Characterising VMS mineralisation at the Palaeoproterozoic Home of Bullion copper deposit, Aileron Province

Catherine A Stuart[1,2]

Introduction

The Home of Bullion deposit is a medium-sized copper–lead–zinc (± silver-gold) deposit located 28 km east of Barrow Creek in the northern Aileron Province, central Australia. Discovered in 1923, samples returned some of the highest reported copper grades in Australia (46.6% Cu; Blanchard 1936), and the deposit produced ~1000 t of copper by 1951 (Sullivan 1953). Subsequent exploration has focused on defining extensions to the deposit, which has total Mineral Resources of 2.5 Mt at 1.8% Cu, 2% Zn, 1.2% Pb, 36 g/t Ag and 0.14 g/t Au (Kidman Barrow Creek Pty Ltd 2015).

Despite a near 100 year history of mining and exploration, the characteristics and style of mineralisation remain largely unstudied. Early investigations determined a strong structural control to mineralisation, and mafic amphibolites were suggested to be the source of copper (Sullivan 1951, Griffiths 1970). Field mapping and petrographic studies concluded mineralisation was stratiform with metasomatic alteration, which lead to a proposed volcanogenic massive sulfide (VMS) classification (Drown 1993, Drown 1996, Benger 2006). However, there is a lack of definitive evidence for volcanic rocks associated with mineralisation.

Under the *Resourcing the Territory* initiative, the Northern Territory Geological Survey (NTGS) has undertaken a project to improve understanding of the geological framework and style of mineralisation at the Home of Bullion deposit. The project generated new constraints on the timing of mineralisation, improved knowledge of the mineralisation and host rocks, and developed a geochemical profile of mineralisation and associated alteration.

Geological setting

The Home of Bullion deposit (**Figure 1**) is hosted by the Palaeoproterozoic Bullion Schist, which comprises thinly bedded metamudstone and metasandstone with minor bedding-parallel mafic amphibolite (Haines *et al* 1991). Outcrops hosting the Home of Bullion deposit have been metamorphosed to lower amphibolite facies, forming quartz–muscovite schists (± biotite, chlorite, andalusite, cordierite, garnet) and amphibole–plagioclase mafic amphibolites (± chlorite, phlogopite, clinozoisite, titanite, quartz), all overprinted by a weak

[1] Northern Territory Geological Survey, GPO Box 4550, Darwin NT 0801, Australia
[2] Email: cait.stuart@nt.gov.au

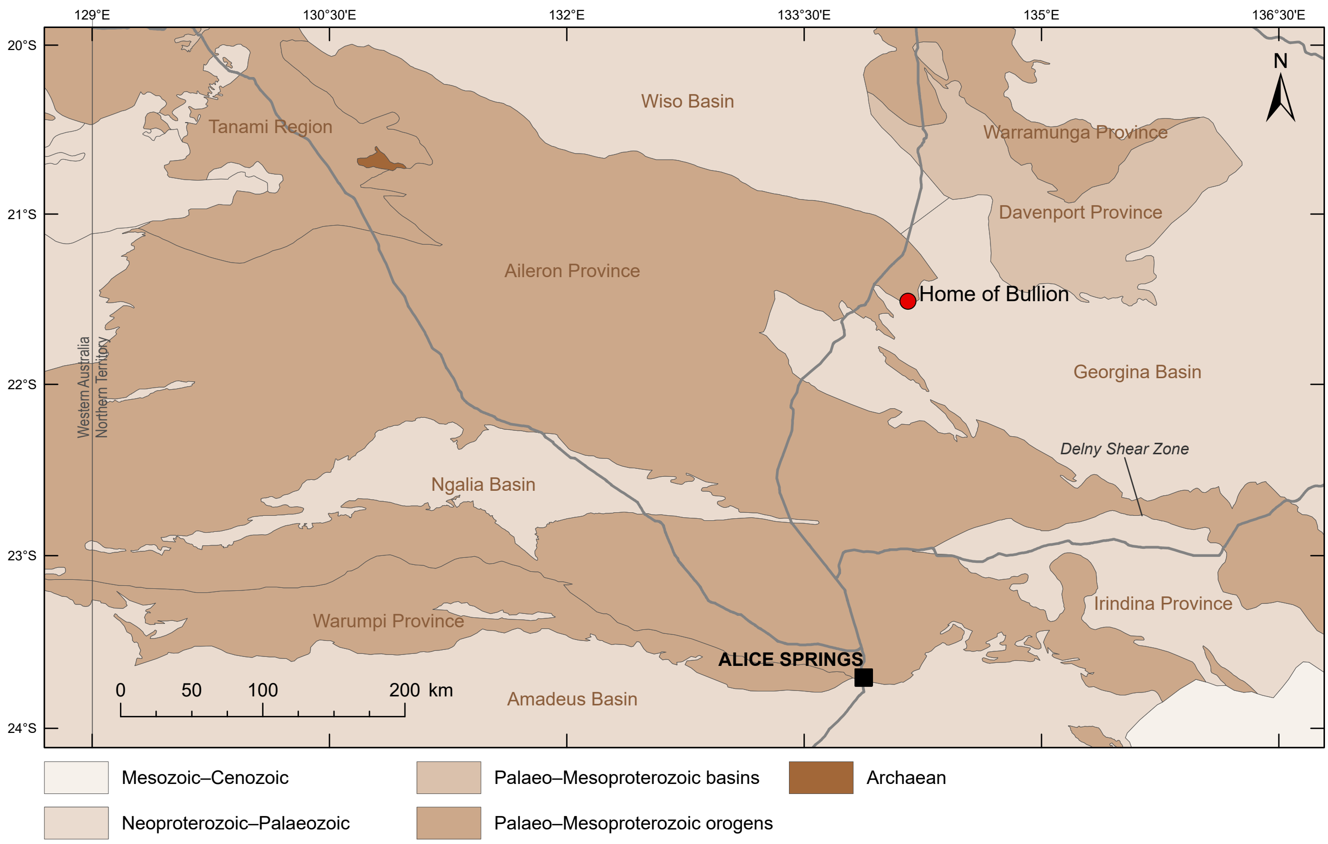

Figure 1. Map of geological regions showing the location of the Home of Bullion deposit.

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foliation (McGloin *et al* 2018). Andalusite, garnet and biotite are all partially to completely replaced by chlorite and sericite during retrograde metamorphism at greenschist facies, which also involved growth of chlorite porphyroblasts.

Lower amphibolite facies metamorphism is considered coeval with multiple deformation events (McGloin *et al* 2016). The first event (D_1) generated west-northwest-trending tight to isoclinal folds, bedding-parallel foliation (**Figure 2**) and limb-parallel reverse shear zones (**Figure 3**). A second event (D_2) generated a mm- to cm-scale crenulation cleavage (**Figure 2**) and north-northwest-trending reverse faults that cross-cut F_1 fold axes. Later events involved minor shearing and folding.

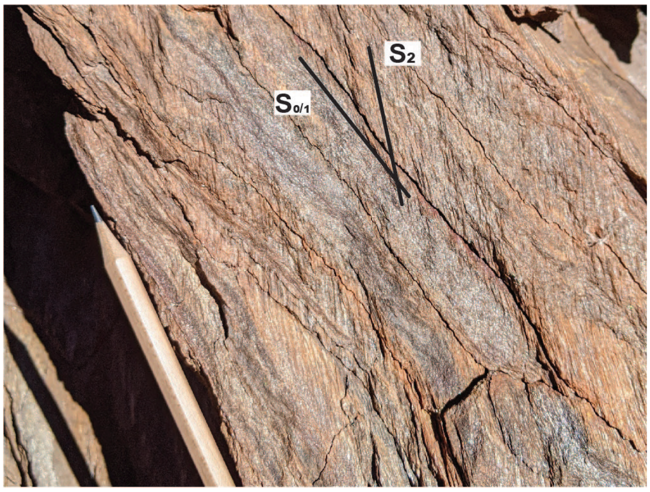

Figure 2. Field photograph of the Bullion Schist. The $S_{0/1}$ foliation is crenulated to form a sub-vertical S_2. Pencil is 7 mm wide.

Mineralisation and alteration

Mineralisation occurs in four sheared tabular lodes in the Bullion Schist: the Main Lode, East Lode, South Lode No 1, and South Lode No 2. Stratiform mineralisation occurs on overturned fold limbs between closely spaced (<10 m) bedding-parallel shear zones (**Figure 3**) adjacent to a metamorphosed mafic amphibolite. Banded textures and horizons of schist are observed in the gossan (Drown 1993), and a <10 cm-thick chert unit is found along the northern boundary. The metamorphic assemblage in the mineralised rocks includes Mg-rich chlorite and phlogopite (± cordierite, cummingtonite, plagioclase, rutile; Stuart in prep). Sulfides are recrystallised and in textural equilibrium with silicates, indicating they formed as part of the metamorphic assemblage and were likely present in the protolith (Stuart in prep). Foliation is defined by chlorite and phlogopite, and in some samples, orientation of amphiboles and sulfide aggregates is also observed (**Figure 4**). Major sulfides in the primary mineralisation (hypogene zone) are pyrrhotite (<40%), sphalerite (<12%) and chalcopyrite (<30%), with minor galena (<2%). Other phases associated with sulfide mineralisation are native bismuth, bismuthinite, chalcocite, arsenopyrite, stannite, pyrite, and marcasite. The primary mineralisation has grades in the range of 3–5% Cu, 1–6% Pb, and up to 15% Zn (Haines *et al* 1991).

Chlorite and sericite alteration is common in outcrops in the vicinity of the Home of Bullion deposit. The proportion of chlorite varies widely within the massive sulfide zones (0–65%) and in the surrounding host rocks (0–70%). In most samples, chlorite is foliated and is interpreted to have formed prior to metamorphism, possibly as a result of

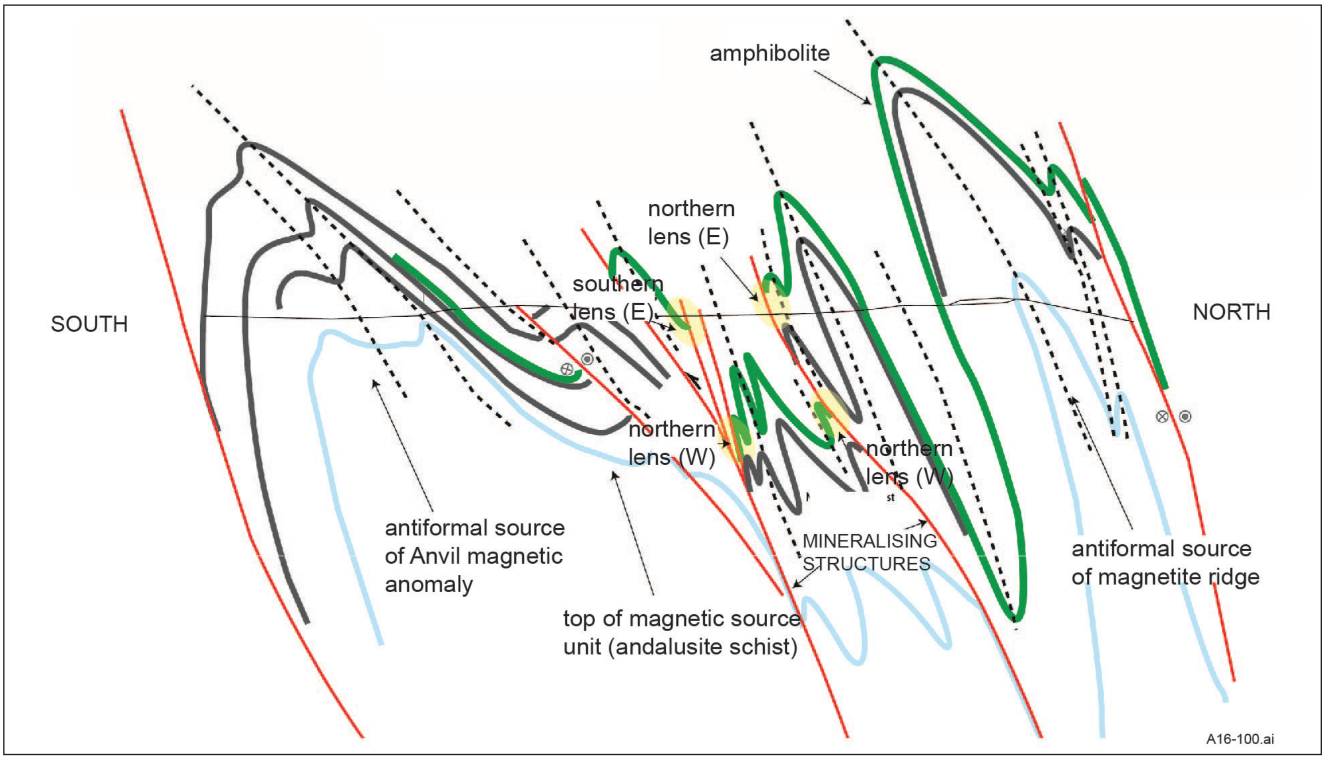

Figure 3. Schematic cross-section through the Home of Bullion deposit showing interpreted structural setting of mineralisation (McGloin *et al* 2016).

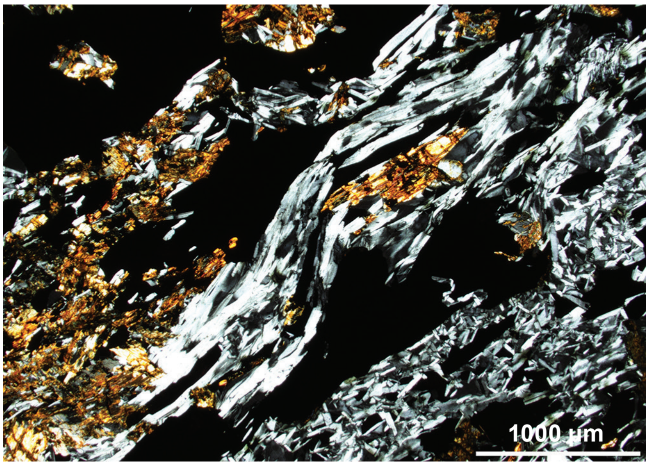

Figure 4. Photomicrograph of massive sulfide zone from the South Lode No 1 (sample BC15MVM013). Foliated chlorite (pale grey), pyrrhotite (black) and cummingtonite (pale yellow). Cummingtonite is locally replaced by brown smectite–chlorite. Cross-polarised light.

hydrothermal alteration (Stuart in prep). The intensity of chlorite alteration does not appear to be linked to distance from mineralisation, although deformation may have interrupted and displaced the stratigraphy sufficiently to mask such a relationship.

The lodes display vertical zonation typical of supergene alteration, with a leached oxidised zone and supergene mineralisation overlying the primary mineralisation. The leached oxidised zone at and near the surface contains goethite, limonite, copper carbonates, cerussite and silica, with grades of 2–12% Cu, 1–5% Pb, <2% Zn, 30–60 ppm Ag, and <1 g/t Au (Drown 1993). The supergene mineralisation is found between 36 and 60 m depth and has significant amounts of chalcocite and tennantite with grades of 12–24% Cu (including a maximum value of 49%), 2–3% Pb, 1% Zn, 30–60 g/t Ag, and 1.5 g/t Au (Haines *et al* 1991, Drown 1993, Ferenczi 2005). Historical mining targeted the oxidised and supergene ore zones, both of which have largely been excavated from the Main Lode.

Timing of mineralisation

The maximum mineralisation age is constrained by the age of the Bullion Schist. At the Home of Bullion deposit, the Bullion Schist has an interpreted maximum depositional age of 1833 ± 15 Ma (sample BC15MVM001; Yang *et al* in prep). Minimum depositional ages are constrained by a metamonzogranite and a metadolerite that cross-cut the Bullion Schist within 10 km of the deposit, yielding igneous crystallisation ages of 1823 ± 9 Ma and 1822 ± 27 Ma respectively (samples BC15MVM005 and BC15MVM008; Yang *et al* in prep).

A minimum mineralisation age is provided by the timing of metamorphism and deformation of the Bullion Schist and mineralised bodies (**Figures 3, 4**). Andalusite porphyroblasts are subparallel to S_1, the dominant foliation in outcrops adjacent to mineralisation. Monazite inclusions in andalusite porphyroblasts yielded ages constraining andalusite growth between 1813 ± 30 Ma and 1762 ± 14 Ma (Reno *et al* 2019).

New geochemical profiles

Trace element geochemistry indicates that protoliths to the mafic amphibolites range from basalt to basaltic andesite. The discrimination plot of Pearce (2008) uses immobile trace elements to identify oceanic or continental crust character of mafic rocks. Mafic amphibolites plot outside of the oceanic basalt field in the volcanic arc array near the metasedimentary units. This suggests the mafic amphibolites did not form in oceanic lithosphere but in a setting that involved extensive crustal input into the original mafic magma (**Figure 5**). This may be a result of the magma originating in a subduction zone or crustal contamination during magma ascent (Pearce 2008); additional samples would be required for further interpretation of the magma source and tectonic setting.

Both mafic amphibolites and metasedimentary units are characterised by variable compositions (**Figure 6**), including SiO_2 (27–80 wt%), Al_2O_3 (9–24 wt%), MgO (0.7–17 wt%), and Fe_2O_3 (3–16 wt%). Differences in the immobile element aluminium likely reflects compositional variation in the sedimentary and igneous components of the protolith to the Bullion Schist. Variations in the mobile elements silicon, magnesium and iron reflect varying degrees of alteration, possibly related to mineralisation. On the box plot of Large *et al* (2001), metasedimentary units plot between the sericite and chlorite/pyrite mineral nodes, spreading back towards the least altered dacite box (**Figure 7**). Mafic amphibolites plot close to the least altered basalt box, with some close to the ankerite/dolomite node and others closer to the chlorite/pyrite node. The alteration box plot suggests the host rocks were affected

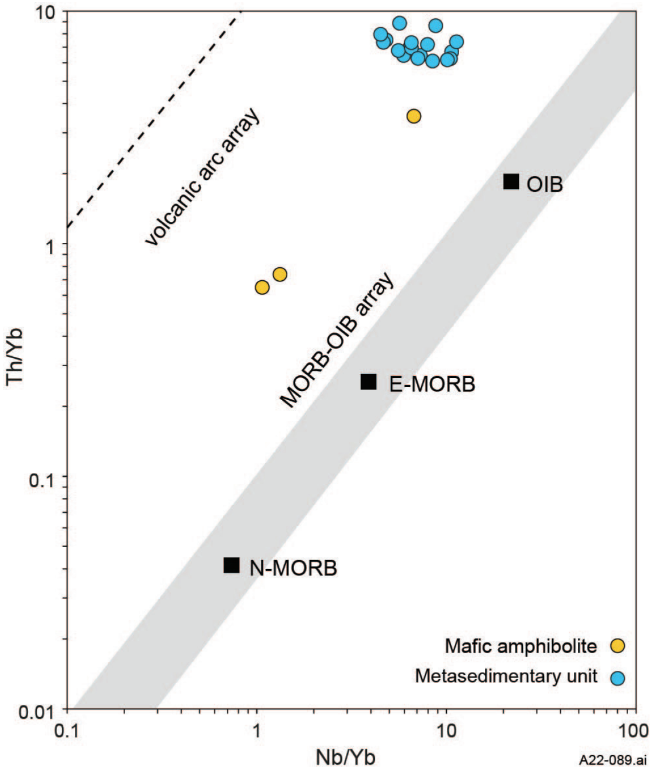

Figure 5. The Th–Nb proxy diagram of Pearce (2008) showing discriminations between oceanic and non-oceanic basalts using immobile trace elements.

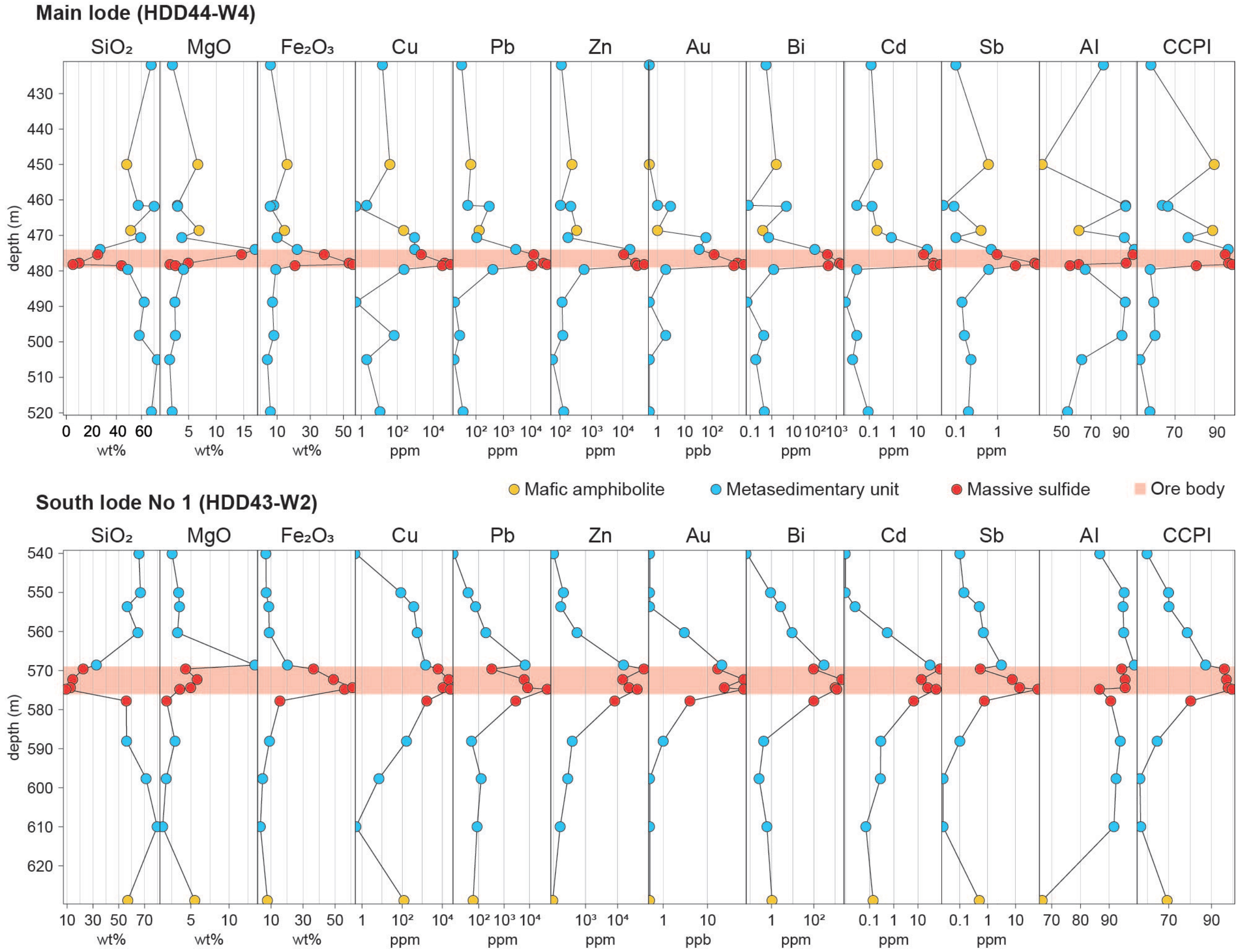

Figure 6. Downhole geochemical profiles for drillholes HDD44-W4 and HDD43-W2, which intersect the Main lode and South lode No 1 respectively. The Alteration Index (AI) of Ishikawa *et al* (1976) and chlorite–carbonate–pyrite index (CCPI) of Large *et al* (2001) are used to show common trends associated with hydrothermal alteration. AI = 100 x (K_2O + MgO) / (K_2O + MgO + Na_2O + CaO); CCPI = 100 x (MgO + $FeO_{(tot)}$) / (MgO + $FeO_{(tot)}$ + Na_2O + K_2O).

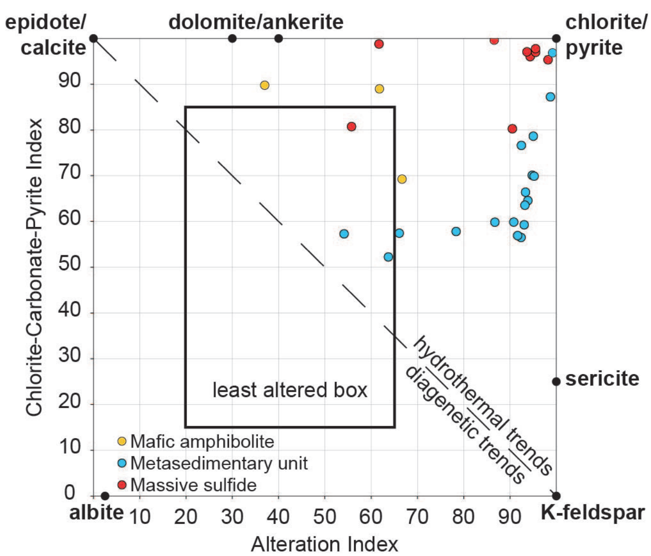

Figure 7. The alteration box plot of Large *et al* (2001), showing common trends associated with hydrothermal alteration. Alteration Index and CCPI calculated as per **Figure 6**.

by hydrothermal alteration, with variable enrichments in Fe and Mg. Pathfinder elements, which strongly correlate with copper, zinc and lead, include gold, bismuth, cadmium and stibnite (**Figure 6**). Concentrations of the pathfinder elements range from below detection limits to high values similar to those measured in the ore bodies.

Style of mineralisation

Previous workers have classified Home of Bullion as a VMS deposit based on the copper–lead–zinc (± silver–gold) assemblage, the stratiform nature of mineralisation, and evidence for metasomatic alteration (Drown 1993, Drown 1996, Benger 2006). Outcrops around the Home of Bullion deposit are dominated by pelitic metasedimentary units with minor basaltic to basaltic andesitic amphibolites, consistent with a siliciclastic-mafic type VMS environment (Shanks and Thurston 2012). Siliciclastic-mafic type VMS deposits form in sill-sediment complexes that may occur in mature oceanic back-arc basins, active spreading centres proximal to continental margins, or in continental margin rifts (Franklin *et al* 2005, Piercey 2011, Shanks and Thurston 2012). Geochemical proxies indicate the mafic amphibolites did not form in oceanic lithosphere, suggesting a continental margin setting is more likely. This is supported by the interpretation that the Aileron Province comprised a large basin on the southern margin of the North Australian Craton during deposition of the Bullion Schist (Ahmad and Scrimgeour 2013).

Metal ratios in VMS deposits are reflective of the tectonic setting and underlying strata. Composition of the igneous rocks is a key factor in mineralisation: mafic VMS types tend to have high copper, high gold and low lead contents, whereas felsic VMS types tend to have high zinc, high lead and low copper contents (Franklin *et al* 2005, Piercey 2011). With high copper, high zinc and low lead contents, the Home of Bullion deposit does not conform to previous observations for a typical siliciclastic-mafic type VMS deposits – this suggests a previously unrecognised felsic component may be involved in mineralisation.

VMS deposits worldwide have a common metal and alteration zonation that is preserved even after metamorphism up to granulite facies (Large 1992, Bonnet and Corriveau 2007, Shanks and Thurston 2012). In siliciclastic-mafic deposits, lenses of massive sulfide overlie footwall feeder or stringer zones of intense quartz–chlorite–chalcopyrite veining within altered host rocks. Host rocks display intense chlorite alteration close to the mineralisation, which decreases in intensity outwards into a sericite zone. At Home of Bullion, whole rock compositions indicate chlorite, sericite and minor ankerite/dolomite alteration (**Figure 7**). However, there is no difference in composition of samples in the hanging wall and footwall for both the Main and South No 1 lodes, and the degree of alteration is not strongly linked to proximity to mineralisation. Most mobile and pathfinder elements have symmetric profiles around the Main and South No 1 lodes. Gold and cadmium pathfinder elements have asymmetric profiles around the Main lode where they are both found in higher concentrations above mineralisation (**Figure 6**). If this pattern reflects alteration in the footwall of a VMS system, it suggests the sequence is locally overturned. This is consistent with the interpreted structural architecture for the deposit that shows the mineralisation occurring on an overturned F_1 fold limb (**Figure 3**). Other elements and alteration indexes lack the zonation typical of VMS systems, although this may have been obscured by post-mineralisation deformation.

Conclusions

Local stratigraphy at the Home of Bullion deposit is characterised by metasedimentary quartz–muscovite schists and minor mafic amphibolite. Mineralisation occurs in tabular, stratiform bodies spatially associated with mafic amphibolite and bedding-parallel faults. Sulfide mineralisation occurs as stratiform pyrrhotite, sphalerite and chalcopyrite, forming four lodes, which comprise the copper–lead–zinc (± silver–gold) deposit. Geochronology and field relationships indicate mineralisation occurred either during sedimentation or shortly after, and prior to deformation and metamorphism. Based on the above evidence, Home of Bullion can be classified as a siliciclastic-mafic VMS deposit.

However, there are several observations that do not fit with this classification. The deposit lacks the footwall alteration sequence typical for VMS deposits, and there is no obvious ‘feeder zone” with intense alteration and veining below the deposit. Additionally, the metal ratios of the primary mineralisation do not conform to published descriptions of VMS deposit styles involving mafic rocks, suggesting an additional metal source or process was involved in mineralisation. The timing of mafic amphibolite formation has not been constrained, and the lack of mineralisation around other mafic amphibolite bodies has not been explained.

Mineralised lodes appear to be at least partly structurally controlled, occurring in fault slices on the southern limbs of anticlines. A focus on the role of deformation in deposit formation or lode concentration together with detailed mapping of other exposures of the Bullion Schist may be useful in identifying additional areas prospective for mineralisation.

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