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***Cover:** Banded iron formation comprising 'tigereye' (fibrous yellowish brown: silicified crocidolite or blue asbestos), haematite–magnetite (grey), ferruginous chert and jasper (yellow and red). Sample from Western Australia; supplied by Dean Hoatson.*

The Western Tharsis deposit

A 'high sulphidation' Cu–Au deposit in the Mt Lyell field, of possible Ordovician age

DL Huston & J Kamprad

The Western Tharsis deposit in the Mt Lyell Cu–Au district of western Tasmania has been reinterpreted as an Ordovician 'high sulphidation' Cu–Au deposit. Mapping of alteration assemblages associated with chalcopyrite-rich and bornite-rich ore types suggests that these deposits formed in a single mineralising event, not in two disparate events as suggested previously. The presence of pyrophyllite, topaz, zunyite and woodhouseite within alteration zones associated with the deposit is diagnostic of 'high sulphidation' Cu–Au deposits. The use of PIMA was essential in mapping the alteration zonation as it identifies minerals such as pyrophyllite, topaz and zunyite effectively. High field strength and rare earth elements—generally considered immobile during alteration—were highly mobile during mineralisation at Western Tharsis and may have direct application as lithogeochemical indicator elements in 'high sulphidation' Cu–Au deposits.

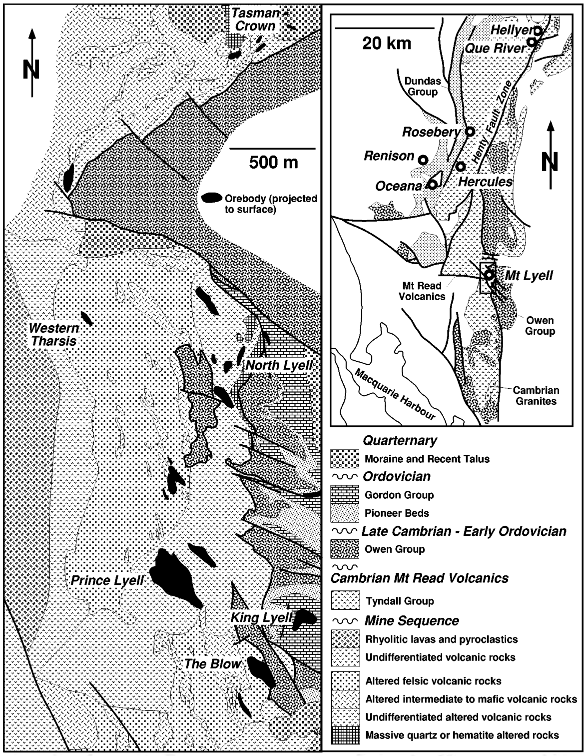

Figure 1. Geology of the Mt Lyell mineral field (modified after Raymond, 1996).

The Cambrian Mount Read Volcanic Belt of western Tasmania is divided into two distinct metallogenic provinces by the north-north-east trending Henty Fault Zone. One domain is dominated by Zn–Pb-rich volcanic-hosted massive sulphide (VHMS) deposits to the north-west, and the other is dominated by Cu–Au volcanic-hosted disseminated sulphide deposits to the south-east (figure 1). The Mount Lyell field, just to the east of Queenstown, contains 22 dominantly Cu–Au deposits and constitutes the major district of the south-eastern province.

Ore deposits in the Mount Lyell field can be subdivided into five groups:

1. disseminated pyrite–chalcopyrite orebodies such as Prince Lyell;
2. bornite–chalcopyrite orebodies such as North Lyell;
3. massive pyrite–chalcopyrite orebodies such as The Blow;
4. stratiform, massive pyrite–galena–sphalerite–galena–pyrite orebodies such as Tasman Crown; and
5. copper–clay orebodies such as King Lyell.[1]

The first two types are by far the most significant. Previously they were inferred to have formed by a Cambrian syn-volcanic mineralising event (disseminated pyrite–chalcopyrite ores) and by an overprinting event related to Devonian granitoid intrusion (bornite–chalcopyrite ores).[2]

As part of AMIRA project P439 (Studies of VHMS-related alteration: Geochemical and mineralogical vectors to mineralisation), geochemical patterns and the zonation of alteration assemblages were investigated around the Western Tharsis deposit. This deposit was chosen because it is the last undeveloped orebody in the district, and it is one of the few orebodies in which pyrite–chalcopyrite and bornite–chalcopyrite ores are juxtaposed.

Geological setting

The Mount Lyell mineral field (figure 1) occurs largely within the Central Volcanic Complex, the volcanic unit that forms the basal member of the Middle to Late Cambrian Mount Read Volcanic Belt. In the Queenstown area, the Central Volcanic Complex (~503 million years[3]) consists of felsic volcaniclastic rocks and lavas intercalated with intermediate volcaniclastic rocks, lavas and sills, together with minor siltstone and epiclastic sandstones. The Central Volcanic Complex is overlain unconformably by the volcaniclastic rocks of the Tyndall Group which, in turn, is overlain by siliciclastic conglomerate and sandstone of the Late Cambrian to Early Ordovician Owen Group. An internal unconformity (Haulage Unconformity) within the Owen Group separates older strata (~493 million years[4]) from a younger unit (~462 million years[5]) termed the Pioneer Beds. Carbonate rocks of the Ordovician Gordon Group overlie the Pioneer Beds (figure 1).

Three deformation events are recognised in the Mount Lyell area. The earliest, interpreted as an Ordovician event, is characterised by the development of inclined, asymmetric folds in the Owen Group and by erosion to form the Haulage unconformity that separates the Pioneer Beds from the rest of the Owen Group. Movement along the Great Lyell Fault, that forms the contact between the volcanic rocks and the Owen Group through much of the Mount Lyell field, began at this time.[2] Another two deformation events occurred during the Devonian Tabberabberran Orogeny.[6]

Most Mount Lyell ore deposits, including Western Tharsis, occur within the Mine Sequence. This unit, comprising mainly felsic volcaniclastic rocks and lavas with lesser intermediate volcanic rocks, has a maximum thickness of 800 metres. Much of the Mine Sequence is overprinted by a pyrite alteration zone that extends along strike for eight kilometres.[6] Nineteen of the 22 known deposits occur within this altered zone.

Figure 2A illustrates the lithological variation of the ore-bearing sequence at Western Tharsis. The host volcanic sequence dips steeply to the west and is overturned. The deposit, which has an indicated and inferred resource totaling

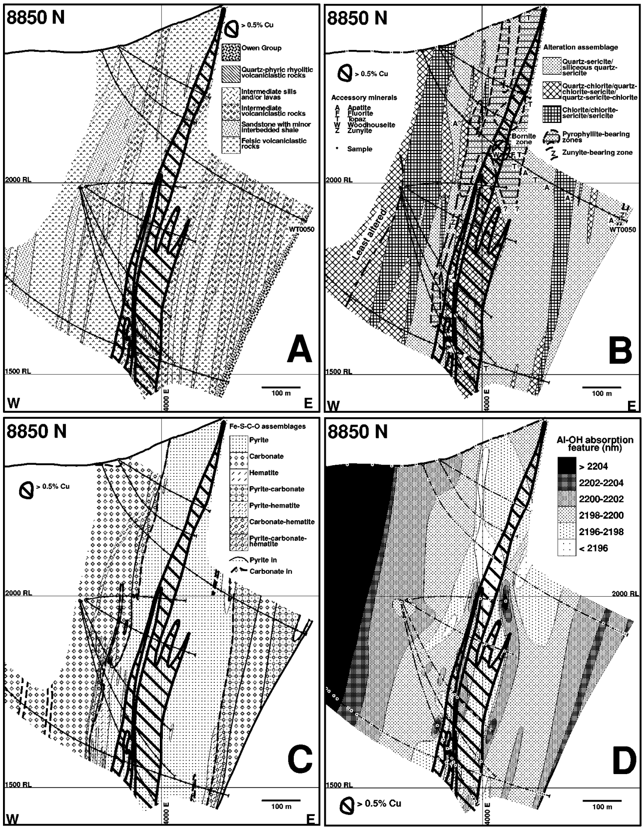

Figure 2. Cross section 885oN showing **A.** the geology of the Western Tharsis deposit **B.** the distribution of silicate alteration assemblages **C.** the distribution of Fe–S–C–O minerals and **D.** variations in the wavelength of the Al–OH absorption feature from PIMA analysis.

12.4 million tonnes at 1.3 per cent Cu, is a stratabound, mainly disseminated, pyrite-chalcopyrite body. The bornite-bearing assemblage that replaces the pyrite–chalcopyrite assemblage also contains minor to trace quantities of chalcocite, mawsonite, chalcopyrite, molybdenite, hematite, enargite, barite and woodhouseite.[7] The pyrite–chalcopyrite assemblage has a simpler mineralogy, with minor to trace barite, apatite and molybdenite, and with local zones of massive magnetite.

Zonation and mineral assemblages

Alteration at Western Tharsis was characterised by the development of zoned silicate (figure 2B) and Fe–S–O–C (figure 2C) mineral assemblages, each having significantly different zonation patterns. Three major silicate alteration assemblages are present at Western Tharsis. The lower part of the ore zone is centered on a pyritic quartz–chlorite±sericite zone that grades outward into a pyritic quartz–sericite±pyrophyllite zone. Within this zone, pyrophyllite, which was identified using PIMA (portable infra-red mineral analyser) analysis, forms a shell that wraps around the upper part of the ore-related quartz–chlorite± sericite zone. The pyrophyllite-bearing zone also contains topaz and zunyite, identified using PIMA. The quartz–sericite±pyrophyllite zone passes outward to a quartz–chlorite–sericite–carbonate zone that lacks pyrite (figures 2B & 2C). Hematite is commonly present along the contact between pyrite-bearing and carbonate-bearing zones. PIMA analysis also indicates that the composition of sericite (as measured by the wavelength of the Al–OH absorption feature) becomes more phengitic marginal to the orebody (figure 2D).

Geochemical dispersion

In concert with core logging, mineralogical and PIMA studies, a suite of more than 200 fresh drill core samples were analysed for major elements and trace elements. Based on contoured sections and inter-element correlations,[#] the elements that show systematic patterns with respect to the orebody can be subdivided into three major groups:

1. elements (As, Bi, Cu, Mo, Ni, S and Se) that are strongly enriched in the ore zone, and in the pyrite-bearing alteration zones, but depleted in the marginal carbonate-bearing alteration zone;
2. elements (K and Cs) that are characterised by uniform values except for extreme depletion within the pyrophyllite-bearing zone that forms a shell around the orebody; and
3. elements (C, Mn, Ca, Zn and Tl) that are enriched in the carbonate halo but depleted in the pyrite halo.

Figure 3A illustrates the distribution of Cu as established using routine company analytical data and data acquired during this study. Molybdenum, Ni and S correlate with Cu and form part of the ore metal assemblage. Although the correlation between Bi and Cu is not great (r = 0.107), Bi is enriched in the ore zone and, to a lesser extent, in the pyrite halo. Although Zn is locally enriched within the ore zone (figure 3B), it is mainly enriched in the carbonate halo (see below). This local Zn enrichment does not appear to be related to late flat veins as in the Prince Lyell orebody.[8]

The distribution of K is characterised by extreme depletion (0.06–0.9% K_2O; figure 3C) in narrow (20–30 m) zones that flank the orebodies both in the footwall and the hanging wall and envelop the orebody at surface. Elsewhere the abundance of K is stable and much higher (K_2O = 2–4%). Cesium correlates with K.

The K and Cs depletion anomalies correlate spatially with the pyrophyllite-bearing alteration zone that wraps around the orebody (figure 2B). The aluminous minerals in this zone developed at the expense of sericite, which accounts for K depletion.

The marginal carbonate-bearing alteration zone is characterised by low order Zn (100–1000 ppm; figure 3B) and Tl (0.5–1.2 ppm) enrichment. This contrasts with the inner pyritic zone, which generally contains less than 50 ppm Zn. In addition to Zn and Tl, the marginal zone is also enriched in C, Mn and Ca.

Mobility of 'immobile' elements

This study shows elements that are generally considered immobile, such as high field strength (HFSE) and rare earth elements (REE), were mobile in the Western Tharsis mineralising environment. Samples from drill hole WT0050, that passed through the bornite zone, were analysed for a suite of elements including HFSE and REE. The HFSE Ga and Y (and Be) were found to be depleted in the pyrophyllite-bearing zone (F and Sr were enriched; figure 4).

Figure 4 illustrates the spatial variation in chondrite normalised REE concentrations of rhyolitic rocks (identified using TiO_2/Zr) in WT0050. More mafic rocks were excluded as they have significantly different initial REE contents to rhyolitic rocks (cf. Crawford et al.[9]). Medium rare earth elements (MREE), represented by Ho and, to a lesser extent, heavy rare earth elements (HREE), represented by Yb, are strongly depleted in the pyrophyllite-bearing alteration zone surrounding the bornite-bearing ore zone. Marginal to this zone, MREE and HREE values rapidly approach those typical of Central Volcanic Complex rhyolites (cf. Crawford et al.[9]).

The distribution of light rare earth elements (LREE), as represented by Ce, is more complicated. From the stratigraphic footwall, LREE concentrations initially increase up to, and including, the ore zone, possibly due to the presence of LREE-bearing woodhouseite. In the hanging wall, LREE are moderately depleted, with zones of more extreme depletion corresponding to extreme F enrichment.

To more critically assess the dispersion of Ce and remove the effects of lithological variations, figure 3D was constructed to display variations in normalised Ce enrichment. Cerium concentrations were normalised to primary Ce concentrations (Ce/Ce_{PR}) of unaltered precursors from the Mt Read Volcanics (precursor data from Crawford et al.). Use of this technique indicates that positive Ce anomalies are developed within and adjacent to the orebody.

The slope of REE patterns, as measured by $[La/Yb]_{CN}$ (figure 4), largely follow the pattern observed for LREE, increasing towards ore except in F-rich samples. Figure 4 also shows variations in the Eu anomaly (Eu/Eu*). A narrow baseline with values of 0.50–0.69 is defined mainly by carbonate-bearing and some quartz–sericite–pyrite altered rocks. Values above 0.70, rising to 2.36 adjacent to the ore zone, define a major symmetrical anomaly about the ore position and a second zone about a smaller pyrophyllite- and zunyite-bearing zone near the base of the drill hole. The anomalously high Eu/Eu* values extend 100–150 metres

Raw analyses were contoured in preference to ratios or mass transfer as they require no assumptions about protoliths and as 'immobile' elements used to calculate mass transfer appear to be mobile at Western Tharsis.

from the ore zone into both the footwall and the hanging wall. This anomalous footprint is the widest of any REE-based anomalies, and is similar in extent to the anomalies associated with most other group one and two elements above.

Genetic implications

Paragenetic and spatial relationships indicate that the disseminated pyrite–chalcopyrite assemblage is associated mainly with a quartz–chlorite±sericite silicate alteration assemblage with accessory hydrothermal apatite. In contrast, the bornite-dominant ore assemblage is associated with a quartz–pyrophyllite±sericite alteration zone that wraps around the core quartz–chlorite±sericite zone. This spatial relationship suggests that the pyrophyllite- and chlorite-bearing assemblages, and the associated pyrite–chalcopyrite and bornite-dominant sulphide assemblages, formed during a single hydrothermal event. This is in contrast to the generally accepted two-event models such as that of Arnold and Carswell.[2] The association of woodhouseite, zunyite, topaz and fluorite with the pyrophyllite-bearing assemblage is diagnostic of hypogene advanced argillic alteration assemblages that occur in deep-level, higher temperature, 'high sulphidation' Cu–Au deposits.[10, 11]

Hart demonstrated that pyrophyllite-bearing alteration assemblages extend through the Owen Group, including the Pioneer beds and, possibly, the base of the Gordon Group.[12] He also reported the presence of bornite within the Owen Group. This suggests that the mineralising event in the Mt Lyell area may have post-dated deposition of the majority of the Owen Group, as suggested by Raymond.[13] As the alteration assemblages are all affected by Tabberabberan cleavages, this mineralising event must have predated this Devonian deformation event. Although an early Tabberabberan timing is possible, all known Tabberabberan granitoids in Tasmania are post-tectonic. This is not consistent with the close relationship with granites required for 'high sulphidation' deposits. These data suggest that much of the mineralisation in the Mt Lyell district may not be Cambrian or Devonian in age, but rather Ordovician in age. This hypothesis is currently being tested using Pb isotopes in apatite.

The geochemical dispersion around the deposits is also consistent with a 'high sulphidation' origin. For instance, White and Hedenquist indicate that K and Zn are depleted, and As, Cu, Bi and Mo are enriched in 'high sulphidation' deposits[10]—as at Western Tharsis. Arribas et al. documented extreme REE mobility and found that advanced argillic and residual silica altered samples from the Rodaqualar 'high sulphidation' deposit in Spain had $[La/Yb]_{CN}$ significantly higher than the ratios in less intensely altered samples.[14]

Conclusions

Zoned alteration assemblages in the Western Tharsis deposit indicate that chalcopyrite-rich and bornite-rich ores formed at essentially the same time, not at two separate times as previously suggested.

The overprinting of ore-related alteration assemblages on Ordovician rocks and the presence of Tabberabberan foliations in the alteration assemblages strongly suggest that Western Tharsis and, by inference, most of the Mt Lyell field formed during the Ordovician.

The presence of pyrophyllite, topaz, zunyite and woodhousite in the alteration assemblages suggests that the Western Tharsis is a deep-level 'high sulphidation' Cu–Au deposit.

Lithogeochemical studies of the deposit indicate proximal enrichment of As, Bi, Cu, Mo, Ni, S and Se, and distal enrichment of Zn, Tl, C, Mn and Ca. Significant K and Cs depletion is associated with pyrophyllite-bearing alteration assemblages.

Extreme alteration in the Western Tharsis deposit has resulted in the mobility of REE and some HFSE. Rare earth element mobility, in particular Ce and Eu may be useful as pathfinders in this and other 'high sulphidation' Cu–Au deposits.

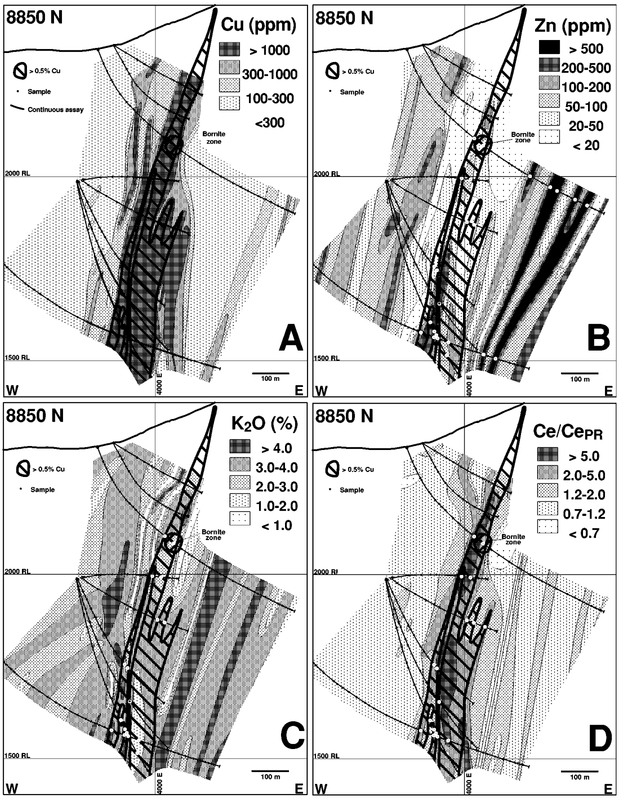

Figure 3. Cross section 8850N showing lithogeochemical dispersion of **A.** Cu **B.** Zn **C.** K and **D.** normalised Ce.

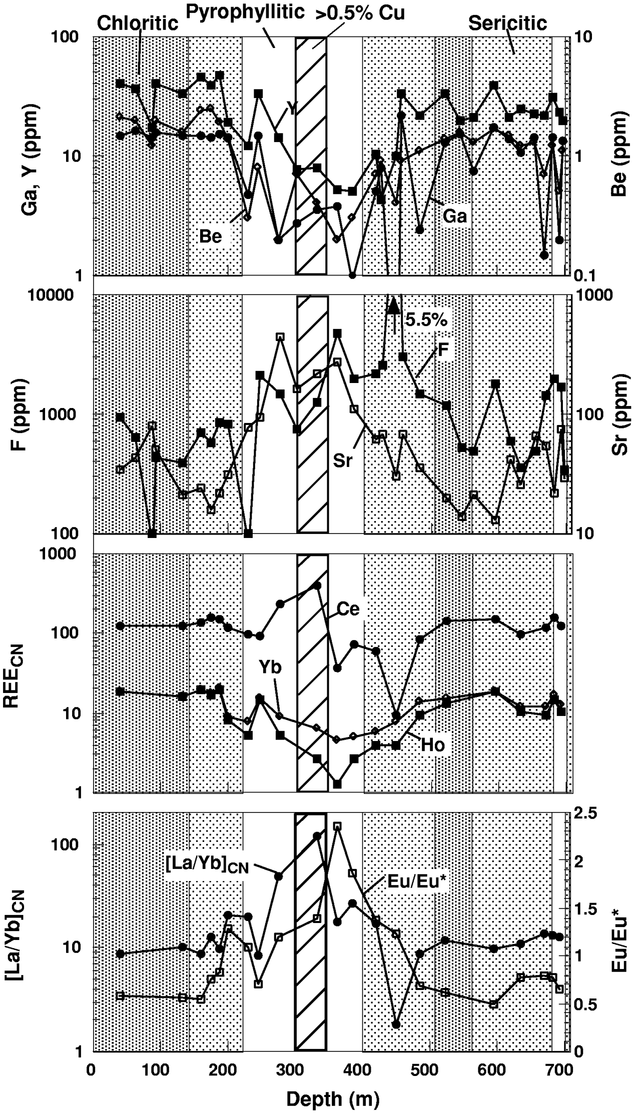

Figure 4. Variations in the concentrations of **A.** Be, Ga and Y **B.** Sr and F **C.** Ce, Ho and Yb and **D.** La/Yb and Eu/Eu* as a function of depth in WT0050. REE analyses are chondrite normalised and restricted to rhyolitic rocks.

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