

Epidosites of the Troodos Ophiolite: A direct link between alteration of dykes and release of base metals into ore-forming hydrothermal systems?

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ABSTRACT: The role of source rocks in the formation of Cyprus-type Volcanogenic Massive Sulphide (VMS) deposits is not fully understood. In this paper we suggest that the formation of epidiosites – episode + quartz ± chlorite ± titanite rocks commonly found at the base of ophiolitic sheeted dyke complexes – has the potential to release cobalt and zinc into active hydrothermal ore forming systems. New geochemical and mineralogical data from the sheeted dyke complex of the Troodos ophiolite indicates that progressive alteration of greenschist facies altered metabasalts to end-member epidiosites results in decreasing base metal concentrations (Zn, Co) in individual dyke units. We believe this relationship provides the clearest evidence that epidiosites act as source rocks for VMS deposits, and, moreover, the process of epidiositisation provides a method of mobilizing metals such as Co and Ni that are considered generally immobile under typical greenschist grade alteration.

KEYWORDS: VMS, basalt, hydrothermal alteration, ophiolite, Troodos

1 INTRODUCTION

Understanding the source-deposit relationship for Volcanogenic Massive Sulphide (VMS) deposits is fundamental both for future mineral exploration and to increase our understanding of ocean floor hydrothermal processes and ocean-crust fluxes. Although it has long been known that metals are stripped from the oceanic crust by high-temperature fluids and redeposited in ore-bodies as the fluids cool, the details of this process are poorly understood. For example, it has been proposed that metal depleted “epidosites” (dykes altered to an assemblage of epidote + quartz ± chlorite ± titanite) are the source of metals in Cyprus-type VMS deposits (e.g. Richardson et al. 1987). However, the movement of base metals within sub-seafloor hydrothermal systems and into ore deposits has not been directly linked with the formation of these potential source rocks. The movement of metals traditionally considered immobile during sub-seafloor alteration, such as Co and Ni, but also found in ore deposits (e.g. Skouriotissa, ~6 Mt, with 2.5% Cu, 1%



Figure 1. Photomicrograph showing typical end-member epidiosite mineralogy (crossed polars). Note the dominance of anhedral quartz and euhedral epidote, and the lack of preservation of igneous texture.

Zn, 0.35% Co and 0.1% Ni) also has not satisfactorily been addressed.

2 THE ROLE OF EPIDOSITES IN ORE FORMATION?

Epidiosites are found in the sheeted dyke complex of many supra-subduction zone ophiolites

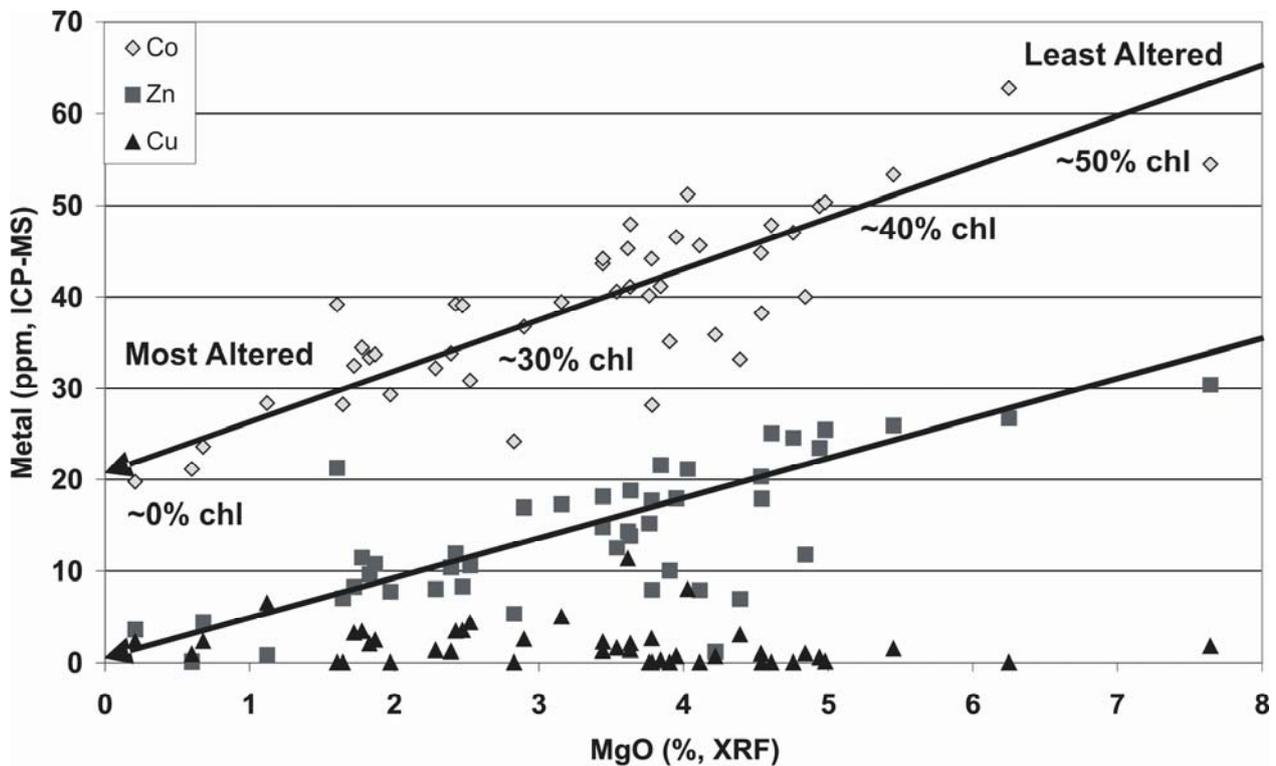


Figure 2. Co, Zn and Cu vs MgO for epidosite zone samples. Arrow denotes progressive alteration from transitional epidosite-greenschist facies to end-member epidosite facies. Chlorite percentages (%chl) correspond to MgO contents and are taken from semi-quantitative XRD analyses.

(e.g. Troodos [this study]), Samail [Nehlig et al. 1994], Josephine [Harper et al. 1995]) in distinct zones up to 1 km or more across dyke strike. Epidosite *zones* are commonly spatially related to plutonic rocks and comprise a mixture of distinct epidosite and metabasalt units. The percentage of individual epidosite *units* present varies from around 40% to as high as 80%, but is generally around 60% (this study). 100% epidosite unit areas are very rare within lower sheeted dyke unit systems, and the majority of epidosite appears to have selectively replaced entire dyke bodies. However, other distinct types of epidosite (e.g. haloes around quartz veins or intercalating with irregular contacts to metabasalt units) are often seen within epidosite zones.

Previous workers used the generally depleted nature of these units in some base metals (using Cu and Zn as evidence) when compared to protolith analyses to suggest that epidosites play a fundamental role as source rocks for Cyprus-type mineral deposits (e.g. Richardson et al. 1989). Oxygen isotopic evidence from the Marathasa and Solea valley areas of the Troodos ophiolite (Schiffman et al. 1990) also suggests that these epidosites were altered at much higher water-rock ratios than the background

alteration represented by actinolite-albite-chlorite greenschist facies metabasalts.

Nevertheless, the formation and the role played by epidosites in ore forming systems is still a poorly understood process. This is further complicated by work undertaken by Bickle and co-workers (1998) who suggest, using strontium isotope analysis of samples from the Troodos ophiolite, that fluid fluxes which formed the epidosites were similar, if not identical, to the fluid flux present in the background metabasalt. Also, although some metals are depleted (primarily Cu) in epidosite zones, other important metals such as Co, which grades up to 0.35% in some Troodos ore deposits, do not seem to be depleted. In contrast Cu appears to be generally depleted throughout the entire sheeted dyke complex.

This conflicting evidence has cast doubt on the role of epidosites as source rocks in VMS systems. However, it is generally agreed that epidosite zones are thought to develop from intermediately altered chlorite-quartz-epidote units and, through further interaction with hydrothermal fluids, progress towards an epidote-quartz end-member (Figure 1). This is supported by petrological investigations conducted during this study. However, quantifying the release of base metals into hydrothermal

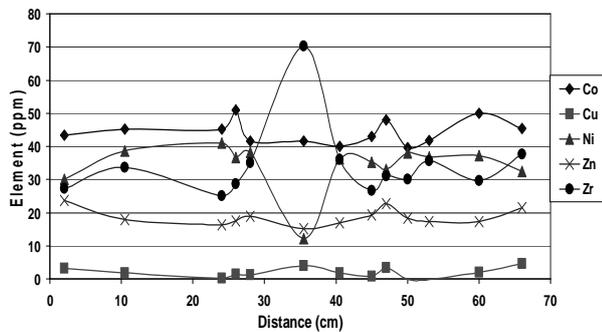


Figure 3. Geochemical variation across a single greenschist altered dyke. Note the preservation of incompatible (e.g. Zr) versus compatible (e.g. Ni) relationships across this dyke indicating immobility for Co, Zn, Zr and Ni. The generally low level of copper suggests that this metal, unlike other important base metals in Cyprus-type ore deposits was mobilised by the background greenschist alteration.

systems during progressive alteration of these units has not previously been investigated.

3 METHODOLOGY

Mapping and sampling of metabasalts and epidosite units from epidosite zones within the Troodos ophiolite was undertaken during 3 separate field seasons. Sampling was on a variety of scales from centimeter scale across individual epidosite and metabasalt units to km long transects over entire epidosite zones, sampling at 30-50 m intervals. A number of samples from background altered metabasalt and fresh rocks were also taken for comparison to epidosite unit samples.

In order to quantify chemical and mineralogical changes represented by epidosite facies alteration geochemical analysis was undertaken on samples obtained during these field seasons. Whole rock samples were analysed by XRF for major and trace elements at the University of Leicester and by solution ICP-MS for a selection of trace elements at the British Geological Survey. Mineralogical analysis at the University of Leicester was carried out using a combination of thin section description and semi-quantitative XRD analysis using crushed whole rock powders and XRF analytical data.

4 RESULTS

Whole rock geochemical analyses of epidosite samples are shown in Figure 2. These plots represent the progressive alteration of epidosite

units from transitional chlorite dominated samples (“Least Altered”) to epidosite end-member (epidote-quartz) compositions (“Most Altered”).

5 DISCUSSION

The new geochemical data presented in this paper indicate a direct relationship between the progressive alteration towards epidosites and the release of Zn and Co into the ore forming hydrothermal fluids (Figure 2). The decrease in modal proportion of chlorite correlates strongly with decreasing Zn and Co – two important metals in Cyprus-type ore deposits. These data are in direct contrast to data from fresh glass protolith analyses which, for example, show increasing Zn with decreasing MgO, an inversion of the epidosite relationship.

A simple interpretation of these data is that Zn and Co are contained mainly in chlorite within these altered rocks. Alternatively, these elements may be distributed between epidote and chlorite with the correlation being due to progressive leaching of metal and a progressive decrease in modal chlorite, both of which could be attributed to increased fluid flux. These data are in direct contrast to the background greenschist facies alteration, where typical igneous incompatible–compatible relationships are preserved within the sheeted dyke complex. Figure 3 shows a transect across a single dyke in the background greenschist altered sheeted dyke complex. The preservation of igneous relationships for metals such as nickel, cobalt and, somewhat surprisingly, zinc, suggests that they are generally immobile under typical sub-seafloor greenschist facies alteration – as seen in previous work undertaken on this style of alteration (e.g. Baragar et al. 1990). This would suggest that another form of alteration is needed to mobilize these metals, epidosite formation being our favored method.

In contrast to these metals, copper concentrations do not correlate with mineralogy. Instead, Cu is generally depleted to very low levels (<4 ppm) in most epidosite zone dykes compared to metabasalt dyke levels (average ~80 ppm, e.g. Baragar et al. 1990). However, both metabasaltic dykes and epidosites are locally enriched in Cu (epidosites generally up to ~50-100 ppm, background up to 2500 ppm [e.g. Baragar et al. 1990]). This rare enrichment to protolith levels, and occasionally above, is in-

terpreted to indicate that Cu was initially mobilized during the early stages of hydrothermal alteration but was locally re-deposited. The localized deposition of copper – unlike cobalt or zinc – may also indicate that copper was mobilised but not removed from the sheeted dyke complex during initial intrusion and intrusion-related hydrothermal metamorphism. Subsequent re-mobilisation and removal of copper from the sheeted dyke system via incorporation into the hydrothermal system could then take place during the formation of epidosite units.

6 CONCLUSIONS

Epidosite formation plays a key role in the formation of Cyprus-type VMS deposits. The mobilisation of cobalt and zinc by the formation of epidosites is a process that enables the movement of these metals. This process does not occur within typical greenschist facies alteration encountered in ophiolitic sheeted dyke complexes. This suggests that the only way to form Co- and Zn-bearing Cyprus-type VMS deposits is via the epidosite facies alteration at depth within the sheeted dyke complex. The presence of copper anomalies throughout the sheeted dyke complex also suggests that copper was locally mobile during the background greenschist alteration event and in many cases the copper did not leave the sheeted dyke complex. During epidosite formation any background facies dykes with copper anomalies would also undergo epidosite alteration. This, whilst releasing zinc and cobalt into the hydrothermal system, would also release the copper contained by the anomalous dyke units.

This documentation of a direct link between progressive alteration and the release of base metals confirms the importance of epidosite formation in forming Zn and Co-rich VMS deposits, whilst also indicating a certain amount of ‘independence’ for Cu within these ore forming hydrothermal systems. These data also allow us to explain the presence of Co in significant amounts within larger Cyprus-type VMS deposits, and suggests Co and associated elements may have uses in the exploration and testing of VMS prospects and targets.

ACKNOWLEDGEMENTS

SMJ acknowledges funding and support for PhD research from the British Geological Sur-

vey University Collaboration Scheme (BUCS) and from the University of Leicester. Fieldwork was funded by a Society of Economic Geologists Student Research Grant, and by the Edgar Pam Fellowship of the Institute of Materials, Minerals and Mining (IoM3), both to SMJ. EMED Mining and the Geological Survey of Cyprus helped with logistics during fieldwork.

REFERENCES

- Baragar WRA, Lambert MB, Baglow N, Gibson IL (1990) The sheeted dyke zone in the Troodos Ophiolite In: Malpas J, Moores EM, Panayiotou A, Xenophontos C (eds) *Ophiolites; oceanic crustal analogues; proceedings of the symposium "Troodos 1987"*. Minist. Agric. and Nat. Resour., Nicosia, Cyprus, pp 37-51.
- Bickle MJ, Teagle DAH, Beynon J, Chapman HJ (1998) The structure and controls on fluid-rock interactions in ocean ridge hydrothermal systems; constraints from the Troodos Ophiolite In: Mills RA, Harrison K (eds) *Modern ocean floor processes and the geological record*. Geological Society of London, London, United Kingdom, pp 127-152.
- Harper GD (1995) Pumpellyosite and prehnite associated with epidosite in the Josephine ophiolite - Ca metasomatism during upwelling of hydrothermal fluids at a spreading axis In: Schiffman P, Day HW (eds) *Low-grade metamorphism of mafic rocks*. 187: 101-123
- Nehlig P, Juteau T, Bendel V, Cotten J (1994) The Root Zones of Oceanic Hydrothermal Systems - Constraints from the Samail Ophiolite (Oman). *J. Geophys. Res.-Solid Earth* 99: 4703-4713.
- Richardson CJ, Cann JR, Richards HG, Cowan JG (1987) Metal-depleted root zones of the Troodos ore-forming hydrothermal systems, Cyprus. *Earth and Planetary Science Letters* 84: 243-253.
- Schiffman P, Bettison LA, Smith BM (1990) Mineralogy and geochemistry of epidosites from the Solea Graben, Troodos Ophiolite, Cyprus In: Malpas J, Moores EM, Panayiotou A, Xenophontos C (eds) *Ophiolites; oceanic crustal analogues; proceedings of the symposium "Troodos 1987"*. Minist. Agric. and Nat. Resour., Nicosia, Cyprus, pp 673-683.