CHAPTER SEVEN
PETROGENESIS OF MOUNT DORE-STYLE BRECCIA-HOSTED COPPER DEPOSITS

7.1 INTRODUCTION

The Mount Dore deposit is now the best documented example of the breccia-hosted style of copper mineralization occurring in the eastern Mount Isa Inlier. Constraints have been placed on the timing of mineralization with respect to deformation, metamorphism and magmatism, on the composition of the primary fluid and its subsequent geochemical evolution, and on the possible provenance for this fluid.

There are several other breccia-hosted copper deposits in the Kuridala-Selwyn belt of rocks which have been productive in the past, or which are presently the subjects of extensive exploration activity (or both, in some instances), and for which there is some geological information: Mount Elliott, the Hampden group, and SWAN (Figure 7.1). All deposits lie along a broadly linear trend close to, and generally to the east of the western contact between the Maronan Supergroup and the Mary Kathleen Group, and share other characteristics, suggesting that they may all have formed by similar processes. A metallogenic model based on the better known Mount Dore deposit might therefore have wider applicability. To test this proposal, the known characteristics of Mount Elliott, SWAN and the Hampden group of deposits are reviewed, and compared with those for Mount Dore. Very few geochemical data are available for any of these deposits, and the comparison therefore will be restricted to a consideration of geologic settings, general descriptions of mineralization and alteration assemblages, and first order estimations of fluid composition based on these data. The salient characteristics are summarized in Table 7.1.

FIGURE 7.1: Summary geological map of the Cloncurry Fold Belt, showing locations of some important breccia-hosted copper deposits. Inferred stratigraphic relationships and distributions of units are those proposed by Newbery *et al.* (Appendix A).

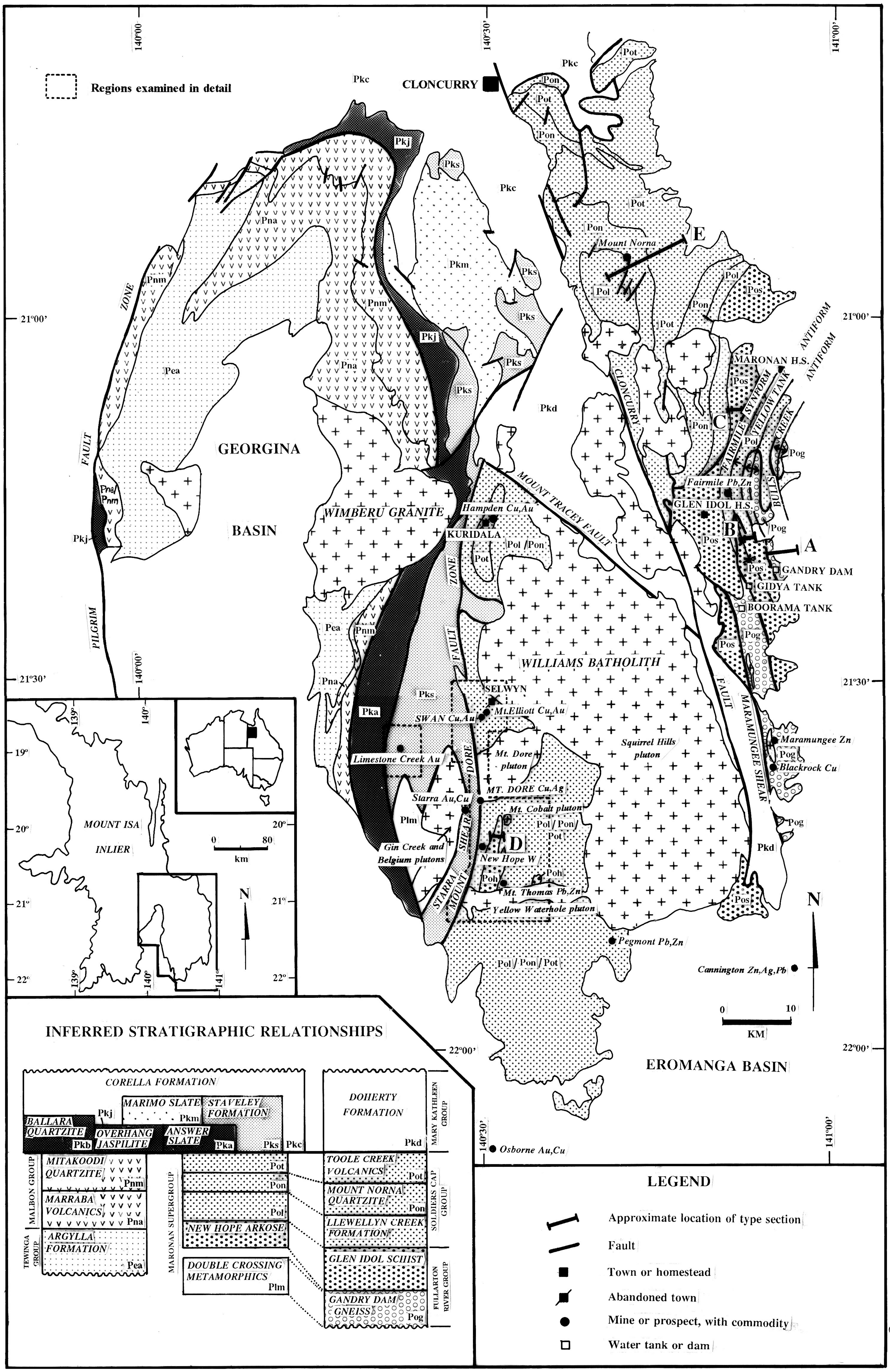

Regions examined in detail
CLONCURRY
GEORGINA
BASIN
WIMBERU GRANITE
WILLIAMS BATHOLITH
EROMANGA BASIN
PILGRIM
FAULT
ZONE
MOUNT TRACEY FAULT
CLONCURRY
FAULT
MARAMUNGEE SHEAR
STARRA MOUNT DORE FAULT ZONE
SHEAR
FAIRMILE SYNFORM
YELLOW TANK ANTIFORM
BULLS CREEK ANTIFORM
MARONAN H.S.
Mount Norna
Fairmile Pb,Zn
GLEN IDOL H.S.
GANDRY DAM
GIDYA TANK
BOORAMA TANK
Maramungee Zn
Blackrock Cu
Hampden Cu,Au
KURIDALA
SELWYN
Mt.Elliott Cu,Au
SWAN Cu,Au
Limestone Creek Au
Mt. Dore pluton
Squirrel Hills pluton
MT. DORE Cu,Ag
Starra Au,Cu
Mt. Cobalt pluton
Gin Creek and Belgium plutons
New Hope W
Mt. Thomas Pb,Zn
Yellow Waterhole pluton
Pegmont Pb,Zn
Cannington Zn,Ag,Pb
Osborne Au,Cu
A
B
C
D
E
140°00'
140°30'
141°00'
21°00'
21°30'
22°00'
0 10
KM
N
MOUNT ISA
INLIER
0 80
km
139°
140°
141°
19°
20°
21°
22°
INFERRED STRATIGRAPHIC RELATIONSHIPS
CORELLA FORMATION
MARIMO SLATE
STAVELEY FORMATION
BALLARA QUARTZITE
OVERHANG JASPILITE
ANSWER SLATE
DOHERTY FORMATION
MARY KATHLEEN GROUP
MALBON GROUP
MITAKOODI QUARTZITE
MARRABA VOLCANICS
TEWINGA GROUP
ARGYLLA FORMATION
MARONAN SUPERGROUP
NEW HOPE ARKOSE
DOUBLE CROSSING METAMORPHICS
SOLDIERS CAP GROUP
TOOLE CREEK VOLCANICS
MOUNT NORNA QUARTZITE
LLEWELLYN CREEK FORMATION
FULLARTON RIVER GROUP
GLEN IDOL SCHIST
GANDRY DAM GNEISS
Pkc Pkj Pkm Pkb Pka Pks Pkd Pnm Pna Pea Pot Pon Pol Pos Pog Poh Plm
LEGEND
Approximate location of type section
Fault
Town or homestead
Abandoned town
Mine or prospect, with commodity
Water tank or dam

TABLE 7.1: Comparison of geological characteristics of the Mount Dore deposit with those of other breccia-hosted deposits.

(act - actinolite; bio - biotite; carb - carbonate; cc - calcite; chc - chalcocite; chr - chrysocolla; cpy - chalcopyrite; cup - cuprite; diop - diopside; dol - dolomite; ep - epidote; fl - fluorite; gal - galena; haem - haematite; ksp - K-feldspar; mal - malachite; mt - magnetite; py - pyrite; qtz - quartz; scap - scapolite; sph - sphalerite; tm - tourmaline; torb - torbernite)

DEPOSIT	***HOST ROCKS***	***LOCALIZING STRUCTURES***	***ALTERATION ASSEMBLAGE***	***SULPHIDES***	***TONNAGE/GRADE***	***REFERENCES***
Mount Dore	carbonaceous slates, quartz-mica schists	F_3 folds, late-tectonic faults (Mount Dore Fault Zone), breccias	ksp, qtz, tm, dol, cc	py, cpy, lesser sph, gal; supergene chc	40 Mt @ 1.08% Cu 6.5g/t Ag	Nisbet, 1980
Mount Elliott	carbonaceous slates, phyllites and schists	F_3 folds, late-tectonic faults, breccias	diop, mt, scap, cc; minor ksp, qtz, ep, fl	py, cpy; supergene chc	609,630 t @ 3% Cu	Nye & Rayner, 1940; Dimo, 1973
Hampden Group	carbonaceous slates	Late-tectonic fault zone (Hampden and Central Faults), breccias	ksp, bio, tm, qtz, carb	py, cpy; supergene chc	2 Mt @ 5% Cu, 2.3 g/t Au, 15 g/t Ag	Stockex Report, 1991
SWAN	meta-calcilutites and calcarenites	F_3 folds(?), late-tectonic fault(s), breccias	ksp, qtz, haem, ep, diop, act, mt, carb	py, cpy; supergene chc	42 Mt @ 0.69% Cu, 0.4 g/t Au	Nyvlt, 1980; Nisbet, 1980, 1983
Lady Ella	carbonaceous slates	F_3 folds(?), late-tectonic faults, breccias	unknown	supergene mal, az; primary sulphides unknown	unknown	Blake *et al.* , 1983
Marilyn	carbonaceous slates	Late-tectonic fault	qtz, others?	supergene mal, az; primary sulphides unknown	unknown	Blake *et al.* , 1983
Mariposa	quartz-mica schists	F_3 folds(?), late-tectonic fault (Mount Dore Fault Zone)	unknown	supergene mal, chr, torb; primary sulphides unknown	unknown	Blake *et al.* , 1983
Stuart	carbonaceous slates and phyllites	F_3 folds(?), late-tectonic fault (Mount Dore Fault Zone)	qtz, ksp, haem	supergene chc, mal, az, chr; primary sulphides unknown	unknown	Blake *et al.* , 1983
Labour Victory	carbonaceous slates and phyllites	Late-tectonic fault	qtz?, haem?	supergene cup, mal, az, chr; primary sulphides unknown	unknown	Honman, 1938

The region is also peppered with innumerable small copper workings. Geological and grade information are sparse or absent for many of these, but enough is known about some of them to suggest that they may be akin to the Mount Dore style. The known features of five small deposits occurring along the same lineament as the larger deposits are also included for comparison. It is important to consider these deposits, firstly because they may provide further corroboration of the metallogenic model presented herein, and secondly because some may actually be larger than is at first apparent. It should be remembered that prior to drilling at Mount Dore, it too was little known, and classified as a minor deposit.

Subsequent to the comparison of deposits, I will propose a petrogenetic model for the Mount Dore deposit, and conclude with some speculations on regional metallogenic processes in the eastern Mount Isa Inlier, some recommendations for further research, and a summary of the major conclusions derived from my studies.

7.2 CHARACTERISTICS OF OTHER COPPER DEPOSITS

7.2.1 Mount Elliott

Local geological setting

The collapsed shafts, pits and relics of the smelter which are the remains of Mount Elliott Mine, and the abandoned township of Selwyn which serviced it, lie about 12 kilometres north of Mount Dore (Figure 7.1). The Mount Elliott Cu-Au lodes occur in grey and black, carbonaceous slates, phyllites and schists (Elliott Beds in the terminology of Dimo, 1973, 1975), red (probably potassically altered) lutites and shales interfingered with amphibolites (Reward Beds; Dimo, *op.cit.*), and quartz-muscovite schists, muscovite schists and minor chlorite schists (Town Beds; Dimo, *op.cit.*), now all assigned to the Toole Creek Volcanics (Beardsmore *et al.*, 1988). The quartz-muscovite schists (Town beds) lie immediately adjacent to the Staveley Formation.

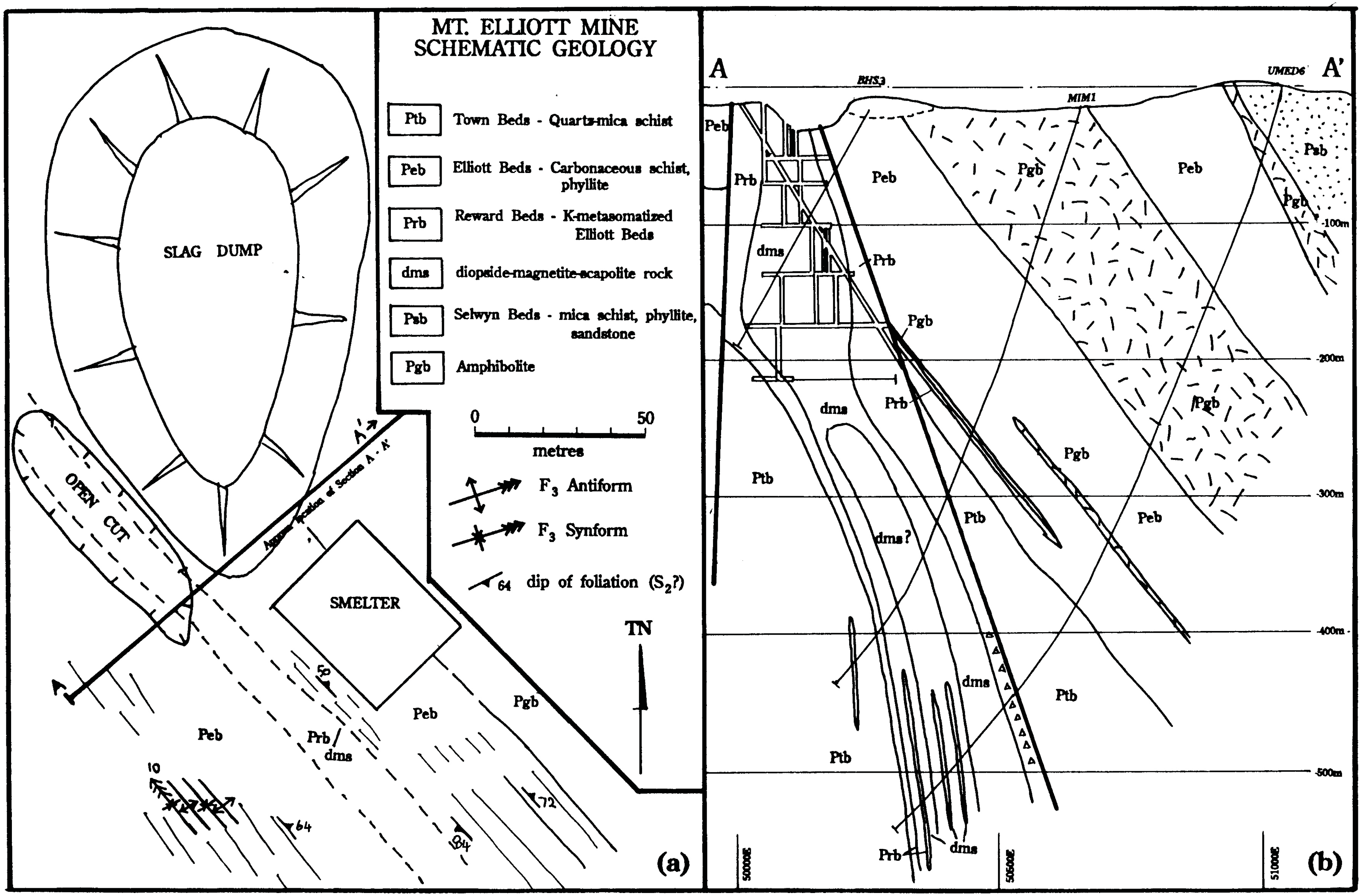
The stratigraphy proposed by Dimo (1973, 1975), with the Toole Creek Volcanics (then known as the Kuridala Formation) being younger than the Staveley Formation, was apparently based on structural relationships; the former structurally overlies the latter in this area. It is the reverse of the stratigraphy derived by interpretation of regional relationships (Blake *et al.*, 1983; this study).

Layering generally dips between 60° and 80° east-northeast. It is folded about roughly northwest-trending F_2 axes, and a strong slaty to differentiated S_2 foliation is present. Evidence for an earlier D_1 event is preserved as small (less than a few cm) transposed isoclinal, intrafolial folds in the slaty lithologies, and as relic submillimetre-scale crenulation hinges in Q-domains in the differentiated S_2 in the quartz-muscovite schists. The Staveley Formation immediately adjacent to these schists has a mylonitic texture, being laminated on a millimetre scale, and porphyroclastic in places. The style of D_1 around the Mount Elliott mine is unclear. Outcrop is particularly poor and weathering intense in this area, obscuring structural (and stratigraphic) relationships. There is regional-scale evidence supporting both extensional detachment and thrusting (Chapter 3). Open, upright F_3 folding is prominent in the immediate vicinity of the mine, along north to north-northwest fold axes (Figure 7.2a; recorded as "omega folding" by Dimo (1973)). Late faulting is also prominent around Mount Elliott, striking north-northwest and dipping steeply east-northeast, generally concordant with layering in the metasediments of the Toole Creek Volcanics (Blake *et al.*, 1983). Most lithological boundaries appear to be faulted. Extensive brecciation within the major fault passing through Mount Elliott is the main host for mineralization and alteration (Figure 7.2b), and can be traced on the surface over a length of about 600 metres (Sullivan, 1953b).

Granite belonging to the Squirrel Hill pluton of the Williams Batholith crops out approximately two kilometres northeast of the Mount Elliott Mine, and Blake *et al.* (1983) record "matchstick" andalusite porphyroblasts within the carbonaceous slates, suggesting some thermal metamorphism during granite intrusion.

FIGURE 7.2: Geologic setting of the Mount Elliott deposit: (a) sketch map of the surface geology in the immediate vicinity of the old mine workings, showing general dip of the dominant (S_2) foliation, and the locations of a number of small F_3 folds, with northwest-trending axial planes. Approximate line of cross-section in (b) is indicated (after Nisbet, 1983); (b) Cross-section through the Mount Elliott deposit, showing the dominant mineralized rocks: "Reward Beds" (Prb) and diopside-magnetite-scapolite rock (dms) with a steeply east-dipping, northwest-striking fault (after Dimo, 1975).

FIGURE 7.2


MT. ELLIOTT MINE
SCHEMATIC GEOLOGY
Ptb Town Beds - Quartz-mica schist
Peb Elliott Beds - Carbonaceous schist, phyllite
Prb Reward Beds - K-metasomatized Elliott Beds
dms diopside-magnetite-scapolite rock
Psb Selwyn Beds - mica schist, phyllite, sandstone
Pgb Amphibolite
0 50
metres
F3 Antiform
F3 Synform
64 dip of foliation (S2?)
TN
SLAG DUMP
OPEN CUT
SMELTER
A'
Peb
Prb / dms
Pgb
(a)
A
A'
BHS3
MIM1
UMED6
Peb
Prb
dms
Ptb
Pgb
Psb
dms?
-100m
-200m
-300m
-400m
-500m
50000E
50500E
51000E
(b)

Mineralization and associated alteration

Mineralization was first detected in the late 1800's as a surface gossan, described by Ball (1908) as an elongate, pear-shaped "knob" of siliceous, ferruginous (jasperoid) rock, 60 metres long and 16 metres wide, striking 325°. It contained cuprite and malachite, and minor chrysocolla, atacamite and gold. Ore grades averaged about 15 percent copper and 3 g/tonne gold, though gold grades to 31g/t were locally encountered, and the gossan was completely removed prior to underground mining (Ball, 1908).

Oxidation extends down-dip for 70 to 80 metres, and is probably the result of intense weathering and leaching during Mesozoic and younger lateritization events. Lateritization has also kaolinized and silicified country rocks immediately surrounding the breccia body (Sullivan, 1953b). Some of this may overprint an earlier, ore-related alteration. Carter *et al.* (1961) report ore averaged 12% Cu and 6.12 to 7.65 g/t (all metric values converted from old imperial measures) to the base of oxidation. Gold grades in the primary sulphide ore below this zone range from 0.77 to 4.59 g/t Au (Dimo, 1973). The mine produced 269 308 tonnes of ore for 24 920 tonne of Cu (9.3%) and 1054.2 kg of gold. When it closed in 1920 estimates of reserves ranged from 365 800 to 609 630 tonnes at 3% Cu (Nye and Rayner, 1940).

Mineralization occurs in a pipe-like body up to 100 metres long in horizontal section, 50 to 60 metres wide and extending down-dip and down-plunge a distance exceeding 270 metres (Sullivan, 1953b). It dips 60° north-northeast, across the breccia zone, and pitches steeply north-northwest, within the breccia (Blake *et al.*, 1983). Four lodes were worked during the underground mining phase. Three of these were solely within the oxidized zone (Main, Kaolin and Footwall Vein lodes), and one extended from the oxidized into the primary sulphide zone (Western lode; Honman, 1938; Sullivan, 1953b). Oxidized ore consisted chiefly of chalcocite, malachite and cuprite, with subordinate tenorite, azurite, chrysocolla and native copper.

Primary ore was encountered at 80 metres in the Western lode, and largely comprises massive ophitic diopsidic pyroxene and scapolite, with interstitial euhedral to subhedral magnetite and minor chalcopyrite, pyrite, pyrrhotite and gold disseminated throughout. Copper content decreases with depth, and the proportion of pyrite to chalcopyrite increases. Opaques comprise 5 to 75 percent of the mineralized zone (Sullivan, 1953b; Dimo, 1975). Other gangue minerals include calcite, and minor gypsum, apatite, sphene and prehnite (Blake *et al.*, 1983). In addition to the massive mineralization, abundant randomly disposed diopside-scapolite veining occurs in metasediments and along the margins of metadolerite sills. Most veins are coarse-grained (0.5 to 2.5 cm), and are mineralogically similar to the massive body, consisting of a mixture of coarse, euhedral magnetite and subordinate pyrite and chalcopyrite, intergrown with equally coarse-grained diopside, scapolite and calcite, with minor feldspar, quartz, epidote and fluorite (Dimo, 1975). Metadolerite distant from veining contains less than 0.5 percent fine, disseminated magnetite, pyrite and chalcopyrite (Dimo, 1975).

Sullivan (1953b) observed a lithological control on mineralization within the breccia body. Individual ore lodes dipped across it in accordance with bedding, and ore grade increased where the quartz-mica schists would be expected to enter it. Black slate was apparently unfavourable for mineralization, containing comparatively little ore where it traversed the breccia. Sullivan (1953b) envisaged ore lenses forming by infill and replacement of brecciated metasediments. Dimo (1975), on the other hand, concluded that primary mineralization is "...alien to, and intrusive into pelitic metasedimentary wallrocks...", and related to post-metamorphic intrusion of a large, compositionally zoned gabbro plug. He interpreted veins as minor structures related to emanation of fluids from the same intrusion. According to Dimo (1975), earlier unspecified workers interpreted this body as a fault-bound slab of metasomatized (skarnified) impure dolomitic metasediment.

7.2.2 Hampden Group

Local geological setting

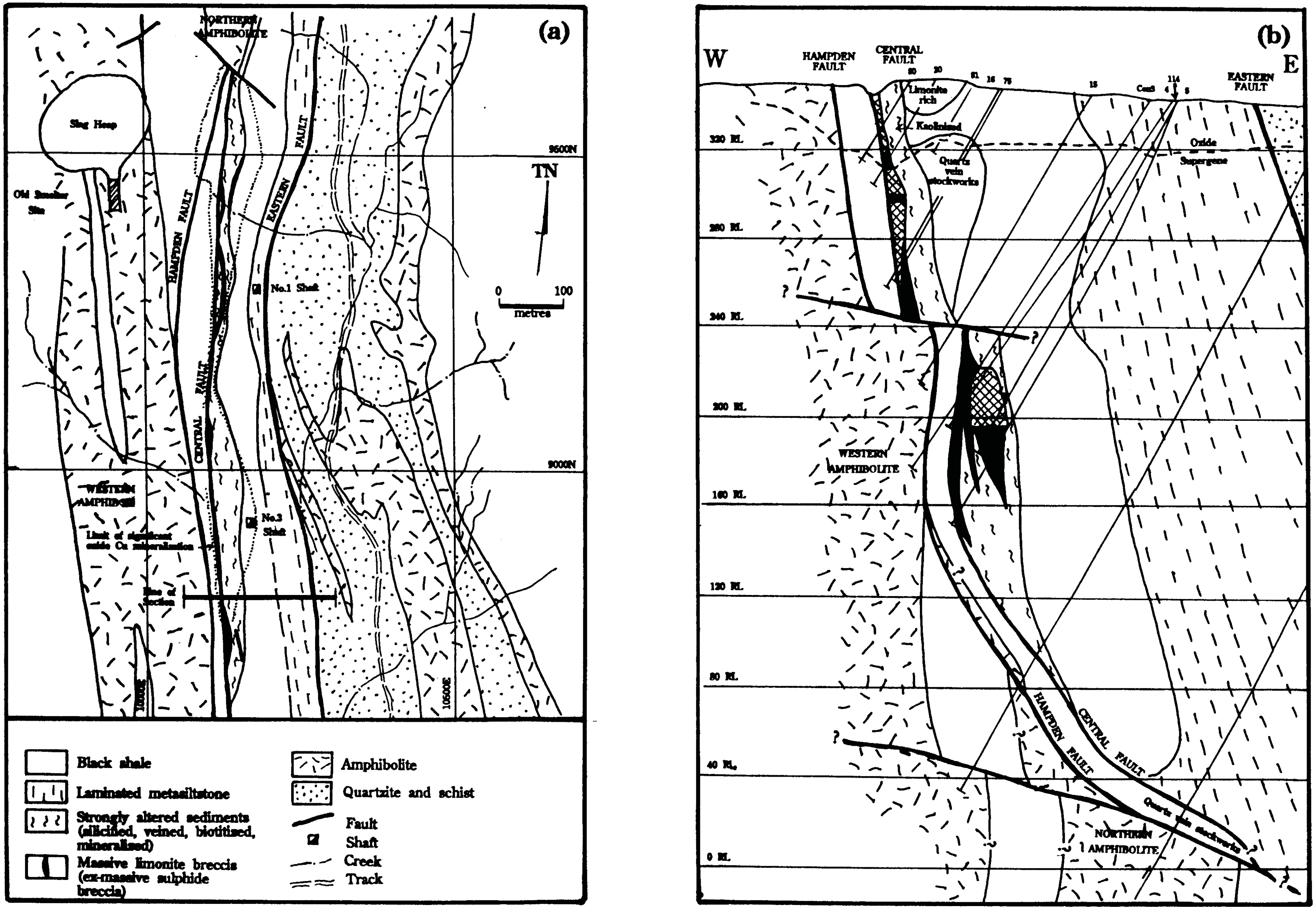
Copper-gold ore was discovered in the Hampden group of lodes in 1898, 40 kilometres north of Mount Dore, near the abandoned township of Kuridala (Figure 7.1). Ore was worked until 1921, when failing grades and falling copper prices forced closure of the mines (Sullivan, 1953a). Mineralization and alteration are hosted by the Toole Creek Volcanics, localized in the Hampden Fault Zone, a system of late tectonic reverse faults of unknown, but probably large displacement, which can be traced over at least 12 km (Figure 7.3a). In interpretive cross-sections, these faults are shown dipping progressively more shallowly to the east with depth (Stockex Report, 1991; Figure 7.3b). The fault system truncates the eastern limb of an overturned (to the east) F_2 syncline containing in its core alternating bands of metadolerite sills, variably carbonaceous slates and sandstones of the Toole Creek Volcanics (Donchak *et al.*, 1983). These grade conformably into Mount Norna Quartzite to the east and west. Further east the latter grades into Llewellyn Creek Formation, but in the west it is faulted against the Staveley Formation, probably along an early (D_1) thrust, which regional map patterns suggest may have involved thrusting of Maronan Supergroup lithologies over the Staveley Formation, and which has subsequently been refolded and faulted during around D_2 and later events (Chapter Three). The Squirrel Hills pluton of the Williams Batholith crops out between 6 and 8 km to the east and southeast of the mineralized zone.

Mineralization and alteration

Mining along the Hampden mineralized trend worked a system of lodes over 900 m (Figure 7.3a). Of the four shafts sunk along the trend, Hampden and Hampden Consols were producers; mining at Hampden Queen and Hampden Central failed to find ore. Total recorded production between 1898 and 1921 was 195740 tonnes of ore for 13833 tonnes of copper and 365777 g Au (Sullivan, 1953a). Ore from the Hampden mine also contained 32.4 g/t silver (Carter *et al.*, 1961).

FIGURE 7.3: Geologic setting of the Hampden group of deposits: (a) Local geology around the Hampden-Consols deposit. Hampden lies about one kilometre to the north and Hampden Queen about 1.5 kilometres to the south. The line of the section in (b) is indicated, just to the south of the number 3 shaft; (b) Cross-section through the Hampden-Consols lode, showing localization in a fault system dipping steeply east. Note that the fault is interpreted to dip less steeply at depth. Both diagrams from the Stockex Report (1991), based on work by Metana Minerals, N.L.

FIGURE 7.3


(a)
NORTHERN AMPHIBOLITE
Slag Heap
Old Smelter Site
HAMPDEN FAULT
EASTERN FAULT
CENTRAL FAULT
No.1 Shaft
No.3 Shaft
WESTERN AMPHIBOLITE
Limit of significant oxide Cu mineralisation
line of Section
9600N
9000N
10000E
10500E
TN
0 100 metres
Black shale
Laminated metasiltstone
Strongly altered sediments (silicified, veined, biotitised, mineralised)
Massive limonite breccia (ex-massive sulphide breccia)
Amphibolite
Quartzite and schist
Fault
Shaft
Creek
Track
(b)
W
E
HAMPDEN FAULT
CENTRAL FAULT
EASTERN FAULT
Limonite rich
Kaolinised
Quartz vein stockworks
Oxide
Supergene
WESTERN AMPHIBOLITE
NORTHERN AMPHIBOLITE
HAMPDEN FAULT
CENTRAL FAULT
Quartz vein stockworks
320 RL
280 RL
240 RL
200 RL
160 RL
120 RL
80 RL
40 RL
0 RL

The upper oxidized and supergene zones were the predominant sources of ore, providing largely loose, sooty chalcocite and some pyrite, chrysocolla, malachite, tenorite and chalcocite in kaolinised slate, in an extensive zone of secondary enrichment ranging from 30 to 106 metres deep (Nye and Rayner, 1940). Chalcocite commonly replaces pyrite. There is lesser bornite and covellite. The supergene zone grades into the primary sulphide zone over at least several tens of metres (Stockex Report, 1991). At the Hampden mine oxidised and secondary sulphide ore occurred in a lode up to 6.1 m wide. In the primary zone below, seams of ore less than 1 m wide were found, some extending to depths of 180 m. The Consols lode forms a bulge to the south of the main Hampden lode. It was worked over a length of 152.4 m, to a depth of 146.3 m, and reportedly attained a width of 27.4 m, though it averaged 12.2 m (Sullivan, 1953a).

Recent diamond drilling in a joint venture exploration program between Uranerz Australia Pty. Ltd. and Metana Minerals N.L. over a 310 m strike length and 210 m depth has defined a resource in excess of 2 million tonnes at 5% Cu and 2.3 g/t Au and 15 g/t Ag (1% Cu cut-off grade; Stockex Report, 1991; Laing, 1991). Primary mineralization occurs as copper-bearing massive sulphide and massive sulphide breccia in semi-continuous, east-dipping sheets. Clasts in the breccias are of silicified shale or vein quartz. The matrix may comprise 30 to 90 percent by volume, and consists mainly of sulphides, with lesser sideritic carbonate gangue. Sulphide mineralization is locally enclosed by strongly biotitized and/or tourmalinized shales, and is flanked on the hangingwall side by pervasively silicified, quartz-sulphide-carbonate veined shales. The entire lot is surrounded by a zone of more weakly silicified shale, containing stockworks of barren white quartz±Kfeldspar±pyrite, which varies in width along strike and down dip (Stockex Report, 1991). Slates adjacent to the amphibolites in the ore zone are carbonated (Sullivan, 1953a). Massive and brecciated sulphide bodies grade into each other, and vary from less than 1 m wide with little alteration, up to 20 m wide and surrounded by a 30 to 40 m wide alteration halo. Sulphides are largely pyrite and chalcopyrite. Gold, and presumably silver are contained in the sulphides (Stockex Report, 1991).

Details of alteration and mineralization parageneses, and the physical properties of the hydrothermal fluid are unknown. Quartz, K-feldspar, biotite and tourmaline indicates the presence of dissolved SiO_2, K^+ and B_2O_3, and carbonate alteration suggests the presence of a CO_2 component. Fluid temperatures may have exceeded several hundred degrees Celsius.

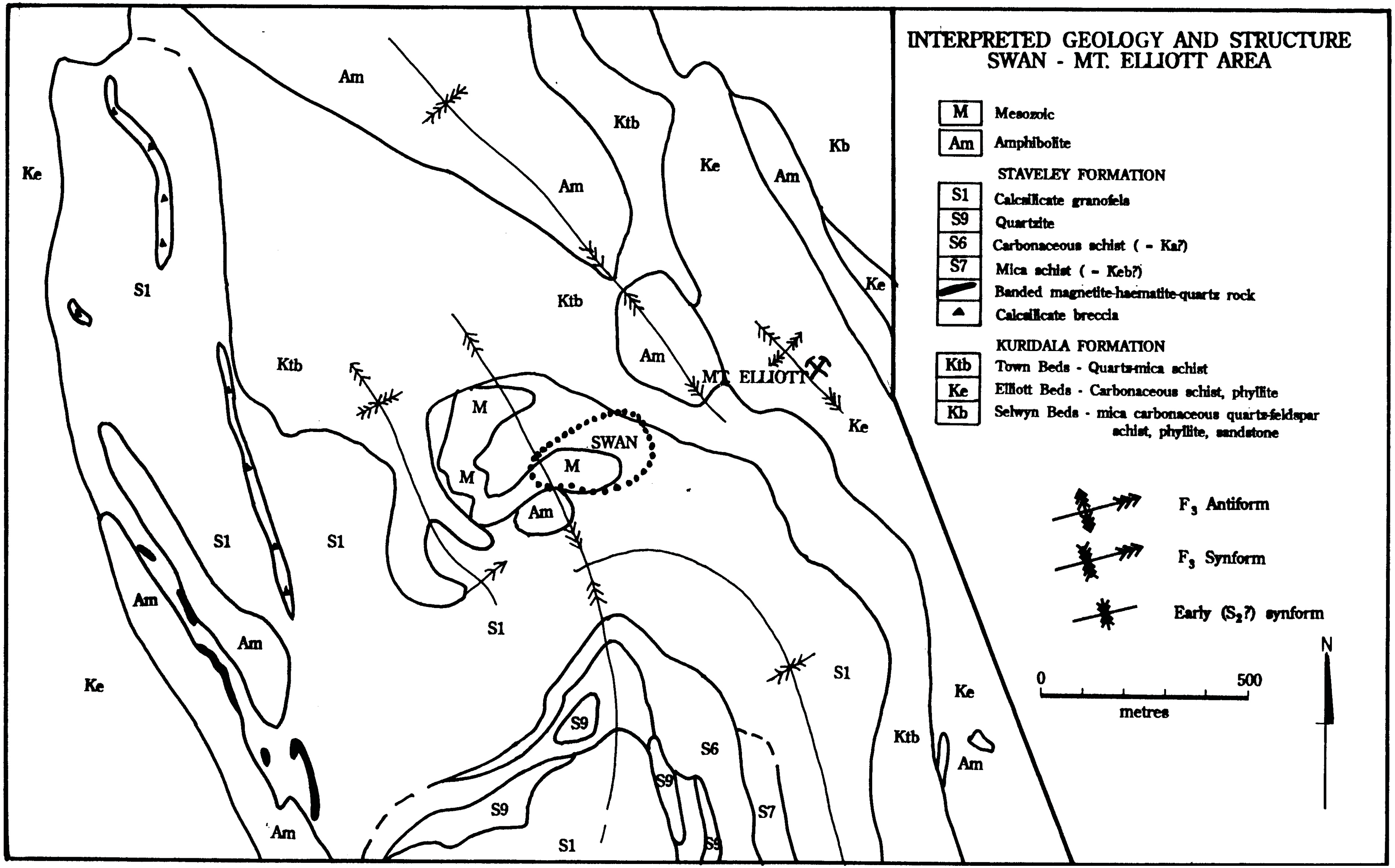
7.2.3 SWAN

Local geological setting

The SWAN (**S**outh **W**est **AN**omaly) prospect was discovered 750 metres west of the old Mount Elliott Mine during a magnetic survey in 1973 as part of a joint exploration programme by Anaconda Australia Incorporated and Union Miniere Mining and Development Corporation Limited (Nyvlt, 1980). Outcrop is poor, and the region deeply weathered, distribution of units therefore poorly constrained (Figure 7.4). Fresh samples from Cyprus Minerals drill core reveals host lithologies to be layered and fragmental, massive and banded calc-silicates of the Staveley Formation. Two types of massive calcareous lithologies have been recognized. One comprises coarse (grains to 4mm) carbonate and diopside, the latter overgrown by tremolite, and lesser quartz and plagioclase. The other is a fine-grained quartz-feldspar$\pm$carbonate rock. Banded calcsilicates are characterized by alternating combinations of pink, cream-white, green and black layers, each from 5 mm to 10 cm thick. Mineralogies are similar to those in massive calc-silicates. Pink layers consist predominantly of fine (<0.5 mm) feldspar and quartz, with lesser carbonate, magnetite, and rare marialitic ($Me_{36.6}$) scapolite porphyroblasts to 3 mm. Cream-white layers are largely coarse carbonate, with minor quartz, feldspar and ferromagnesian minerals. Black layers comprise fine (<0.1 mm) biotite and lesser feldspar, with minor carbonate, epidote, pyroxene and amphibole. Green layers consist mainly of pyroxene, amphibole and carbonate. Brecciation and folding of the calc-silicate rocks is very common in drill core, and Nyvlt (1980) interpreted these features as dominantly of sedimentary origin. Breccia fragments are not appreciably flattened however, and appear to have formed by syn-

FIGURE 7.4: Geologic setting of the SWAN deposit. Outcrop is very poor in this region, but the deposit is hosted by calc-silicate lithologies of the Staveley Formation. Note the abundance of interpreted F_3 folds passing through and close by the main zone of subsurface copper mineralization. There are also numerous faults through this region which are not indicated. The location of the Mount Elliott deposit is also depicted, lying just over 500 metres to the northeast of SWAN. Diagram after Nisbet (1983).

FIGURE 7.4



INTERPRETED GEOLOGY AND STRUCTURE
SWAN - MT. ELLIOTT AREA
M Mesozoic
Am Amphibolite
STAVELEY FORMATION
S1 Calcsilicate granofels
S9 Quartzite
S6 Carbonaceous schist (= Ka?)
S7 Mica schist (= Keb?)
Banded magnetite-haematite-quartz rock
Calcsilicate breccia
KURIDALA FORMATION
Ktb Town Beds - Quartz-mica schist
Ke Elliott Beds - Carbonaceous schist, phyllite
Kb Selwyn Beds - mica carbonaceous quartz-feldspar schist, phyllite, sandstone
F3 Antiform
F3 Synform
Early (S2?) synform
0
500
metres
N
SWAN
MT. ELLIOTT
Am
Ktb
Ke
Kb
S1
M
S9
S6
S7

tectonic disruption of layering or by later faulting, and a strong, layer-parallel foliation also bends around the folds.

The Staveley Formation structurally underlies the Toole Creek Volcanics, which crop out to the east. This contact has conventionally been interpreted as a stratigraphic contact (*e.g.* Dimo, 1975 Nyvlt, 1980), but drill-core crossing the contact reveals large brittle faults and also an earlier (D_1?) layer-parallel mylonitic foliation. Quartz-muscovite schists are also present in this region, at the boundary between the two rock types. Subsequent deformation produced upright, tight to isoclinal, north-trending F_2 folds, then north- to northwest-trending F_3 folds, and later steeply-dipping faulting, largely parallel to earlier fold axial planes. Both SWAN and the neighbouring Mount Elliott deposits lie in the hinge regions of F_3 folds (Nisbet, 1983). Regional metamorphism peaked during D_2 and produced lower greenschist to middle amphibolite facies mineral assemblages (Nyvlt, 1980).

Amphibolites containing plagioclase and tremolitic amphibole are present in both the Staveley Formation and Toole Creek Volcanics, generally concordant with bedding. The Squirrel Hills pluton of the Williams Batholith lies several kilometres to the northeast of the prospect, and Nyvlt (1980) interprets it to lie at least 1500 m below the surface here.

Mineralization and alteration

Dimo (1975) made some casual observations of the SWAN system, but the most exhaustive study to date is that by Nyvlt (1980), who recognized two hydrothermal events. Alteration related to the first event is strongly foliated and restricted to the amphibolite bodies, and comprises relatively fine-grained biotite and pargasitic hornblende, and porphyroblastic scapolite. The latter is flattened parallel to the foliation, which is locally folded around later (F_3) folds. Nyvlt (1980) reports cross-cutting, nearly monomineralic marialitic (av. 24.4% Me) scapolite veins, without specifying whether or not these are deformed. He interprets this alteration episode as the result of alkali-chlorine metasomatism of metadolerites by fluids released from intercalated evaporitic sediments during regional metamorphism.

Alteration related to the second hydrothermal event is more common. It is most obvious as a pervasive red-orange replacement style, occurring in zones and patches, and consisting of a mixture of fine-grained quartz, alkali feldspar and haematite (Nyvlt, 1980). It is temporally and spatially associated with brecciation, permeating along fractures and foliation planes. Veins of later alteration associated with the same event transect the pervasive "red-rock" replacement, and range from 1mm to more than 15 cm wide. Nyvlt (1980) interpreted a general alteration paragenesis from observations of vein contents and overprinting relationships. Early alteration comprises epidote, diopside and actinolitic amphibole, with accessory sphene and allanite (up to 25% by volume, particularly in diopside-rich veins). Later alteration includes magnetite and carbonate. Sulphides (predominantly pyrite and chalcopyrite) are spatially and temporally associated with this stage.

Magnetite and sulphides occur mainly as massive matrix infill and replacement in breccias. In parts of the deposit, calc-silicate mineral assemblages and textures are entirely obliterated. In other places, replacement is selective, yielding thin layers of magnetite, intercalated with thin calc-silicate bands. Copper is only abundant with massive and semi-massive magnetite, but the reverse is not necessarily true. Carbonate is only prevalent where sulphides are absent. Oxidation extends to depths of up to 200 metres, and native copper-chalcocite-magnetite assemblages are regarded as supergene enrichment products of primary pyrite-chalcopyrite-magnetite mineralization (Dimo, 1975). Both chalcocite and chalcopyrite fill veins through and replace early iron oxides and sulphides (Kidd, 1981), and mineralization reportedly terminates at the contact with Toole Creek Volcanics, which here are quartz-muscovite schists locally known as the Town beds. These would have been comparatively unreactive rocks (Nyvlt, 1980). Drilling by Cyprus Minerals Australia Company has defined a resource of 42 million tonnes of ore with an average grade in the primary sulphide zone of 0.69% percent copper (locally exceeding 3% Cu) and 0.4 g/t gold (Nisbet, 1980, 1983).

The hydrothermal assemblages suggest the involvement of hot, saline, alkali-rich chloride solutions having temperatures in excess of 500°C in both episodes of alteration (Nyvlt, 1980). The later fluid additionally carried appreciable quantities of metals. The source of these metals remains problematical. Nyvlt (1980) observed thin (a few millimetres?), fine-grained, alternating magnetite-rich and magnetite-poor laminae, and suggested that at least some of the massive magnetite alteration could have been remobilized from iron-rich sediments. The implication is that other elements have a similar local derivation. Nyvlt (1980) dismissed the granite as a metal source, perhaps prematurely, on the grounds that is was too distant from the prospect, and that metal grades decrease downwards. Relatively high concentrations of rare-earth elements (REE) are implied by the abundance of allanite in the alteration assemblage. The significance of this for ore genesis is unknown, but it is interesting to note that high REE concentrations are also known from the nearby and very similar Starra ironstone-hosted Cu-Au mineralization (Wall, 1986, 1987; Switzer, 1987), and from the Mount Cobalt deposit (Devlin, 1980).

7.2.4 Some small deposits

Lady Ella Mine

This deposit lies 9 km to the north of Mount Dore, close to the northern margin of the Mount Dore Granite (Figure 7.1). The disused mine consists of two vertical shafts and assorted pits. Country rocks are grey, crenulated, medium- to fine-grained mica schists of the Soldiers Cap Group, some with relic andalusite porphyroblasts (Blake *et al.*, 1983). About 40 m to the east, these rocks are faulted against calc-silicate lithologies of the Staveley Formation. The main north-northeast-trending foliation is vertical, and the ore lode lies in a shear zone concordant with this foliation. Primary mineralization is unrecorded, but Blake *et al.* (1983) noted malachite and azurite on the dumps.

Marilyn Mine

The vertical shaft used to mine this copper deposit lies in sub-vertical, north-trending carbonaceous slates of the Solders Cap Group, and is almost totally surrounded by apophyses of the Mount Dore Granite, close to its southwest corner (Figure 7.1). The lode is in a shear zone which is concordant with bedding, and malachite, chrysocolla and quartz have been found on the dumps (Blake *et al.*, 1983).

Mariposa Prospect

This disused mine lies about two kilometres south of Mount Dore (Figure 7.1), and is unusual in the Selwyn region because uranium is present in addition to copper. Shafts and pits are in a thin band of partly bleached carbonaceous slate, phyllite and fine-grained mica schist (Soldiers Cap Group), and bedding (?) dips steeply east. The lode occurs in a shear zone dipping 85^{o} east, concordant with bedding, and Blake *et al.* (1983) report mineralization consists of malachite, chrysocolla, torbernite, and possibly saleeite. The primary ore from which these secondary supergene minerals were derived is unknown.

Stuart Mine

This copper lode lies about 12 km south of Mount Dore, close to the northwestern corner of the Yellow Waterhole Granite (Figure 7.1). A collapsed shaft, some pits and a recently bulldozed costean are the only evidence of old workings (Blake *et al.*, 1983). The production history of the mine prior to 1968 is not documented, but between 1968 and 1970, 321.6 tonnes of ore produced 16.4 tonnes of copper, and in 1979 72.2 tonnes of ore yielded 4.6 tonnes Cu (Krosch, 1981). No assays exist for other metals. Host rocks are thin-bedded, steeply east-dipping, grey phyllite, slate and carbonaceous metasiltstone of the Soldiers Cap Group (Toole Creek Volcanics). Brecciation and alteration are clearly evident in surface outcrop, and metarhyolite, agglomerate and bedded tuff recorded in the Stuart region by Blake *et al.* (1983) are actually brecciated and potassically altered deformed metasediments, and not of volcanic origin. The narrow north-south trending lode occurs foliation-concordant shear zone in the slaty to schistose host, and ore consists of malachite, azurite, chrysocolla and chalcocite (Blake *et al.*, 1983). Quartz, K-feldspar and iron-oxides comprise the gangue mineralogy. A larger sulphide body may exist at depth.

Labour Victory

Two partly collapsed shafts are all that remain of this mine (Blake *et al.*, 1983). Mineralization occurs along joints and shears parallel to the slaty cleavage in carbonaceous slates and siltstones of the Toole Creek Volcanics (Figure 7.1). Ore minerals included cuprite, malachite, azurite and chrysocolla, occurring in a siliceous and ferruginous gangue (Honman, 1938). Total recorded production was 1490.54 tonnes of ore, of which 1086.66 tonnes yielded 286.83 tonnes of copper (= 26.4%), and another 171.31 tonnes contained 37.19 tonnes Cu (= 21.7%) and 595.6 g of gold (= 3.5 g/t; Honman, *ibid.*).

7.3 COMPARISON OF CHARACTERISTICS

7.3.1 Structural controls

A structural control on localization of alteration and mineralization appears to be a universal feature of these deposits. All those examined are hosted within steeply dipping, generally north-trending "layer-parallel shear zones" or faults, and within breccias associated with these. There is an apparent association with fault jogs, or with earlier ductile structures, particularly F_3 folds, which locally cause the normally steeply dipping layering to assume shallowly dipping to subhorizontal attitudes. Both geometric arrangements would be dilational during subsequent reverse faulting, thereby enhancing brecciation, and thus permeability and reactivity of rocks when they are flooded with hydrothermal fluids. All well-known deposits also lie within a few kilometres of an apparently regional layer-parallel D_1 detachment, along which the possibly allochthonous Maronan Supergroup allochthon has been juxtaposed westwards against the remainder of the Mount Isa Inlier (Laing, 1991; this work). If of truly regional extent, this structure may have provided the ultimate control on the escape of deep crustal fluids to shallower levels. A relationship to F_2 folds is less clear, but D_2 was important for rotating bedding and S_1 into generally steep orientations, thereby imparting a regional "grain" which has subsequently controlled the orientation of later faults.

7.3.2 Host lithologies

There is a bias in the literature for describing the largest, historically most productive or recently discovered deposits. The majority of these are hosted by the carbonaceous metasediments of the Toole Creek Volcanics, and one might be led to conclude that there is a stratigraphic control on mineralization. The discovery of the SWAN deposit in the calcareous Staveley Formation demonstrates, however, that other lithologies can prove prospective, and should not be discounted in exploration programmes. The possibility of other hosts is also indicated by the distribution of copper shows in the Eastern Mount Isa Inlier. Even cursory examination of geologic maps of the region reveals these are hosted by a variety of lithologies. What little is known of the geological settings of many of these deposits may be found in the mammoth compilation by Carter *et al.* (1961), and the works of Carter and Brooks (1965), Wilson *et al.* (1972), Brooks *et al.* (1975), Brooks (1977) and Krosch (1981). The apparently small sizes of these deposits may be misleading, given the example of the Mount Dore deposit, which was itself only a "minor" scratching before exploratory drilling to depth defined a body of major proportions. There is still potential for bodies of up to several tens of millions of tonnes.

7.3.3 Alteration assemblages

Alteration assemblages show some similarity between deposits. Paragenetic sequences are only known in any detail for Mount Dore and SWAN, and in both cases alteration was characterized by early formation of potassic phases (predominantly K-feldspar, but also biotite), later quartz, and late carbonate. These phases and tourmaline are recorded from Mount Elliott and the Hampden group of deposits, and may define similar paragenetic sequences, though confirmation requires detailed petrography.

There are also some differences. Calc-silicate assemblages are much more prevalent at SWAN and Mount Elliott, as massive replacement and veins containing variable amounts of diopside, epidote, actinolite, scapolite and carbonate. The host rocks at SWAN are predominantly metamorphosed calcareous lithologies of the Staveley Formation, which were more reactive than the predominantly argillaceous lithologies present at Mount Dore. Calc-silicate assemblages are developed on a smaller scale at Mount Dore, where calcareous lithologies are subordinate. The regional metasomatic scapolite-biotite-amphibole assemblage developed in amphibolitic rocks at SWAN is not developed at Mount Dore, where this lithology is absent.

Alteration at SWAN and Mount Elliott is also characterized by being much richer in iron than that at Mount Dore, with development of abundant magnetite. This difference can again be attributed to the predominance of Staveley Formation as host, a unit enriched in iron on a regional scale adjacent to its contact with the Maronan Supergroup. This iron was demonstrably present prior to the time of breccia-hosted mineralization, occurring as detrital haematite, small pods of oxide-facies banded iron-formation, and massive ironstone bodies of controversial origin, and would have been readily remobilized.

Differences in alteration assemblages could therefore reflect reaction of the hydrothermal fluid with lithologies having different bulk compositions, rather than marked differences in fluid composition or ore-forming processes.

7.3.4 Primary mineralization

Sulphide mineralogy is relatively simple in all cases, consisting predominantly of pyrite and chalcopyrite, with minor sphalerite and galena. At Mount Dore and SWAN pyrite precipitated first, and copper and other base metal sulphides formed later, apparently in part by scavenging of sulphur from the earlier pyrite. The paragenetic sequences are unknown for the other deposits. In addition to base metal sulphides, each deposit also boasts a range of other metals in small concentrations. Most important of these are silver and gold. Gold is an important credit at SWAN, Mount Elliott and the Hampden group, but is conspicuously less abundant at Mount Dore, where silver is more important. The reason for this difference is not known. It could reflect different source rocks for the metals, or differences in transport and precipitation mechanisms at different sites. Rare-earth elements are enriched in the SWAN deposit (Nyvlt, 1980). This probably also reflects source rock differences, but further studies are required, particularly since elevated REE contents have also been noted at Starra (Wall, 1986) and Mount Cobalt (Nyvlt, 1980), two deposits conventionally regarded to be of different styles, and unrelated to SWAN.

7.3.5 Hydrothermal fluid

Fluid temperature, compositional and provenance data are moderately well constrained for the Mount Dore deposit only. Here, a deep-seated metamorphic high temperature (>500^{o}C), highly saline H_2O-CO_2 fluid entered a brecciated dilatant zone, where it underwent immiscible phase separation, cooling, and apparently dilution with a less saline fluid, also possibly of metamorphic derivation. Detailed characteristics for hydrothermal fluids at other deposits cannot be established without fluid inclusion and isotopic studies, but mineral assemblages all suggest involvement of a fluid markedly out of equilibrium with host rocks, at temperatures comparable to those determined at Mount Dore. This is most apparent at SWAN, where the fluid passed into highly reactive, carbonate-rich rocks, and produced pyroxene-amphibole-scapolite assemblages. High temperatures of formation (> 500^{o}C?) are also implied by the pyroxene-scapolite alteration assemblage at Mount Elliott. The occurrence of gypsum in the Mount Elliott alteration assemblage is also significant, because it indicates the presence in the fluid of sulphur dominantly in sulphate form. This evidence for an oxidized fluid supports the interpretation for a similar fluid at Mount Dore (Chapter 6). The same provenance is envisaged for all hydrothermal fluids.

7.3.6 Conclusion

In conclusion, then, the better known copper deposits in the Kuridala-Selwyn region are similar to the Mount Dore deposit in structural controls, sulphide parageneses, and broadly defined hydrothermal fluid chemistry. Host rocks are dominantly, but by no means exclusively carbonaceous metasediments of the Toole Creek Volcanics. Differences in alteration parageneses are related to the type of rock reacting with the high temperature fluids passing along tectonically prepared conduits through it. Petrogenetic interpretations made from mineral and fluid geochemical studies of the range of different lithologies represented in the Mount Dore deposit should therefore provide insights to processes occurring in other deposits which are dominated by one or other of these lithologies, and the general petrogenetic model derived for Mount Dore can probably be adapted with relatively minor modification to these and perhaps other deposits. The known features of the smaller, less well-known copper deposits described herein are similar to the larger deposits, encouraging the conclusion that they formed in a similar manner, and suggesting that some of them may possibly be larger than first apparent.

Interestingly, the Starra and Osborne ironstone-hosted Au-Cu deposits share many similarities with Mount Dore-style mineralization, particularly the SWAN variant. Starra and Osborne are variably interpreted as deformed and metamorphosed volcanogenic exhalative oxide deposits (*e.g.* Davidson *et al.*, 1989), or syn-deformational metamorphogenic deposits (*e.g.* Switzer, 1987; Switzer *et al.*, 1988; Laing *et al.*, 1988). Both may have been overprinted by, or be exclusively the result of the "Mount Dore style" mineralizing event, possibility which has been neglected to date.

7.3.7 Comparison with the Mount Isa copper deposit

The Mount Isa copper ore formed during regional deformation and greenschist facies grade metamorphism. Bell *et al.* (1988) proposed that the interaction of ductile D_1, D_2 and D_3 structures produced regions of dilation, fluid pressure decrease and subsequent explosive hydraulic brecciation, hence producing a structural trap into which fluids could flow and react extensively with host rocks. Ore-related alteration occurred during D_3, and comprises early dolomitization, overprinted by silicification. Chalcopyrite is temporally and spatially associated with silicification, and commonly replaces slightly earlier iron and cobalt sulphides (Perkins, 1984b; Swager, 1985).

Two fluids were associated with dolomitic alteration: a $CaCl_2$-rich, relatively saline (25 wt% NaCl equivalent) fluid, and a low salinity, CO_2-bearing (10 to 20 mole%) fluid. An evolving, NaCl-rich fluid of variable salinity (4 to 20 wt% NaCl equivalent), containing minor CH_4 and showing no evidence for boiling, was associated with silicification (Heinrich *et al.*, 1989). Stable isotopic and fluid inclusion studies indicate that the fluids were of metamorphic origin, derived from, or at least having equilibrated with the different major lithologies represented in the immediate ore environment (Heinrich *et al.*, 1989). Sulphur isotopic studies by Andrew *et al.* (1989) support the contention of Robertson (1982) that sedimentary sulphides (including the lead-zinc orebodies) have been the major source of sulphur required for sulphide precipitation. Metals are believed to have been derived by leaching from the surrounding rocks, specifically from metabasic (greenstone) lithologies in the case of copper (Perkins, 1984).

The structural controls on ore localization, the involvement of saline, CO_2-bearing metamorphic fluids, and the derivation of metals by leaching of crustal rocks are reminiscent of mechanisms determined for the origin of the Mount Dore copper deposit. The similarities suggest that these two widely separated deposits may be closely akin, related by regional metallogenic processes (see below).

7.4 PETROGENESIS OF THE MOUNT DORE COPPER DEPOSIT

This section reviews the evolutionary model for the Mount Dore breccia-hosted copper deposit interpreted from the foregoing studies of structural controls and alteration and fluid geochemistry. With modification, this model will probably account for the formation of similar deposits in the Kuridala-Selwyn region.

Processes responsible for mineralization at Mount Dore and similar deposits may have begun as early as initial sedimentation, when the parts of the stratigraphic succession which would ultimately host these deposits were preferentially enriched in copper and associated elements, through extensive basic volcanism, and perhaps associated volcanoexhalative hydrothermal activity. Ultimately, however, these deposits are localized in structural traps, at sites characterized by the intersection of structures from several generations. In the vicinity of the Mount Dore deposit, ductile deformation produced a steeply east-dipping grain to the rock, with localized zones of shallowly-dipping fabric, which became dilatant during the late-tectonic formation of the reverse dip-slip Mount Dore Fault Zone. Movement along this and similar regional-scale faults was probably largely related to waning compressional tectonism, although buoyancy forces exerted by synchronous intrusion of plutons of the Williams Batholith may have contributed, as may have the hydrothermal fluid, where its pressure locally exceeded the lithostatic load.

Extensive brecciation and fault block shuffling occurred after solidification of the granite, in the dilatant zones along the faults, providing regions where the fluid could enter and interact with relatively large areas of rock. The primary hydrothermal fluid was a hot (>500^{o}C), highly saline, relatively oxidized fluid derived from a deep-seated metamorphic source, and containing substantial quantities of CO_2, K^+, Na^+, Fe^{2+}, Ca^{2+}, Cl^-, and possibly SiO_2 and B_2O_3. Sulphur if present was mostly as SO_2. Subsequent evolution of the chemical and physical characteristics of the fluid appears to have been controlled largely by fluid-rock interactions within the general zone of alteration and mineralization, and mixing with fluids of separate provenance.

The earliest identifiable alteration phase was potassic. Orthoclase was produced initially in all lithologies, although later in the paragenesis within the main zone of alteration, or away from the main fluid path, where substantial interaction of the fluid with host rocks had depleted the K^+ content of the former, sericite was produced. Biotite (technically phlogopite) also formed somewhat later in the calcilutites, in response to local changes in fluid f_{O_2}. Replacement of plagioclase and mafic phases (mainly biotite) in the granite and quartz+carbonate+plagioclase assemblages in slabs of Staveley Formation entrained in the fault zone liberated Ca^{2+}, Fe^{2+} and Mg^{2+} to the fluid. Although the source of the base and precious metals is not known, they may have been released from the metasediments at this time (Section 7.5.2). Potassic alteration in general added SiO_2 and K^+ to the rocks.

There is no evidence that the fluid was boiling during K-metasomatism. The general paucity of alteration as infill also suggests that large open spaces could not be supported by rock strength at prevailing pressure. This fact, in combination with high fluid temperatures, suggests large confining pressures; the fluid may been under a close to lithostatic load at this time, possibly up to several hundred MPa.

Potassic alteration was superseded by an episode of silicification, and local tourmaline precipitation. An immiscible CO_2-rich fluid phase separated and was subsequently lost from the primary fluid at around about this time, perhaps in response to decreasing fluid temperature or pressure. Immiscible phase separation elegantly explains the extraordinarily saline primary fluid inclusions observed in quartz, and even the precipitation of quartz itself. The saline fluid was the residual aqueous phase, into which the salts preferentially partitioned. The subsequent rise in the activities of many of the species in this residual solution could have resulted in saturation of components. The apparent coincidence of silicification with CO_2 loss becomes explicable. Quartz precipitation may also have been partly in response to formation of tourmaline, as SiO_2 solubility in a fluid is known to decrease with decreasing B content of the fluid (*e.g.* Manning and Pichavant, 1984). Deposition of the tourmaline may also have been in response to CO_2 phase separation, or to decreasing fluid temperature, or reaction with wall-rocks. Calcareous Staveley Formation lithologies also locally developed calc-silicate assemblages at about this stage in the alteration - essentially micro-skarns, where they interacted with the hot, saline fluid.

Sulphides formed relatively late in the paragenesis, probably reflecting the lack of reduced sulphur in solution until late in the alteration history. Sulphur and iron could be transported together in solution because the fluid was relatively oxidizing, but partial sulphate reduction by reaction with reduced carbon released from the carbonaceous slates eventually led to the precipitation of pyrite.

Carbonate formed after pyrite. The dominance of dolomite or calcite at any particular place was likely a function of variable proportions of Mg^{2+} and Ca^{2+} in the fluid, but actual precipitation was controlled by lowering of the activities of CO_2 and H^+ in solution. These may be lowered by boiling of volatile phases away, or by dilution of the fluid. Dilution is the favoured mode of precipitation. Boiling may have occurred locally at Mount Dore, it cannot have been dominant, because the fluid evolved towards less saline compositions. Boiling, or even simply cooling the fluid cannot produce this trend. Introduction of a second, dilute aqueous fluid is necessary. A meteoric derivation is an attractive option for this fluid, but stable isotope evidence suggests it may instead have been a low-salinity metamorphic fluid, perhaps derived from argillaceous or otherwise salt-poor successions.

Reduced sulphur remained low in the fluid throughout its evolution. Copper- and other base metal sulphides formed by scavenging sulphur and iron from earlier pyrite, and either precipitating directly on or nearby this phase, or by partially replacing earlier carbonates. The latest identifiable stage in hydrothermal alteration was formation of chlorite, as veins or partial replacement in earlier alteration phases.

Continuing uplift of the region exposed the copper deposits to near-surface oxidizing conditions several times (Cambrian, Mesozoic and Recent), at which times significant enrichment occurred, generally producing extensive high-grade supergene chalcocite blankets and overlying Cu-oxide and carbonate deposits.

7.5 SPECULATIONS ON REGIONAL METALLOGENY

7.5.1 Absolute age of alteration and mineralization

The absolute age of alteration-mineralization has not been determined for any of the Mount Dore style of deposit. The maximum age of the type deposit may be constrained, however, by a consideration of both large- and small-scale evidence. The Mount Dore Granite cuts across D_2 structures, but is noticeably, albeit weakly foliated, probably during D_3. The western margin of the Mount Dore Granite is bounded by the Mount Dore Fault Zone and final, solid-state emplacement was along this structure. Brecciation and hydrothermal activity affect the granite, and therefore occurred after, or at the very earliest during D_3, and during development of the Mount Dore Fault Zone (Chapters 4 and 5). Contact metamorphic assemblages in the Soldiers Cap Group and Staveley Formation have been replaced by hydrothermal alteration phases (Chapter 5). This evidence indicates that the Mount Dore deposit is younger than the Mount Dore Granite, but still associated with the waning stages of regional deformation.

A sample of Mount Dore Granite from close to Mount Dore yielded a Rb-Sr whole rock age of 1509±22 Ma (Nisbet *et al.*, 1983; initial Sr^{87}/Sr^{86} ratio assumed to be 0.705). This date is the minimum age of the granite, because Rb-Sr systematics of rocks are notoriously susceptible to resetting by hydrothermal leaching, during even low-grade metamorphism and associated deformation events (Page, 1978; Page and Bell, 1986). At Mount Dore the Rb-Sr clock may have been reset either by the D_3 event, or by the later hydrothermal activity, and therefore indicates the maximum possible age of alteration and mineralization. There are no geochronological data for the other deposits, but structural and textural evidence yield a similar late tectonic timing, suggesting similar ages. Further geochronological studies would be expedient.

7.5.2 Source of metals

Mineralization in the Mount Isa Inlier is dominated by copper, but although copper is the dominant metal in many deposits, these are in fact polymetallic, containing varying amounts of Au, Ag, Pb, Zn, Co, W and U. The metal association occurring at any particular deposit could depend to varying degrees on the sources of metals, and the solution and precipitation mechanisms. The dominance of copper regardless of host, and the efficaciousness with which the hot, saline brines would have leached metals from the crust suggest that selective solution or precipitation of particular elements are unlikely to control the resulting metal associations, and that bulk metal contents of the source rocks are the dominant control.

The main rock types associated with these deposits are carbonaceous slates, variably calcareous metasiltstones, metabasites and granites. Table 7.2 presents world average abundances of a range of selected elements for seven major rock groupings. It is evident from this table that basaltic rocks are relatively enriched in Cu, Ag, Co and Zn, and relatively depleted in Pb relative to average crustal values, in accord with observations of relative metal abundances.

Metamorphosed basic igneous rocks occur in all metasedimentary units in the Kuridala-Selwyn Region, but are particularly abundant in the upper part of the Soldiers Cap Group (Toole Creek Volcanics), and the basal part of the Staveley Formation. Metabasites as a source of ore elements is not a new idea. Ball (1908; p.31) believed that the "Cloncurry deposits may possibly be due, at least in part, to the metamorphism of originally cupriferous igneous rocks...". Copper in the epigenetic Mammoth group of deposits (about 120 km north of Mount Isa) is thought to have been leached from adjacent basic igneous rocks (Scott and Taylor, 1982). Bennett (1965) suggested that copper in the Mount Isa orebody was weathered from the Eastern Creek Volcanics and biogenically precipitated into the overlying host sedimentary succession. Perkins (1984) believes, however, that this copper was derived by hydrothermal leaching of footwall rocks.

TABLE 7.2: Average abundance of selected minor elements in the earth's crust. All values in ppm. Dashes (-) indicate no data available (Extract from Levinson, 1974. Reproduced in Berkman, 1989, pp. 54-55).

Element	**Earth's crust**	**Ultra-mafic**	**Basalt**	**Grano-diorite**	**Granite**	**Shale**	**Lime-stone**
Ag	0.07	0.06	0.1	0.07	0.04	0.05	1
Au	0.004	0.005	0.004	0.004	0.004	0.004	0.005
B	10	5	5	20	15	100	10
Ba	425	2	250	500	600	700	100
Ce	60	8	35	40	46	50	10
Cl	130	85	60	-	165	180	150
Co	25	150	50	10	1	20	4
Cu	55	10	100	30	10	50	15
Eu	1.2	0.16	1.27	1.2	-	1	-
F	625	100	400	-	735	740	330
La	30	3.3	10.5	36	25	20	6
Nd	28	3.4	17.8	26	18	24	3
Ni	75	2000	150	20	0.5	70	12
Pb	12.5	0.1	5	15	20	20	8
Sm	6	0.57	4.2	6.8	3	6	0.8
U	2.7	0.001	0.6	3	4.8	4	2
W	1.5	0.5	1	2	2	2	0.5
Zn	70	50	100	60	40	100	25

Basaltic rocks are therefore attractive as a potential source for metals. Significantly, however, they are relatively poor in Ba, B and U, elements known to occur in elevated concentrations at Mount Dore. Average, carbon-poor shales are enriched in these elements, and have abundances of Cu, Zn, Pb and Co only slightly less or comparable with metabasite. Carbonaceous shales (not illustrated in Table 7.2) commonly have more than twice as much copper, silver and zinc as carbon-poor shales (Maynard, 1983). The metasediments of the Toole Creek Volcanics could therefore also provide the necessary metals, an idea supported for the Mount Dore deposit by Scott (1986).

Evaporitic or exhalative rocks can be even more enriched in boron than argillaceous sediments (Brown and Ayuso, 1985; Slack, 1982). Both these rock types have been interpreted for the Staveley Formation (Blake *et al.*, 1983; Davidson *et al.*, 1989; this work). Evaporites are attractive because they can also provide a source for the high NaCl and KCl contents in the hydrothermal fluid. The granites may also have provided some barium and uranium, and perhaps boron, although most plutons of the Williams Batholith have no recorded tourmaline, suggesting low boron contents.

Gold was an important by-product during copper mining at Mount Elliott and the Hampden group of mines, and gold continues to provide an important exploration incentive at these and similar deposits. Table 7.2 indicates that gold contents of all rock types are very low, and no rock type will be particularly favourable as a source of gold.

It therefore appears that all major rock types represented in the mineralized regions could have provided at least some of the metals. In those deposits examined, however, carbonaceous shales and metabasites are dominant, and would have provided the bulk of the metals, if local rocks were the source. Low concentrations of lead relative to other base metals can then be attributed to its generally low abundance in these sources, and also to its very low solubility in the proposed oxidized, sulphur-poor or sulphate-bearing hydrothermal fluid (Cotton and Wilkinson, 1980, p.399). More difficult to explain, however, is the relative paucity of zinc in breccia-hosted copper deposits, as it occurs in similar concentrations to copper in most of the proposed source rocks, and is probably at least as soluble as copper (Barnes, 1979; Barrett and Anderson, 1988). It is possible that under the conditions of copper precipitation zinc remained in solution, to be carried away.

Not all deposits in the eastern Mount Isa Inlier are copper-dominant. A number of lead-zinc(± silver) deposits are known, such as Pegmont, Fairmile, Dugald River, Maramungee, and the recently discovered Cannington deposit (Figure 7.1). Many of these deposits occur associated with small iron-formations, and are usually assigned a syn-sedimentary volcano-exhalative origin (see for example, the works of Locsei, 1977; Stanton and Vaughan, 1979; Connor *et al.*, 1982; Vaughan and Stanton, 1984, 1986; Newbery, 1991), although the Maramungee deposit was recently interpreted as a skarn (Williams and Heinemann, 1991). These lead-zinc dominant deposits are largely found around the periphery of exposed (or only shallowly covered) rocks of the Maronan Supergroup, in the dominantly quartzofeldspathic constituent formations (Mount Norna Quartzite and Fullarton River Group). Such broadly granitic compositions would be enriched in lead and zinc relative to copper (Table 7.2). This suggests that regional leaching of particular gross crustal compositions may dictate the dominant metal association. Thus copper deposits predominate where the crust contains a high proportion of mafic volcanics and argillaceous sedimentary rocks, and lead-zinc mineralization occurs in crust containing a high proportion of quartzofeldspathic rocks.

7.5.3 Mineralizing role of granitoids

The Mount Dore and similar deposits in the Kuridala-Selwyn region all lie within a few kilometres of exposed plutons of the Williams Batholith (Figure 7.1). Petrologic and structural evidence indicate, however, that the granite pluton adjacent to the Mount Dore deposit had crystallized before brecciation and hydrothermal activity, seemingly discounting granite at Mount Dore (and by inference at the other breccia-hosted deposits considered) as a contributor to metallogenesis in anything more than a passive way, by perhaps providing a source for a proportion of the introduced elements.

Granites should not, however, be dismissed as mineralizing agents in the eastern Mount Isa Inlier. Textural evidence and strong enrichment in LREE and other incompatible elements indicate that plutons of the Williams Batholith were derived by partial melting of a mafic crustal underplate (Wyborn *et al.*, 1988). The batholith was probably also emplaced as a liquid (L. Wyborn, pers. comm., 1987), with subsequent fractional crystallization producing the compositional heterogeneities between individual plutons (Wyborn *et al.*, 1988). Fractional crystallization is a powerful mechanism for concentrating ore (and other incompatible) elements into later melt and vapour phases (*e.g.* McCarthy and Hasty, 1976; Whalen *et al.*, 1982). The Williams Batholith is aluminous (Wyborn *et al.*, 1988) and magnetite-rich, placing it in the magnetite series of Ishihara (1981). Such granites are most commonly associated with massive sulphide mineralization, where this develops (Ishihara, 1981). Aluminous magmas are the only type capable of producing late-magmatic hydrothermal fluids containing significant concentrations of ore elements (Urabe, 1985). The type of fluid generated is likely to be acidic, chloride-rich and sulphur-bearing (Holland, 1972).

That the granites of the Williams Batholith are hydrous, and therefore probably capable of producing a magmatic fluid, is indicated by the presence of biotite and hornblende. Unfortunately, erosion has long ago removed the apical region of much of the batholith, and therefore any mineralization which may have lain above it. Granite-related mineralization may yet persist around the peripheries, however. Wyborn *et al.* (1988) cite abundant breccias and alteration around the northern margins of the batholith as evidence for fracturing and hydrothermal activity associated with second boiling and decompression of a volatile-rich vapour phase. This vapour phase may even have contributed to the formation of Mount Dore-style mineralization, if it exsolved from the magma at depth, travelled as a separate phase, and only escaped when a pathway was provided by the faulting which controlled the solid-state emplacement of the Mount Dore Granite.

Granite intrusion may have contributed more directly to other styles of mineralization than is presently recognized. Enrichment of LREE and other incompatible elements has been noted in the Starra ironstone-hosted copper-gold deposit (Wall, 1986; Switzer, 1987; Davidson *et al.*, 1989), and at Mount Cobalt (Devlin, 1980; Nisbet *et al.*, 1983), orebodies which all current metallogenic models suggest formed before granite intrusion. The role of magmatism in the formation of these deposits has not yet been considered.

7.5.4 Metallogeny and tectonics

The largest breccia hosted copper-gold deposits, all having similar geological characteristics, are distributed adjacent to the western and northern margins of the Maronan Supergroup, close to the contact between this unit and the Mary Kathleen Group. This distribution may be coincidental, reflecting simply those deposits that have been discovered to date, or it may say something more significant about the relationship between tectonics and metallogeny.

The boundary is interpreted as a major tectonic contact, and metabasaltic and argillaceous metasedimentary lithologies identified as favourable metal sources are common here. This relationship suggests that some form of preferred channelling of fluids occurred. Any metallogenic model must account for these features, and also must explain the coincidence of favourable structures, and the interaction of at least two fluids having markedly different compositions.

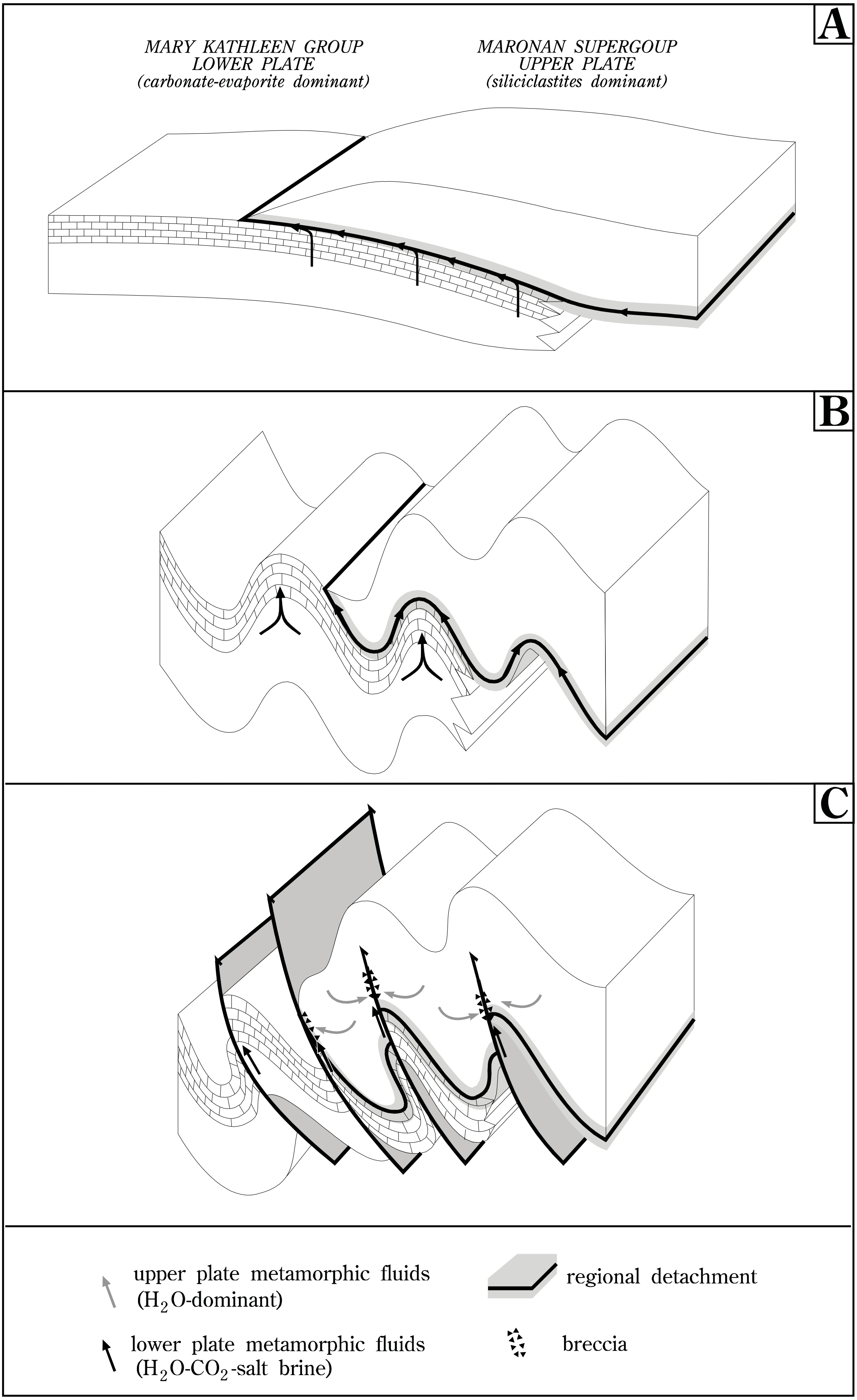
A speculative regional-scale model which can explain the known features of the Mount Dore-style of deposits is presented in Figure 7.5. Basin evolution in the Mount Isa Inlier was terminated by fast convective thinning (Loosveld, 1989b). Rapid closure of the basins was achieved initially by thrusting. In this scenario, at least one large allochthonous slab of Maronan Supergroup was emplaced over the carbonate-evaporite successions of the Mary Kathleen Group. The evaporite-carbonate succession would have provided a well-lubricated decollement during underthrusting, and would also during subsequent (D_2) prograde regional metamorphism have provided a ready source of highly saline, CO_2-bearing fluids.

FIGURE 7.5: Schematic diagram of a speculative model for regional epigenetic mineralization, based on interpretations of petrogenesis of the Mount Dore style of copper mineralization.

A Emplacement during D_1 of at least one large allochthonous slab of Maronan Supergroup over the carbonate-evaporite successions of the Mary Kathleen Group. Highly saline, CO_2-bearing connate and prograde metamorphic fluids evolved from the underlying succession passed upwards into and along the decollement.

B Subsequent upright to inclined F_2 folding caused ponding of fluids emanating from the underlying carbonate-evaporite sequence into antiforms, where they may have "stewed" for a period of time in contact with relatively metal-rich lithologies in the overriding slab. Alternatively, fluids may have dissolved in lower crustal anatectic melts (not shown, for clarity), to be released as a separate, hybrid, "metamorphic-magmatic" phase again only when plutons reached vapour saturation during ascent and/or crystallization.

C Eventual release of fluid to higher crustal levels occurred only when F_2 structures were breached during late-tectonic reverse faulting. This faulting also allowed final, solid-state emplacement of at least some plutons of the Williams Batholith (not shown, for clarity). Passing rapidly upwards along these faults, the fluids would have encountered local dilatant zones, where relatively large fluid-rock ratios prevailed, and where extensive alteration and sulphide precipitation would have occurred. Low salinity fluids of meteoric, or more likely upper-plate metamorphic derivation could have migrated into the dilatant zones when the deeply penetrating fault structures became available, and subsequently mixed with the saline fluids, perhaps initiating some styles of mineralization in the process.


A
MARY KATHLEEN GROUP
LOWER PLATE
(carbonate-evaporite dominant)
MARONAN SUPERGOUP
UPPER PLATE
(siliciclastites dominant)
B
C
upper plate metamorphic fluids
(H_2O-dominant)
lower plate metamorphic fluids
(H_2O-CO_2-salt brine)
regional detachment
breccia

The fluids would have passed upwards into and then been squeezed along the decollement by the overriding thrust sheet or sheets (Figure 7.5A), in a manner akin to that suggested by Oliver (1986). Subsequent deformation produced upright to inclined F_2 folds. Fluid continuing to emanate from the underlying carbonate-evaporite sequence, or moving along the D_1 decollement may have been ponded in F_2 antiforms (Figure 7.5B), where they may have "stewed" with relatively metal-rich lithologies in the overriding slab, thereby becoming enriched with these metals. This continuous evolution of fluid may have had a role to play in other styles of mineralization in the region (*e.g.* Starra).

Rapid release of fluid to higher crustal levels only occurred when F_2 folds were breached by late-tectonic reverse faults (Figure 7.5C). The fluids may even have had a role to play in the generation of these structures (*e.g.* Phillips, 1972; Sibson *et al.*, 1988). Fluid passing rapidly upwards along these structures would have encountered local dilatant zones, where relatively large fluid-rock ratios would have prevailed, and where extensive alteration and sulphide precipitation would have occurred.

There is a problem with proposing the involvement of metamorphic fluids in metallogenesis. There was a lapse of 40 to 50 million years between metamorphic peak (1545 Ma; D_2) and mineralization (1500 Ma?; post-D_3), if we accept for the eastern part of the Mount Isa Inlier the same geochronology determined for the western part by Page and Bell (1986). Recent modelling by Baumgartner and Ferry (1991) and Ferry and Dipple (1991, 1992) suggest that fluid flow through non-fractured metamorphic rocks can occur at up to 1 mm per year, and in fractured rocks will be substantially faster. This means that metamorphic fluids should have escaped long before the proposed time of mineralization.

It is entirely possible that the deformation chronology of Page and Bell (1986) is invalid for the eastern Mount Isa Inlier, and that peak metamorphism and mineralization here occurred more closely together in time. In addition, the mobility of fluid may have been reduced by dissolution in Williams Batholith magmas, which would have been produced by partial melting of deep crustal material at the peak of metamorphism. Rapid fluid movement would have been restored only when vapour separation occurred in the rising plutons, and when permeable reverse faults, which also controlled the solid-state emplacement of the plutons, were formed.

Low salinity fluids entering dilatant zones and mixing with the saline fluids could have two origins. Meteoric waters may have penetrated down the fault structures and interacted with still hot (but cooling) upper-plate metamorphic rocks in the brittle regime. Low fluid-rock ratios would be required, however, for such a fluid to acquire a metamorphic stable isotopic signature, and also a mechanism for deep penetration into the crust; "seismic pumping" may have occurred (Sibson *et al.*, 1975; McCaig, 1988). Alternatively, low-salinity metamorphic fluids may have been derived directly from the upper plate, dominated by evaporite-poor Maronan Supergroup. These fluids might also have become mobile only when deeply penetrating fault structures became available, and could have percolated into these structure after the saline fluid.

In summary, then, province-wide base metal mineralization appears to be related to scavenging of metals from the local lithologies by upwelling metamorphic fluids, and precipitated in suitable structural, and in some cases lithological traps. The contention by Laing (1991) that many superficially distinct styles of mineralization may be all controlled by the same underlying processes therefore appears justified, and we may be reminded of the foresighted speculations of Ball (1908) who stated (p. 30) "...both iron and copper ores are due primarily to regional metamorphism, perhaps enriched in parts by ascending metalliferous solutions".

7.5.5 Recommendations for further work

Tectonic studies

This study, and others like it (*e.g.* Loosveld, 1989a,b; Reinhardt and Rubenach, 1989; Newbery, 1991; Reinhardt, 1992) go some way towards unravelling the tectonic history of the eastern part of the Mount Isa Inlier, but this knowledge is still fragmentary. Most significantly, the geological development of the Maronan Supergroup and its relationship to the remainder of the inlier remain relatively poorly understood. It is generally accepted that the volcanosedimentary basins of the Mount Isa Inlier formed by intracontinental extension (*e.g.* Derrick, 1982; Beardsmore *et al.*, 1988). The Maronan Supergroup is believed to have been deposited in a separate basin, and circumstantial evidence suggests it may be older than all other units in the inlier except the Leichhardt Volcanics and cogenetic intrusives (Beardsmore *et al.*, 1988). In reality, however, the age of this unit is at present unconstrained. The results of collaborative geochronological studies of the Maronan Supergroup recently initiated between James Cook University and the Australian Geological Survey Organization (formerly the Bureau of Mineral Resources) will be important for constraining tectonic modelling.

The nature of the structural contact between the Maronan Supergroup and the Mary Kathleen Group is also poorly known. Mapping to date suggests the former unit has been thrusted some considerable distance over the latter, particularly in the Kuridala-to-Cloncurry region (Loosveld, 1989; Newbery, 1991; this work), but there has been little detailed mapping over a wide area to confirm this. In addition, a better understanding is needed of the relationship between the blocks of Maronan Supergroup in the northern and southern parts of the Kuridala-Selwyn region, and between this belt and the Soldiers Cap belt east of the Williams Batholith, where several extra deformation events have been recognized (Newbery, 1991). If large-scale thrusting demonstrably occurred early in the deformation history of the eastern part of the Mount Isa Inlier, a source for highly saline, CO_2-bearing hydrothermal fluids becomes apparent, via metamorphic devolatilization of the evaporitic Mary Kathleen Group underlying the allochthonous Maronan Supergroup.

The spatial and temporal relationships between metamorphic zones and structures remain poorly constrained in the southeastern part of the Mount Isa Inlier. Tectonic modelling requires knowledge of at least segments of the pressure-temperature-time (P-T-t) paths followed by rock volumes in this region. If the Maronan Supergroup proves to be allochthonous, it may have followed a P-T-t path different from the remainder of the Mount Isa Inlier. Such integrated metamorphic and structural studies are important for determining the history of tectonic assembly of the Mount Isa Inlier, and more generally for characterization of Proterozoic tectonic processes, which are still relatively poorly understood (see, for example, Kröner, 1991).

Metallogenic studies

This study also presents the first detailed multi-facetted study of an epigenetic breccia-hosted copper deposit in the eastern half of the Mount Isa Inlier. The Mount Dore deposit has now been placed into context with the regional deformation history of the eastern part of the Mount Isa Inlier, constraints have been placed on alteration and mineralization parageneses, and on hydrothermal fluid provenance and evolution, and a petrogenetic model devised. Several aspects of the model require further research, however.

Circumstantial evidence suggests that the source of many elements, including ore metals in the Mount Dore deposit is "local", in that they were leached from crustal rocks by a throughgoing hydrothermal fluid, then deposited in suitable, dominantly structural traps at higher crustal levels. Mass balance calculations would constrain net fluxes of different elements into and out of the system, and therefore more satisfactorily illustrate which major elements have been introduced from elsewhere, and which have merely been redistributed. Lead isotope studies of galena from Mount Dore (and similar deposits) may help determine the source of Pb, and hence other base metals.

Stable isotope and fluid inclusion data from the Mount Dore deposit suggest mixing of an early, saline fluid of deep-seated, metamorphic and/or magmatic derivation with a more dilute metamorphic fluid during the advanced stages of alteration and mineralization. More detailed fluid inclusion and isotope studies are required to confirm the involvement of, and more closely characterize the natures of the fluids involved, and estimate fluid flux through the Mount Dore deposit. Also requiring consideration are the implications of channelling and late mixing of two metamorphic fluids of such diverse compositions in relatively localized zones for regional crustal hydrology and fluid escape.

The other large breccia-hosted deposits in the Kuridala-Selwyn region (Mount Elliott, Hampden, SWAN) have many characteristics in common with that at Mount Dore, and are therefore considered to have formed in a similar fashion. This assertion clearly requires confirmation using detailed lithological and structural mapping around these deposits, and petrographic and geochemical studies of fresh samples now available through extensive exploratory drilling. Closer examination of the apparently less similar deposits scattered across the eastern part of the Mount Isa Inlier should also be undertaken, to test the metallogenic model for wider applicability.

Perceived similarities between Mount Dore and other deposits in the Kuridala-Selwyn region imply the same fluid provenance. Isotope and fluid inclusion studies of mineral deposits at Mount Isa and Mary Kathleen also indicate a metamorphic origin for mineralizing fluids (Heinrich *et al.*, 1989, and Oliver and Wall, 1987, respectively). A single $\delta^{18}O_{quartz}$ value of 13.3 permil was obtained from gold-bearing quartz in a metamorphic host near Cloncurry, and interpreted to indicate a deep-seated metamorphic or juvenile fluid source (Wilson and Golding, 1988). These results suggest widespread involvement of metamorphic fluids in metallogenesis. Data are still sparse, however, and further regional-scale stable isotope investigations of both major and minor deposits are highly desirable.

Ideally, further research should assess the assertion by Laing (1991) that much of the mineralization in the eastern Mount Isa Inlier is metamorphogenic, in the sense of Pohl (1992), with apparent differences between deposits related to site-specific controls on precipitation of ore and alteration elements. Ultimately, we would hope to better understand the relationship between regional metallogeny and tectonics.

7.6 SUMMARY OF RESULTS AND CONCLUSIONS

This study has been a wide-ranging examination of large- and small-scale aspects of the geology and metallogeny of the Kuridala-Selwyn region, in the eastern part of the Mount Isa Inlier. The ultimate aims of this study have been to deduce the origin of the Mount Dore breccia-hosted copper deposit in the southern part of this region, and place it within the wider regional tectonic and metallogenic context. These aims have been achieved; the main results and conclusions drawn are as follows:

1. **Stratigraphic revisions:** The package of metasedimentary rocks previously defined by Carter *et al.* (1961) as the Kuridala Formation is now known to be a conglomeration of previously defined or newly recognized units, and the name is therefore obsolete. Three of the four distinct, conformable packages are extensions of the constituent formations of the Soldiers Cap Group (Llewellyn Creek Formation, Mount Norna Quartzite, Toole Creek Volcanics; Derrick *et al.*, 1976e). The remaining, older unit has no recognized correlatives in the type Soldiers Cap Group, and is defined as a new unit, the New Hope Arkose, and correlated with other newly recognized units along the southeastern margin of the Mount Isa Inlier (Glen Idol Schist and Gandry Dam Gneiss; Beardsmore *et al.*, 1988; Newbery, 1990; Appendix A). These three predominantly thick-bedded clastic, quartzofeldspathic metasedimentary units collectively comprise the Fullarton River Group, which is conformable beneath the Soldiers Cap Group; the two together comprise the Maronan Supergroup (Beardsmore *et al.*., 1988; Appendix A).

2. **Tectonostratigraphic evolution of the eastern Mount Isa Inlier:** The Maronan Supergroup represents a near-complete sequence of rift sedimentation. Rock types generally mature compositionally and texturally up-sequence, and reflect initial rapid deepening of the basin, and later basin widening and shallowing. The pattern of sedimentation is best explained by an ensialic rift model, which is consistent with interpretations for other parts of the Mount Isa Inlier (*e.g.* Derrick, 1982). The absolute age of the Maronan

Supergroup and its stratigraphic relationship to other units are presently unconstrained. All present boundaries with other units are tectonic. It is believed to have formed in a separate rift basin, which could have any age relative to other such basins in the Mount Isa Inlier.

3. **Deformation history:** The regional structural geometry in the Kuridala-Selwyn region results from the interplay of three major ductile events and one major brittle event. The earliest recognisable deformation (D_1) involved detachment of major lithologies from one another, and produced major shear zones up to one kilometre thick. Extension, possibly in a north-south direction, is postulated for at least some of the structures in the southern (Selwyn) part of the region (Switzer, 1987; Laing *et al.*, 1988), but regional map patterns in the northern (Kuridala) part might be better explained by early thrusting. The precise definition of style and movement direction for the D_1 event (or events) requires further work. D_1 was followed by east-west compression, which caused major folding and reactivation of earlier structures. F_2 folds are upright, tight to isoclinal, north-trending structures with wavelengths ranging from several thousand metres to millimetres. Peak prograde metamorphism occurred early during this event. D_3 deformation produced scattered bands of upright, open folds which locally tilted the steeply-dipping D_2 grain of the region to shallow orientations. D_3 may have been broadly synchronous with intrusion and crystallization of the Williams Batholith. Late regional-scale reverse faulting reactivates earlier structures, and truncates plutons of the Williams Batholith. It occurred sometime after, but probably not much later than D_3.

4. **Petrogenesis of the Mount Dore breccia-hosted copper deposit:** The Mount Dore deposit is localized in a structural trap, at the intersection of structures from several generations. Ductile deformation produced a steeply east-dipping grain to the rock, with localized zones of shallowly-dipping fabric, which became dilatant during the late-tectonic formation of the reverse dip-slip Mount Dore Fault Zone. Extensive brecciation and fault block shuffling occurred in the dilatant zones along the faults, providing regions where hydrothermal fluid

could enter and interact with relatively large areas of rock. The primary hydrothermal fluid was a hot (>500^{o}C), highly saline, relatively oxidized fluid derived from a deep-seated metamorphic and/or magmatic source, and containing substantial quantities of CO_2, K^+, Na^+, Fe^{2+}, Ca^{2+}, Cl^-, SiO_2, B_2O_3, and probably oxidized sulphur (as SO_2). Alteration developed through potassic, then silicic ($\pm$ tourmaline), then carbonatic, and finally chloritic stages, at near-lithostatic pressures possibly ranging up to several hundred MPa. Separation of an immiscible CO_2-rich fluid phase early in the evolution of the system may have encouraged alteration by saturating the residual aqueous fluid in alteration components. The fluid evolved towards cooler, less saline compositions. Boiling, or even simply cooling the fluid cannot produce this trend, and introduction of a second, dilute aqueous fluid of meteoric, or more likely low-salinity metamorphic derivation is necessary.

Sulphides formed relatively late in the paragenesis, probably reflecting the lack of reduced sulphur in solution. Pyrite precipitation occurred only when sulphate was partly reduced by reaction with reduced carbon released from the carbonaceous slates. Reduced sulphur remained low in the fluid, however, and copper- and other base metal sulphides formed by scavenging sulphur and iron from earlier pyrite, and either precipitating directly on this phase or nearby, or by partially replacing earlier carbonates. Extended exposure of the copper deposits to near-surface oxidizing conditions produced an enriched supergene chalcocite blanket and overlying Cu-oxide and carbonate deposit.

5. **Regional metallogenesis:** Similarities in geological settings and general style of the Mount Dore deposit with those of several other large copper deposits in the Kuridala-Selwyn suggest wider applicability of the petrogenetic model derived for Mount Dore, and may point to a regional metallogenic process, related to overall tectonic development of this part of the Mount Isa Inlier.

A speculative regional-scale model proposes emplacement of at least one large allochthonous slab of Maronan Supergroup over the carbonate-evaporite successions of the Mary Kathleen Group. The latter would have provided the highly saline, CO_2-bearing fluids during subsequent D_2 metamorphism. The fluids would have passed upwards into and along the decollement, or perhaps have been dissolved into the anatectic magmas which would later comprise the Williams Batholith. Fluids released by dehydration reactions, or exsolved from rising and crystallising magmas, may have ponded in F_2 antiforms, where they may have "stewed" for some time in contact with relatively metal-rich lithologies in the overriding slab. Eventual release to higher crustal levels would have occurred when these structures were breached during late-tectonic reverse faulting, which also controlled emplacement in the solid state of at least some of the plutons of the Williams Batholith. Passing rapidly upwards along these faults, the fluids would have encountered local dilatant zones, where relatively large fluid-rock ratios would have prevailed, and where extensive alteration and sulphide precipitation would have occurred. Low salinity fluids of meteoric, or more likely upper-plate metamorphic derivation could have migrated into the dilatant zones when the deeply penetrating fault structures became available, and subsequently mixed with the saline fluids, perhaps initiating some styles of mineralization in the process.

Epigenetic mineralization across the Cloncurry Fold Belt (and perhaps the entire Mount Isa Inlier) appears to be the result of large-scale devolatilization of the crust during the waning stages of regional deformation and metamorphism. The characteristics of individual deposits depends on the combination of local factors a such as structure and lithologies available adjacent to these structures for leaching of metals.