matrix-supported nature of the breccia and the igneous-type texture and relatively uniform composition of its matrix (factors 2–6), militate against the breccia being merely an aggregate of metamorphosed and metasomatised calc-silicate rock fragments, an additional possibility suggested by Derrick & others (1977a, 1977b). However, the spatial association of the Mount Philp Breccia with the Corella Formation (factor 1) does indicate a possible genetic relationship between the breccia bodies and calc-silicate rocks.

A likely explanation, in our view, is that the Mount Philp Breccia fills pipes and fissures that may have reached the surface as diatremes. We suggest that the breccia bodies formed when magma was intruded into already hot, regionally metamorphosed calc-silicate rocks of the Corella Formation at depth: the magma further raised the temperature of the calcareous rocks, causing CO_2 and H_2O to be liberated (e.g. Winkler, 1979), and the resultant increases in pressure locally became sufficient to explosively fracture the overlying Corella rocks. With each explosive release of pressure, a melt derived either from the magma, the calcareous rocks, or both, was injected upwards into the brecciated rocks, perhaps as a fluidised mixture of melt, gases, and solid particles in the manner suggested by Reynolds (1954) for somewhat similar intrusive breccias in Ireland, described by Pitcher & Read (1952). During this process many of the originally angular fragments in the breccia were abraded to subangular and rounded shapes. The fragments became suspended in the melt, which rapidly cooled and crystallised as the matrix of the breccia; gases remaining in the crystallising matrix caused miarolitic cavities to develop. Marginal alteration of fragments in the breccia may be attributed to chemical reaction between susceptible fragments and adjacent matrix and also, in some cases, to partial melting or replacement of mineral phases in fragment margins.

The magma triggering breccia formation near Duchess may have remained sufficiently hot (~1000°C) for long enough to partially melt significant amounts of adjacent Corella calc-silicate rocks. If this was the case, the breccia matrix could conceivably represent the partial melt. Such an explanation would account for the igneous texture but non-igneous composition of the breccia matrix, and also for the presence, in breccia north of Pelican Waterhole, of irregular dolerite bodies with bulbous margins—these may represent bodies of mafic magma injected into only partly solidified breccia.

Alternatively, the breccia matrix may represent a magma derived from deeper in the crust, rather than a partial melt derived from the Corella Formation. Such a magma is unlikely to have had the same composition as the present breccia matrix, which is not that of a normal igneous rock. Possibly it was syenitic, and the breccia matrix, though originally of this composition, became enriched in sodium and depleted in potassium during post-emplacement metasomatism. However, there is no petrographic evidence of much soda metasomatism in the breccia matrix: the main constituents are plagioclase laths, which are now albite, but may have been more calcic (rather than potassic) prior to any subsequent alteration, and euhedral megacrysts of

Table 2. Chemical analyses of Mount Philp Breccia matrix

	1	2
SiO_2	59.8	61.2
TiO_2	0.43	0.45
Al_2O_3	12.1	15.4
Fe_2O_3	4.79	5.15
FeO	3.59	1.94
MnO	0.04	0.04
MgO	6.90	3.43
CaO	4.36	2.31
Na_2O	7.05	8.10
K_2O	0.17	0.10
P_2O_5	0.09	0.08
H_2O+	0.96	0.79
H_2O-	0.17	0.26
CO_2	0.05	0.10
Total	100.5	99.35
Rb	6	6
Ba	<10	15
Pb	<2	75
Sr	26	34
La	20	15
Ce	25	15
Y	24	16
Zr	160	110
Nb	14	14
U	2	n.a.
Cu	15	n.a.
Co	<5	n.a.
Ni	<5	n.a.

1. Sample 77536005 from Pelican Waterhole (GR933792), Mary Kathleen 1:100 000 Sheet area.
2. Sample 77540040 from GR877306, Duchess 1:100 000 Sheet area.

Values, determined by a combination of XRF, atomic absorption spectroscopy, and colorimetric and gravimetric methods, were supplied by the Australian Mineral Development Laboratories, Adelaide.
Trace elements in ppm.
n.a.—not analysed.

tremolite/actinolite, not a sodic amphibole. Also there is no independent evidence indicating that the north-trending belt of Corella Formation may be underlain by large volumes of syenite (igneous rocks of this composition are rare or absent in the Mount Isa Inlier).

The suggested mechanism for breccia formation is similar in some respects to that proposed by Knutson & others (1979) for the breccia pipes in the Redbank area of the McArthur Basin, Northern Territory: the Redbank breccias are considered to have formed by high-level trachytic igneous activity and associated hydrothermal processes causing explosive releases of fluids. However, the Redbank breccias are fragment-supported, rather than matrix-supported, have a detrital rather than igneous matrix, and were evidently emplaced at temperatures between 300°–150°C, much lower temperatures than thought likely for the matrix of the Mount Philp Breccia bodies. Also a hydrothermal fluid would not be sufficiently viscous to hold rock fragments in suspension and prevent them from touching.

The Mount Philp Breccia bodies are thought to be younger than the 1720–1740 m.y.-old Burstall Granite and probably related granites near Duchess, which have been regionally metamorphosed and deformed, and older than dykes of unmetamorphosed Lakeview Dolerite, isotopically dated by the Rb-Sr method at 1116 ± 12 m.y. (Page, quoted in Derrick & others, 1978).

Apparently similar intrusive breccias have been described by Reinhardt (1972) from the East Arm of Great Slave Lake, Canada. These breccias form highly irregular pipe-like bodies mainly cutting sedimentary rocks, some of which are calcareous, and they are locally associated with a red, fine-grained felsitic rock, described as igneous, which may be comparable to that forming the matrix of the Mount Philp Breccia. According to Reinhardt (1972), the breccias were probably formed by explosions involving gases derived at depth from either magmatic crystallisation or interaction of magma and water, and, as suggested for the Mount Philp Breccia bodies, the fragments in the pipes may have been transported by fluidisation processes.

Acknowledgements

Critical reviews of earlier versions of the manuscript by J. Knutson, R. N. England, D. Wyborn, and L. A. I. Wyborn are gratefully acknowledged. R. J. Bultitude and P. J. T. Donchak publish with the permission of the Director-General, Department of Mines, Queensland.

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ABSTRACTS—11th BMR SYMPOSIUM, CANBERRA, 4-5 MAY 1982

Mineral sands—a dwindling resource?

J. Ward

In the late 1940s BMR drilled known economic deposits of heavy-mineral sands along the east coast, primarily to determine reserves of monazite and its contained thoria, then regarded to be of considerable strategic importance. On the basis of this investigation Australian reserves of heavy mineral sands in 1950 were assessed as: rutile—700 000 tons; zircon — 950 000 tons; ilmenite — 470 000 tons; monazite—12 000 tons. Since then Australia has produced: rutile—6.4 Mt; zircon—7.4 Mt; ilmenite—(commercial-grade) 14.9 Mt; monazite—(saleable-grade) 102 000 t.

In its annual update of mineral resources, BMR has estimated Australian demonstrated economic resources of mineral sands in 1981 as: rutile—9.5 Mt; zircon—13.7 Mt; ilmenite—43.6 Mt; monazite—334 000 t.

This paper traces the history of discovery and expansion of mineral-sand resources, and clarifies the paradox of the foregoing statistics. In particular, since 1950, major additional deposits of mineral sands have been delineated on both the eastern and western seaboards, and technological advances in mining and concentrating techniques, as well as increased prices for the relevant mineral commodities, have enabled mining operations to be conducted on head grades as little as one-tenth of those considered payable in the early 1950s.

Projected output from known deposits indicates that, by the turn of the century, approximately 70 percent of demonstrated economic resources of mineral sands will be depleted. However, a substantial proportion of known reserves are 'frozen' because of environmental and other considerations, and reserves actually available for mining will be depleted much earlier, particularly in the case of rutile. Patently, known reserves of mineral sands have reached the threshold of concern, and BMR has initiated a program of fundamental research into the provenance and geological controls of heavy-mineral sand deposits, and has recently undertaken a reconnaissance survey and sampling campaign on potential deposits off the east coast.

An assessment of Australian chromite resources

R. Pratt

Chromite has been mined intermittently on a small scale in Australia since 1882. However, like most of the industrialised countries, we import nearly all our chromite, and are almost wholly dependent on imports of chromite, ferrochromium, and chromium chemicals to meet our requirements.

The known chromite deposits in Australia can be divided into three types: (i) Podiform deposits in the Palaeozoic serpentinites in eastern Australia; (ii) Stratiform deposits in Archaean and Lower Proterozoic mafic and ultramafic intrusives in Western Australia; and (iii) Alluvial concentrations such as those of Tertiary age at Beaconsfield in Tasmania.

The podiform deposits are the most numerous, but individual deposits are relatively small. The largest of this type known are at Princhester in Queensland. Exploitation of these deposits is dependent on the development of a suitable beneficiation process. The stratiform deposits in Western Australia are larger, and are considered to have the potential for development to meet local metallurgical and chemical demand, and supply overseas markets if certain mining and beneficiation problems can be overcome. Alluvial chromite was mined at Beaconsfield from 1978 to 1980, and this activity has stimulated interest in alluvial sources of chromite. Additional deposits of alluvial chromite are known at Beaconsfield, and further exploration for and testing of alluvial chromite deposits would appear to be warranted.

The assessment conducted by BMR with the assistance of industry has shown that Australian chromite resources are larger than previously believed. Demonstrated resources of chromite in known deposits are large enough to be developed to meet Australia's domestic requirements. However, development of known deposits cannot be economically justified at current prices, and some technical problems need to be overcome.

The use of diagenetic features for evaluating reservoir quality, Sydney Basin

S. Ozimic

The sediments of the Permian Shoalhaven and Maitland Groups in the Sydney Basin have been subjected to at least three diagenetic phases (syndiagenesis, anadiagenesis, and epidiagenesis); and three diastrophic events (Permian Hunter-Bowen orogeny, Upper Triassic movements, and probable Tertiary epeirogenic movements). In the arenaceous members the progressive diagenesis produced a sequence of diagenetic features that have considerably decreased the quality of the potential reservoirs, mainly by the reduction of porosity and permeability. The reduction of primary and secondary porosity as well as permeability is, therefore, attributed to the following diagenetic features that have been produced during the burial and subsequent uplift: • early pore fill (calcite dolomite, dawsonite, siderite, silica and pyrite); • clay coating of detrital grains (illite); • silica pore fill (quartz overgrowths); and • late pore and fracture fill (carbonates and clay).

The Nabarlek uranium deposit—petrology, geochemistry, and some constraints on genesis

G. R. Ewers, John Ferguson, & T. H. Donnelly

The Nabarlek uranium deposit is located in the Alligator Rivers Uranium Field (ARUF) near the other major deposits of Jabiluka, Ranger, and Koongarra. Broad similarities and some significant differences in the features and setting of the mineralisation at Nabarlek, as compared to the other ARUF deposits, have prompted the present study. The petrology and geochemistry of the host rocks and ore zone have been investigated and, in conjunction with limited stable-isotope data, have enabled some constraints to be applied to the genesis of the Nabarlek deposit.

Mineralisation is confined to a crush zone in Early Proterozoic schists, and occurs near an unconformity with overlying Middle Proterozoic sandstone. The results indicate that uranium was transported to the site of deposition as a uranyl complex. and that the earliest mineralisation was associated with massive chlorite and, possibly, carbonaceous material. This carbonaceous material has since been largely or completely oxidised by high-temperature fluids entering the ore zone. At or after 920 m.y., the orebody was extensively sericitised. This sericitisation has caused a remobilisation of uranium and appears to have reset uraninite ages to 920 m.y. The replacement of chlorite by sericite has been accompanied by the formation of hematite, and where residual uraninite is present, redox reactions involving iron and uranium are evident. Erosion of the Middle Proterozoic cover rocks in the recent past has exposed the deposit to the effects of weathering.

The influence of tectonism on petrogenetic processes in the South Alligator Valley area in Early to Middle Proterozoic time

P. G. Stuart-Smith & R. S. Needham

The Alligator Valley area lies in a broad, major northwest-trending crustal structure, which has been the locus of tectonic activity since Early Proterozoic time. Tectonism in the area has influenced sedimentation patterns, igneous activity, metamorphism, and the distribution of uranium mineralisation.

During the Early Proterozoic, the area formed part of the northwest-trending South Alligator Trough, an incipient fault trough that formed the central axis of the Pine Creek Geosyncline. The trough was the locus of several periods of mafic to felsic volcanism, and thicker sedimentation than in other areas of the geosyncline. Facies changes in the South Alligator Group across the eastern margin of the trough indicate penecontemporaneous faulting and partial erosion to the east. This margin continued to be a major zone of dislocation during metamorphism and deformation between 1870 and 1800 m.y. ago.

Following uplift and erosion of the Early Proterozoic metasediments between 1800 and 1760 m.y. ago, renewed igneous activity accompanied block faulting along reactivated northwest-trending Early Proterozoic faults within the trough. Two separate sequences of felsic volcanics and fluviatile sediments were deposited in fault-bounded basins. Volcanics in the latter sequence were probably comagmatic with granite intrusion at about 1760 m.y. Faulting was active before, during, and after sedimentation.

At about 1650 m.y., Middle Proterozoic platform sedimentation of the western McArthur Basin sequence of northern Australia extended across a relatively stable, peneplaned, metamorphic basement (the Arnhem Shelf). In the South Alligator Valley area the braided alluvial sandstone of the Kombolgie Formation was deposited. Considerable subsidence related to reactivation of faults resulted in at least double the thickness of Kombolgie Formation sedimentation compared to other parts of the Arnhem Shelf.

A very long stable erosional period followed, during which the marginal faults of the trough remained active and the Middle Proterozoic sediments were locally drag-folded. Continued faulting is evidenced by the deformation and basin development of Cretaceous and Tertiary sediments. These long-lived faults have also been important in localising uranium mineralisation at around 800 and 500 m.y. ago in the area, by providing suitable structural sites, and contacts between the probably Middle Proterozoic volcanic source rock and host Early Proterozoic carbonaceous strata.

Design and interpretation of gamma-spectrometer and radon surveys for mapping and exploration in the Pine Creek Geosyncline

D. C. Stuart

Field and theoretical studies provide a guide to the use of gamma-spectrometry and radon surveys for mapping and exploration in the Pine Creek Geosyncline. Regional traverses, employing surface and down-hole gamma-spectrometry, and radon surveys establish the radioelement characteristics of important stratigraphic units of the geosyncline. The results indicate that the radiometric characteristics of overburden and weathered rocks commonly reflect the radioelement concentration of fresh bedrock. Iron-rich units in the important Koolpin Formation produce a characteristic radiometric response, which can be used to map the formation on a regional scale and assist in the delineation of areas prospective for uranium mineralisation.

Detailed surface and down-hole gamma-spectrometer and radon surveys over zones of mineralisation and radiometric anomalies at Rum Jungle and in the Alligator Rivers area indicate the radiometric characteristics of uranium mineralisation in the geosyncline. The results suggest that uranium mineralisation is commonly accompanied by a surficial radiometric halo that gives rise to both gamma-spectrometer and radon anomalies. Although the investigation of a strong radon anomaly without a coincident gamma-spectrometer anomaly illustrates the potential for radon methods to indicate the presence of deposits blind to gamma-spectrometry, the results show that finding the source of such anomalies will be difficult. Radon methods are also shown to be particularly useful for prospecting in areas of radioactive contamination.

Modelling indicates that important surface expressions of uranium mineralisation may not be detected by high-sensitivity, close-spaced airborne surveys. Even on the ground, high-sensitivity close-spaced surveys are necessary to ensure detection of small but significant surface expression of bedrock radioelement concentrations. Field and model studies of emanometer surveys indicate that ratio measurements provide a quick and effective guide to anomalous concentrations of radon. The potential advantages of high-sensitivity, down-hole gamma-spectrometer surveys are shown to be difficult to achieve owing to instrument, calibration, and geological noise problems.

Geology of the Davenport Geosyncline—preliminiary results

D. H. Blake & A. J. Stewart

The Davenport Geosyncline is a relatively little known Precambrian region containing deposits of W, Au, Cu, Pb, Ag, and U. It links the Precambrian Arunta and Tennant Creek regions to the south and north, and is overlain to the east and west by flat-lying Palaeozoic sediments of the Georgina and Wiso Basin successions. A joint BMR-NTGS project, started in 1981 and planned for completion by 1985, is aimed at determining the geosyncline's detailed stratigraphy, structure, geological history, tectonic setting, and mineral potential.

Most of the rocks exposed in the area examined so far are assigned to the Early or Middle Proterozoic Hatches Creek Group. No rocks older than this group have been identified, and the presence of the Warramunga Group in the region has not been verified; a possibility yet to be dismissed is that the Hatches Creek and Warramunga Groups are partly lateral equivalents. The Hatches Creek Group is at least 10 000 m thick and consists of resistant ridge-forming sandstone units interlayered with less resistant and commonly much-weathered sedimentary and volcanic units. The sedimentary rocks are shallow-water deposits, consisting largely of quartz derived from elsewhere and volcanic detritus that is probably locally derived; they also include carbonates (some containing stromatolites) and evaporites. The volcanic rocks are represented by both lavas and pyroclastics, and appear to show a complete range in composition from olivine-bearing basalt to rhyolite; however, no chemical data are available yet.

The Hatches Creek Group is subdivided at present into eighteen formations, and more generally into lower, middle, and upper parts. In the lower part the constituent formations interfinger laterally with one another, but the middle and upper parts show a general layer-cake stratigraphy. The upper part differs from the other two parts in being essentially non-volcanic. There may be a significant unconformity at the base of the middle Hatches Creek Group, where a major ridge-forming sandstone unit overlies several different volcanic and sedimentary units of the lower Hatches Creek Group. The group has been folded into domes and open to tight anticlines and synclines, extensively faulted, and has been regionally metamorphosed to mainly middle and upper greenschist facies. The major folds have steeply inclined arcuate axial planes and gentle to moderate plunges. Axial-plane cleavage is common, and schistose rocks are present locally. Two folding episodes can be recognised in places. Most faults postdate the folding. Primary sedimentary and volcanic textures are generally well preserved within the group, but metamorphic greenish-brown biotite, epidote, white mica, and chlorite are widespread.

Numerous mafic and felsic sill-like bodies, metamorphosed to greenschist facies, intrude the Hatches Creek Group, especially the lower part, and may be comagmatic with extrusive volcanics of the group. The mafic intrusions consist of gabbro and dolerite and commonly contain country rock screens. The felsic sills are predominantly granophyre. There are also some granite intrusions that appear to post-date the folding and regional metamorphism, and hence may be much younger than the Hatches Creek Group. A Rb-Sr age of 1660 m.y. and K-Ar ages of between 1540 and 1320 m.y. have been obtained previously on some of these granites.

The known metalliferous mineral deposits are mainly located in quartz veins, at least some of which (e.g. the tungsten lodes at Hatches Creek) appear to post-date folding and are possibly related to granite emplacement. However, there may be some syngenetic mineralisation, as copper and lead minerals locally occur in amygdales in basaltic lavas, and gabbro, dolerite, and granophyre commonly contain sulphide minerals.

Economic prospects for manganese nodules in the Southwest Pacific

N. F. Exon

Manganese nodules are present at 75 percent of 300 deep-sea stations in the Kiribati-Cook Islands region of the Southwest Pacific, which extends from 6°N to 25°S. They are most abundant and of highest metal grade (% Ni + Cu + Co) near the calcite-compensation depth, which deepens northward from 4500 m to 5500 m. Major variations in nodule concentrations and metal grades appear to be largely controlled by plankton productivity, and the deposits fall into three groups separable by latitude. The main features of these groups are tabulated below.

Nodule grades are too low in the two southern groups for these groups to have any apparent economic potential. However, the grades in parts of the poorly sampled East Central Pacific Basin are as high as those in the ore-grade fields of the Northeast Equatorial Pacific, and concentrations are moderate to high. Despite a tendency for very high grades to be associated with lower concentrations, the basin's economic potential appears to be high. More sampling is needed to confirm this potential, especially in the east and west.

	Basins	Basinal sediment	*Concentration (kg/m^2)* Mean	Max.	*Grade (%Ni+Cu+Co)* Mean	Max.	*Economic prospects*
6°N–5°S	East Central Pacific	Siliceous ooze	8	31.6	1.73	3.55	High
5–9°S	North Penrhyn	Calcareous and zeolitic clay	1	10.7	1.32	2.10	Low
9–25°S	South Penrhyn, SW Pacific	Calcareous and zeolitic clay	13	62	1.02	2.02	Low

Reassessment of the tectonic setting of the Mount Isa Inlier in the light of new field, petrographic, and geochemical data

L. A. I. Wyborn & D. H. Blake

It has been proposed recently that the Mount Isa Inlier represents a Proterozoic continental margin on the eastern side of the Australian craton. This proposal is based largely on geochemical criteria: volcanics of the Tewinga Group are reported to be comparable in chemistry to those of the Andean region, and to have K_2O/SiO_2 values that decrease eastwards; basalts in the west have been related to continental tholeiites and those in the east to ocean-floor tholeiites. Additional evidence put forward in support of the suggestion includes: (1) older Precambrian basement is known only to the west of the inlier; (2) deep water sediments, represented by turbidites, are restricted to the easternmost part of the inlier; and (3) a general increase in regional metamorphic grade from west to east and a predominance of folding in the east and faulting in the west (and also regional Bouguer gravity anomalies) indicate eastward crustal thinning. However, none of these criteria may be valid.

The Tewinga Group consists mainly of felsic volcanics, which belong to two quite separate suites: the 1870 m.y. old Leichhardt suite, and the much younger Argylla suite, which is dated at about 1780 m.y. Andesite, the characteristic volcanic rock of the Andes, is either very rare or absent in both suites and also elsewhere in the Mount Isa Inlier. The K_2O values of the felsic igneous rocks are somewhat variable, but do not show a general decrease eastwards. The main mafic volcanic units exposed in the inlier are probably between about 1810 and 1760 m.y. old, and are remarkably uniform in chemistry except for one part of the Eastern Creek Volcanics in the west, which is relatively enriched in incompatible elements such as Ti, P, Y, and Nb.

Scattered outcrop and drillhole data show that granite and metamorphic rocks of probably Precambrian age, but not oceanic crustal rocks, underlie Mesozoic sediments of the Carpentaria and Eromanga Basins separating the Mount Isa Inlier from the Georgetown Inlier, which includes Precambrian rocks at least 1550 m.y. old, to the east. The turbiditic sediments in the southeasternmost part of the Mount Isa Inlier decrease in grainsize and feldspar content westwards, indicating a source to the east rather than to the west. Amphibolite-facies metamorphics occur throughout the Mount Isa Inlier and are not restricted in the west to thermal aureoles around granites. Most granites are themselves regionally metamorphosed to amphibolite facies. The main metamorphism postdates the deposition of the 1670 m.y. old Mount Isa Group, and hence is 100 to 200 m.y. younger than most of the volcanism. Folding is prevalent within the inlier where layered metasediments predominate, in the west as well as in the east; faulting is most evident where relatively rigid units, such as large granite plutons and thick volcanic sequences, have been involved in the deformation. Regional gravity maps show that the Mount Isa Inlier is a gravity high that is flanked to the east and west by gravity lows, and they do not indicate that the crust is significantly thinner to the east than to the west.

Rather than being formed at a continental margin the pronounced bimodal volcanic chemistry and other available evidence indicate that most of the Mount Isa Inlier may have developed in an intracratonic setting during a mainly tensional regime which lasted from about 1880 m.y. to about 1670 m.y. or possibly 1600 m.y. ago. Major deformation during a succeeding compressional regime caused tight folding and greenschist to amphibolite-facies regional metamorphism.

The origin of megapolygon–spelean limestone associations

Robert V. Burne

Probably the most complex products of early carbonate diagenesis described so far are limestones that originally formed as fenestral intertidal carbonates as part of a regressive sequence, and which have been subsequently altered to produce a lithology characterised by speleothemic cements lining decimetre-scale cavities, secondary pisoliths, 5–30 m scale megapolygons, and tepee structures. Rocks of this type have been described from the Permian of west Texas, the Triassic of Lombardy, and the Jurassic of the Atlas Mountains. The origin of this megapolygon-spelean limestone association (MSLA) has never been satisfactorily explained, although it has been suggested that it forms under 'vadose schizohaline' conditions in a peritidal environment subject to alternate flushing by fresh meteoric waters and flooding by hypersaline waters of marine origin swept in by storm tides.

At Fisherman Bay, South Australia, saline continental groundwaters, rising from a confined Tertiary carbonate aquifer, form springs in the supratidal zone of a Holocene regressive marine-carbonate complex. When the carbonate-rich spring waters approach the surface, CO_2 is evolved and aragonite is precipitated to form areas of limestone, which have close spatial relationship with the present-day springs. These limestones contain a variety of diagenetic features, including megapolygons, tepee structures, fenestral and cavernous textures, secondary pisoliths, and aragonitic speleothems and fibrous cements. Aragonite plates, found piled loosely on the floors of some cavities in the limestone, are considered to be deposits of floe aragonite, analogous to the floe calcite that forms on the surface of tranquil pools in some present-day caves. The close parallels between these limestones and the ancient examples of MSLA referred to above suggest that they share a common origin.

The petrifying spring at Fisherman Bay has a hydrological setting in which a series of independent conduits exist that are analogous to karst cave systems, except for the fact that water-flow is directed *upward*, towards the piezometric surface of the confined aquifer. The hydrological conditions in adjacent conduits may differ markedly at any one time, and hence reference to vadose and phreatic hydrological zones based on the concept of a general water table is not relevant in such an area.

The ancient MSLA form extensive belts 30–300 km long, and are considered to have formed along belts of peritidal springs of saline continental groundwaters. This characteristic facies is therefore a geologically important indicator of a paralic environment adjacent to a land mass with karst-type cryptorheic drainage and where deposits of processes of surface drainage are absent.

Geochemical and isotopic studies of carbonate environments at Lake Eliza, Shark Bay, and Spencer Gulf

J. Ferguson & L. Plumb

Lake Eliza, South Australia, Shark Bay, Western Australia, and Spencer Gulf, South Australia are Holocene carbonate environments where marine and continental groundwaters influence a wide variety of diagenetic processes, including some implicated in the accumulation of hydrocarbons and base metals. Concentrations of 3 to 4% organic C are preserved in fine-grained carbonate sediments in Lake Eliza, a coastal salt lake with a predominantly continental groundwater input. At Shark Bay comparable concentrations of organic matter are associated with highly saline, marine groundwater environments in the intertidal zone.

Continental groundwaters in peritidal areas at Shark Bay are restricted to the landward fringe of the supratidal zone. They are similar in chemical and isotopic composition ($\delta^{34}S$, +21‰ CDT; $\delta^{18}O$, −1 to +4‰ SMOW) to marine groundwaters and do not induce major diagenetic changes in the sediments. Continental groundwaters at Spencer Gulf have a much wider range of chemical composition and are responsible for the precipitation of gypsum, lithification of supratidal carbonate sediments, and the generation of high concentrations of Fe_2O_3 (30 to 70%). The continental groundwaters may be identified from their sulphur, carbon, oxygen, and deuterium stable-isotope ratios, which are usually considerably lower than the corresponding marine values. Sulphur becomes incorporated into the sediments as gypsum ($\delta^{34}S$, +15‰), and carbon and oxygen are introduced in the form of aragonite cement ($\delta^{13}C$, −4.5; $\delta^{18}O$ −5‰ PDB) precipitated from groundwater springs.

The hydrogeochemical processes that produce high concentrations of Fe_2O_3 at Spencer Gulf are similar to those proposed for the formation of some types of low-temperature, stratiform Cu deposits, but the source rocks do not contain significant concentrations of readily available Cu, Pb, or Zn.

Australian seismic refraction results, isostasy, and altitude anomalies

Peter Wellman

Although seismic refraction surveys have been carried out over extensive areas of continental crust, the causes of variation in crustal thickness and mean crustal velocity, are poorly understood. If the crust is in regional (3° x 3°) isostatic equilibrium, as is suggested by many regional gravity studies, variation in crustal thickness should be caused largely by variation in surface altitude and mean crustal density. An analysis of Australian seismic refraction results gives the following causes of crustal thickness variation. Surface altitude effects cause about 2 percent of the variation. Changes in mean crustal density cause about 38 per cent. Non-planar layering and local deviations from isostatic equilibrium cause about 17 per cent. The remaining 43 per cent of the variation is caused by differences between geological provinces, and is thought to reflect variations in lower lithospheric density.

This study suggests that, within a geological province, 66 per cent of the crustal thickness variation is caused by variations in mean crustal density. Between adjacent geological provinces 40 per cent of the crustal thickness variation is caused by changes in the mean crustal density across the boundary, and 40 per cent is caused by changes in the mean density of the lower lithosphere across the boundary.

BMR in Antarctica—history and achievements

R. J. Tingey

The establishment of the BMR in 1946 was closely followed by that of the Australian National Antarctic Research Expeditions (ANARE) in 1947; since then the two organisations have had a long association. A BMR geologist and a geophysicist accompanied the first ANARE to Heard and Macquarie Islands in the 1947–48 summer, and BMR scientists have been members of many subsequent ANARE groups.

ANARE activities in the Australian Antarctic Territory proper did not start until 1954, when Mawson Station was established. BMR has operated a geophysical observatory there since 1955, and its Mawson-based geologists and geophysicists were, from 1954 until 1961 at least, members of exploratory parties that reconnoitred the Mawson hinterland for distances of up to 650 km. In particular, long reconnaissance journeys were made by air and by various modes of surface transport to the Prince Charles Mountains, where basement metamorphic rocks and a small enclave of Permian sediments were found, and to Enderby Land, where only metamorphic rocks crop out. There were also expeditions along the Antarctic coast with the expedition support ships. However, by 1961 it became evident that too much of the station geologists' time was being occupied in travelling, and a change was made to helicopter-supported summer operations. At this time also a start was made on systematic 1:250 000-scale mapping near Mawson.

Reconnaissance geological work essentially finished in 1965, when ANARE provided three helicopters and a fixed-wing aircraft to support a group that included a four-man BMR geological party. The more systematic approach was further developed in 1969, when a five-year investigation started in the Prince Charles Mountains, the largest inland exposure of the East Antarctic Shield. The ANARE investigations were multi-disciplinary and supported by turbine helicopters and fixed-wing aircraft; supplies were delivered to the field area by tractor train. The main geological result of this work was the subdivision of the Precambrian basement rocks into Archaean and Proterozoic components and the development of ideas that might be applied elsewhere. Field techniques were also refined, and a successful program of colour vertical air photography completed.

These techniques and ideas were then applied with considerable success in Enderby Land between 1975 and 1980. Previous reconnaissance there had revealed the existence of some very unusual high-grade metamorphics, and it was again possible to separate the Archaean and Proterozoic components of the basement metamorphic complex. BMR and university specialists also contributed structural, geochronological, geochemical, and petrological studies to the investigations (e.g. L.P. Black, this Symposium). Since the end of the Enderby Land programs, onshore field programs have been confined, by a lack of resources and a new emphasis on marine work, to limited operations near the permanent ANARE Stations.

The BMR Antarctic geophysical effort can be divided into observatory operations and regional surveys. Since the mid-1950s, BMR has operated a magnetic and seismic observatory at Mawson, a site well placed for monitoring man-made as well as natural earth tremors. An observatory was also operated for a few years at Wilkes Station, and readings are made for BMR at Casey and Davis Stations. The station geophysicists have been involved in field programs of third-order magnetic observations and gravity surveys in conjunction with the geological mapping programs. Regional surveys have included early seismic and gravity programs for ice thickness measurement, gravity work to determine crustal structure, and reconnaissance aeromagnetic surveys in conjunction with airborne radar ice-thickness profiling. In recent years marine geophysical surveys have started, the first component being magnetometer observations from the ANARE supply ships in order to upgrade information on the seafloor spreading processes involved in the isolation of Antarctica from the other Gondwanaland fragments. This was followed in the recent summer by a program in which marine seismic data were additionally gathered.

A feature of BMR involvement in Antarctica and of Antarctic research in general is international co-operation; this probably stems from the International Geophysical Year experience in 1957. For example, in 1965 a BMR geophysicist joined a Soviet party in the Prince Charles Mountains area, and in 1973 Dr E. Truswell took part in the Antarctic Leg (28) of the Deep Sea Drilling Project. More recently Mr D. Wyborn joined a West German expedition to north Victoria Land in 1980, and a larger Australian contingent joined a US exercise in the same area this last summer.

Geochronology of high-grade polymetamorphic rocks—an Antarctic example

L. P. Black

Isotopic systematics define a long and involved geologic history for the cratonic rocks of the Napier Complex, Enderby Land. This history was dominated by high-grade metamorphism and three major phases of deformation in the late Archaean. The first of these (D_1) was widespread and pervasive, producing isoclinal folding, boudinage, transposed layering, and the varied development of an LS tectonite fabric. The second deformation (D_2) occurred under similar (medium granulite facies) conditions. It was more localised and produced asymmetric tight to isoclinal folds with inclined axial planes showing a consistent vergence and asymmetry, but no penetrative fabric. Upright open to tight folds of varied style and intensity and with horizontal to shallow plunges were produced during upper amphibolite to granulite facies metamorphism at D_3. Except for the southwestern part of the Napier Complex, no more than weak upright penetrative schistosity was developed at this time. These tectonothermal events were intense enough to cause widespread resetting of both U-Pb zircon and Rb-Sr systems. Varied development of their effects at different localities, however, has allowed the derivation of a chronology.

Initial acid igneous crustal formation at 3700–3800 m.y. establishes these rocks as remnants of the Earth's oldest preserved crust. However, it was considerably later, at about 3050 m.y., after significant enrichment in ^{207}Pb (over ^{206}Pb) and ^{87}Sr, that the rocks were first subjected to major tectonism (D_1). The less intense D_2 event is more difficult to define, but probably occurred at about 2900 m.y. A small but significant age spread from about 2450 to 2500 m.y. has been obtained for D_3. This might indicate either an extended event or the retention of small inherited Pb components in zircon at some locations. In the latter case, the youngest part of the range would be the most realistic age estimate for D_3. Granitoid emplacement was roughly synchronous with at least D_1 and D_3. Two geochemically distinct suites of tholeiite dykes were emplaced at about 2350 ± 48 m.y., shortly after the effective cratonisation of the Napier Complex. Another suite of tholeiite dykes was emplaced at 1190 ± 200 m.y. There is little evidence of geological activity in the Napier Complex during major tectonism in the adjacent Rayner Complex at about 1000 m.y. However, most zircon populations appear to have lost small amounts of Pb at that time. Minor pegmatites were emplaced in the Casey Bay area at about 520 m.y. The youngest age obtained, for a small alkaline dyke, is 482 ± 3 m.y.

Complementary results have been obtained for both U-Pb zircon and Rb-Sr systems at most sites. In common with observations made by the author on lower-grade rocks, Rb-Sr total-rock data have been found to date the development of penetrative schistosity, and thus to correlate more directly with deformation than with the thermal component of metamorphism.

Basement geology of northern Victoria Land, and some possible relations with southeastern Australia

Doone Wyborn

Northern Victoria Land geology is dominated by a thick monotonous sequence of Late Precambrian to possible Early Cambrian quartz-rich greywackes, the Robertson Bay Group, which was deposited on both sides of a meridional volcanic belt, the Glasgow Volcanics and their clastic apron, the Sledgers Group. The chemistry of the greywackes shows some systematic changes from east to west. In the east, remote from the volcanic belt, the sediments are low in Na_2O and probably represent second-cycle sediments derived from earlier sedimentary sequences to the south; closer to the volcanic belt they increase in Na_2O, and particularly Cr, reflecting a detrital input from the volcanic belt. To the west of the volcanic belt the rocks are higher in Na_2O and also Sr, but low in Cr. Here they probably represent first-cycle sediments derived from a granitic hinterland.

The northern Victoria Land rocks were deformed and metamorphosed in the Early Ordovician, during the

Ross Orogeny, at the time when large quantities of quartz-rich detritus began to be deposited in the Lachlan Fold Belt of southeastern Australia. Palaeocurrent directions in the Ordovician greywackes of the Lachlan Fold Belt and chemical comparison of these rocks with Robertson Bay Group sediments strongly suggest that the Ordovician greywackes in Australia have been largely recycled from the Robertson Bay Group in Antarctica. During the Ross Orogeny the Robertson Bay Group, west of the Glasgow Volcanic belt, partially melted to produce S-type granites. These granites are higher in Na_2O than Lachlan Fold Belt S-type granites, since their source sediments were high in Na_2O. The chemistry of S-type granites in the Lachlan Fold Belt is what one would expect if they had been derived from sediments chemically similar to the eastern strata of the Robertson Bay Group, and the chemical data thus suggest that such strata underlie the Lachlan Fold Belt and were the source of its S-type granites.

If it is assumed that similar weathering conditions prevailed during the sediment recycling phases, the Na_2O content can provide a measure of the number of sedimentary cycles through which a given sediment has passed. Likewise, the Na_2O content of S-type granites can give the same information. S-type granites produced in the Ross Orogeny with 3% Na_2O are derived from first-cycle sediments, most southeastern Australian S-types with 2–2.5% Na_2O are derived from second-cycle sediments, and rare southeastern Australian S-types derived from the Ordovician greywackes, such as the Cooma Granite, with 1–1.5% Na_2O, are derived from third-cycle sediments.

East Antarctica—where are the Phanerozoic sedimentary basins?

E. M. Truswell

In the wide span of the East Antarctic coastline, from the Amery Ice Shelf at 70°E to Cape Adare at 170°E, geophysical evidence has to date suggested the presence of Phanerozoic sedimentary basins at only three points on the continental shelf. At Prydz Bay, at the mouth of the rift structure now filled by the Lambert Glacier aeromagnetic data have been used to suggest the presence there of up to 5 km of sediments. The age of these is unknown, but Cretaceous and early Tertiary sequences are suspected. Further east, radio echo-sounding delineation of subglacial topography has suggested that the extensive Wilkes Basin of the continental interior reaches the East Antarctic coast in the vicinity of the Ninnis Glacier and Cook Ice Shelf. The area drained by the Mertz Glacier may represent a separate sedimentary basin. The recently reported discovery of in-situ continental siltstones of Cretaceous age offshore from the Ninnis Glacier supports the concept of sedimentary basins in the area.

In a current study, the distribution of recycled palynomorphs in recent muds around Antarctica has been used as a broad guide to the position of hidden sedimentary sequences on the continental shelf. In three areas, concentrations of recycled microfossils are sufficiently great to suggest the presence nearby of eroding sedimentary sequences. Near the western edge of the Shackleton Ice Shelf, the presence of Early to Late Permian, Late Jurassic to mid-Cretaceous, and Late Cretaceous to early Tertiary sedimentary sequences is suspected. Near the outer edge of the continental shelf and slope east of Cape Carr, there are indications of Early Cretaceous and Late Cretaceous to early Tertiary clastic sediments. The same age span is suggested for sequences near the western side of the Mertz Glacier Tongue.

On a reconstructed Australia-Antarctica, the sedimentary sequence predicted for the Shackleton Ice Shelf area probably faced the open Indian Ocean, at least since the northward retreat of India in the Cretaceous. Cretaceous sequences predicted for the other localities occur at points on the Antarctic coast where they would be expected on the basis of most reconstructions. The area east of Cape Carr has as its conjugate coast part of the Great Australian Bight Basin; that off the Mertz Glacier, the area west of the Otway Basin. At both these areas on the southern Australian margin thick Cretaceous rift valley sequences occur.

Geochemistry of Archaean komatiite-tholeiite suites: petrogenetic implications and early mantle evolution

A. Y. Glikson

Major and trace-element distribution patterns observed in Archaean volcanic suites, when coupled with precise geochronological and stratigraphic controls, allow an insight into the geochemical evolution of the early mantle, possible mantle heterogeneities, petrogenetic processes, and the nature of the crustal environments in which the volcanic rocks were emplaced. The documentation of Archaean geochemical data in the Pilbara and Yilgarn Blocks and the Barberton Mountain Land in the Kaapvaal Craton, Transvaal, allow a meaningful discussion of these questions. Recent U-Pb zircon and Sm-Nd whole-rock isotopic studies of Archaean volcanic rocks in these terrains have furnished precise primary igneous ages for these units, rendering temporal comparisons of the geochemical data possible. The aim of this paper is to examine the geochemistry of ultramafic-mafic volcanic suites from the Pilbara, Yilgarn and Kaapvaal shields with reference to the following questions: (1) Comparisons between critical element ratios in the Archaean lavas, modern volcanic suites, and chondrites; (2) possible existence of geochemical variations with time; (3) possible existence of lateral (geographic) geochemical variations; (4) implications for petrogenesis of the komatiite-tholeiite suite; (5) implications for composition and geochemical evolution of the early mantle, mantle-crust, and mantle-core fractionation.

Consistent trace-element anomalies are shown by associated tholeiitic basalt (TB), high-Mg basalts (HMB), and peridotitic komatiites (PK), e.g. (1) high Ni and Cr in Yilgarn mafic-ultramafic rocks, and low Ni and Cr in Pilbara mafic-ultramafic volcanics; (2) high Ti and other high-field-strength (HFS) ions in associated TB, HMB, and PK in the lower Warrawoona Group (Pilbara) and in the Sandspruit Formation (Barberton). Long-term and cyclic short-term depletion in HFS and siderophile elements is shown by early Archaean mafic-ultramafic successions. The lateral and temporal variations in ratios of mafic/ultramafic rocks and trace-element distinctions, indicated by comparisons between the 3500–3300 m.y. Pilbara and Barberton volcanics and the 2800–2600 m.y. Yilgarn volcanics, indicate significant lateral and temporal heterogeneities in the early terrestrial mantle.

There is a compositional gap between HMB and PK with respect to MgO, Mg′ number, and Al_2O_3. In the main, this break militates against a crystal fractionation relation between HMB and PK, although fractionation was likely in some instances. The gap suggests a two-source model for Archaean komatiite derivation: (a) 20–40% partial melting of hydrous pyrolite in a relatively shallow (<50 km) low-velocity zone, accompanied by low-pressure olivine fractionation at shallow depths to produce TB, and (b) episodic ascent of mantle diapirs from depths >180 km and PK magma segregation (~50% melting) at depths of 90–120 km. Green's 1981 model II Archaean geotherm of ca 25°C/km is supported by (1) the quartz-normative to olivine-poor composition of Archaean TB and the orthopyroxene-rich normative composition of Archaean HMB compared to mid-ocean-ridge tholeiitic basalts (MORB), and magnesian and picritic

MORB; and (2) the absence of alkaline volcanic rocks in Archaean greenstone belts, except for late Archaean trachytic flows. The indicated instability of orthopyroxene in refractory residues of Archaean magmas thus suggests relatively shallow-level melting in the Archaean.

Evidence exists for geochemical differences between Archaean and modern oceanic mantle sources. Consistently high FeO/TiO_2 ratios pertain to Archaean TB, HMB, and PK, and chondritic or high LREE/HREE (light rare earth/heavy rare earth) ratios pertain to Archaean volcanics, as distinct from the negative LREE anomaly of modern oceanic volcanics. Commonly high CaO/Al_2O_3 and low Al_2O_3/TiO_2 ratios as compared to chondrites is a feature of many Archaean PK. It is considered likely, though by no means proved, that the Archaean mantle was relatively enriched in iron. This observation is relevant to the possible secular segregation of FeO from the lower mantle to the outer core.

Stratigraphic correlation of the Upper Coal Measures of the Sydney Basin with their equivalents in the Bowen Basin

A. T. Brakel

To understand the sedimentary and structural evolution of the 1750 km-long Sydney-Gunnedah-Bowen Basins trough in Late Permian time, it is first necessary to have reliable region-wide stratigraphic control. The normal correlation tools are inadequate for this task, either because they are inapplicable to coal-measure sequences or because their degree of time resolution is not fine enough. The work of Vail & others established that cycles of relative change of sea level on a global scale have occurred throughout Phanerozoic time and offer a new means of correlating between basins. To use this method, marine incursions of considerable extent in each basin are interpreted to represent time lines recording global rises in sea level. Such incursions occur at two levels in both the Sydney and Bowen Basins. The Kulnura Marine Tongue (Sydney Basin) can be correlated with the Arkarula Sandstone (Gunnedah Basin) and the MacMillan Formation (Bowen Basin). The higher Denman Formation and its equivalents in the Sydney Basin can in turn be equated with an unnamed burrowed portion of the Burngrove Formation in the Bowen Basin.

Among the implications of this model are (1) the German Creek Formation is equivalent to the basal portion of the Tomago and Illawarra Coal Measure, and Late Permian coal measure deposition started in both basins at about the same time, and (2) the Newcastle Coal Measures are equivalent to the Rangal Coal Measures and the upper tuffaceous section of the Burngrove Formation. No environmental Denman equivalent is known from the Gunnedah region, either because it has not yet been recognised or because the area stood above sea level at the time of this eustatic high-stand.

It is clear from the literature that correlations of the Sydney and Bowen Basin sequences using marine faunas and palynology give different results. Palynological correlation is also discordant with correlation of the upper coal measures, using the global eustasy model, and this leads to the suggestion that certain palynomorph species appeared in the Bowen Basin long before they appeared in the Sydney Basin. It is argued that this occurred because the palynology records climate-controlled vegetation zones that migrated polewards as the edges of the Permian ice cap receded.

Submarine and subaerial diagenesis in coral reefs

John F. Marshall

The earliest stages of diagenesis in coral reefs occur in the near-surface, initially in the marine environment when the reef is actively accreting, and ultimately in the subaerial environment when the reef is raised above sea level either by tectonic or eustatic events. Different diagenetic processes occur within these two distinct zones.

In the marine environment, alterations to the original reef framework are produced by boring organisms, sediment filling skeletal chambers, borings, and cavities, and formation of submarine cements. The submarine cements consist of aragonite and Mg-calcite, which exhibit various fabrics and textures. The distribution of the cements indicates pervasive lithification in the relatively massive framework of the windward margin, whereas the cements tend to be less abundant in the more open framework of the leeward margin, and are absent as intergranular cements within the lagoonal sediments. If the reef is subaerially exposed, the upper part is subjected to diagenesis in the vadose environment, where both air and meteoric water are present in the pores. In this zone there is widespread development of secondary porosity, resulting from solution of skeletal material. Previously unconsolidated lagoonal sediments are cemented by calcite, and calcite cement begins to fill the moulds and vugs that were produced by solution. Beneath the water table, in the phreatic environment, pores are constantly filled by fresh water, and extensive neomorphism and cement infilling of both primary and secondary porosity takes place.

The geological history of coral reefs, such as those of the Great Barrier Reef, indicates that periods of growth have alternated with relatively long periods of exposure. This repetitive change between marine and subaerial environments has resulted, in many instances, in superimposition of marine, vadose, and phreatic diagenetic products, resulting in complex changes to the original reef framework.

The Papua New Guinea thrust belt, longitude 141°–144° East

H. L. Davies

The western part of Papua New Guinea, between 141° and 144°E, consists of a central cordillera flanked by the Fly-Strickland plains in the south, and the Sepik plains and north Sepik ranges in the north. The region has the appearance of a classic pericratonic orogenic belt, with deformed and crystalline rocks in the north (Sepik complex; north coast complex), a foreland thrust belt in the centre, and a craton with virtually undeformed cover in the south. The north coast complex consists of Late Cretaceous to earliest Miocene intrusive and marine volcanic rocks, unconformably overlain by Early Miocene and younger sediments. The Sepik complex consists of Jurassic to Eocene metamorphic, ultramafic, intermediate intrusive, volcanic and sedimentary rocks, unconformably overlain by Middle Miocene sediments. The foreland thrust belt and cratonic area consist of Permian granite, etc., overlain by a paraconformable sequence of Mesozoic clastic sediments and Cainozoic carbonates, which are in turn overlain unconformably by Plio-Quaternary sediments and volcanics.

The region has evolved by arc-continent collisions in the Oligocene (Sepik complex emplaced) and the earliest Miocene (north coast complex emplaced), and by north-south convergence and east-west left-lateral strike-slip faulting, which continues to the present day. The north coast complex has been disrupted by strike-slip faulting. The Sepik complex is thought to be entirely allochthonous and to consist of a thrust sheet, or series of thrust sheets, which have moved as much as 200 km to the south, over possibly cratonic basement. The locus of convergent tectonic activity has migrated southwards with time, and now coincides with the foreland thrust belt that forms the southern slopes of the central cordillera. This is a zone of active folding and thrusting, including both thin-skinned (supra-crustal) and thick-skinned (crustal) tectonism, as indicated by interpretation of surface structures and by strong earthquakes at crustal depths. Magmatic activity, also, has migrated southwards with time, from the line of the Sepik plains in the earliest Miocene, to the southern foothills of the central cordillera in the Pliocene and Quaternary; some of the intrusives are mineralised in copper and/or gold (Frieda River, Star Mountains, Porgera, Ok Tedi). The intrusives are not clearly related to an active subduction system, and possibly were generated by thickening and consequent depression of the base of the lithosphere, induced by continued lithospheric shortening.

INTERNATIONAL CONFERENCE ON GROUNDWATER AND MAN

The International Conference on Groundwater and Man is to be held in **Sydney** from **5–9 December 1983.** It is the first international groundwater conference to be held in Australia.

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Pre and post-conference technical excursions will focus on aspects of arid zone hydrogeology, salinity problems and groundwater management problems.

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