

Sulfur sources and magmatic sulfide mineralization in the Fraser Zone: insights from mineral prospects

by

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Introduction

The Albany–Fraser Orogen (AFO) is a Paleoproterozoic to Mesoproterozoic orogenic belt located along the southern and southeastern margin of the Archean Yilgarn Craton (Fig. 1). The AFO contains multiple economic mineral deposits, including Tropicana Au and the Nova-Bollinger Ni–Cu deposits, the latter hosted within the Fraser Zone of the AFO. The Fraser Zone includes the 1310–1283 Ma Fraser Range Metamorphics, a sequence of amphibolite to granulite metamorphic-grade metasedimentary rocks, intruded by significant volumes of gabbroic and granitic rocks (Spaggiari et al., 2011). As the host for the Nova-Bollinger deposit, the Fraser Zone is a prospective area for significant magmatic sulfide mineralization.

The formation of a magmatic sulfide deposit requires sources of both sulfur and metals. The former is frequently assimilated as a component of country rock by the parental mafic melt (Naldrett, 2004), while the latter is usually sourced from a substantial volume of the parental magma itself. Once sulfur has been incorporated into a melt to the degree that it is no longer soluble, an immiscible sulfide phase precipitates into which metals will partition from the silicate melt. Sulfides are present in the Fraser Zone in several forms: pyrrhotite (\pm chalcopyrite) within metasedimentary rocks; and pyrrhotite, pentlandite and chalcopyrite (\pm pyrite) within mineralized metagabbros. To better understand magmatic sulfide formation within the Fraser Zone, isotopic tracers can be utilized to track the sources of sulfur and understand how metals have partitioned between the different sulfide phases.

Identifying sulfur sources and Archean sulfur in the Fraser Zone

Sulfur isotope geochemistry is a powerful tool that can fingerprint sulfur incorporated into mineral prospects. Geological processes fractionate sulfur isotopes based on differences in mass (mass-dependent fractionation), with deviations expressed in delta (δ) notation and measured per mil (‰) relative to a reference isotopic ratio (0.0‰;

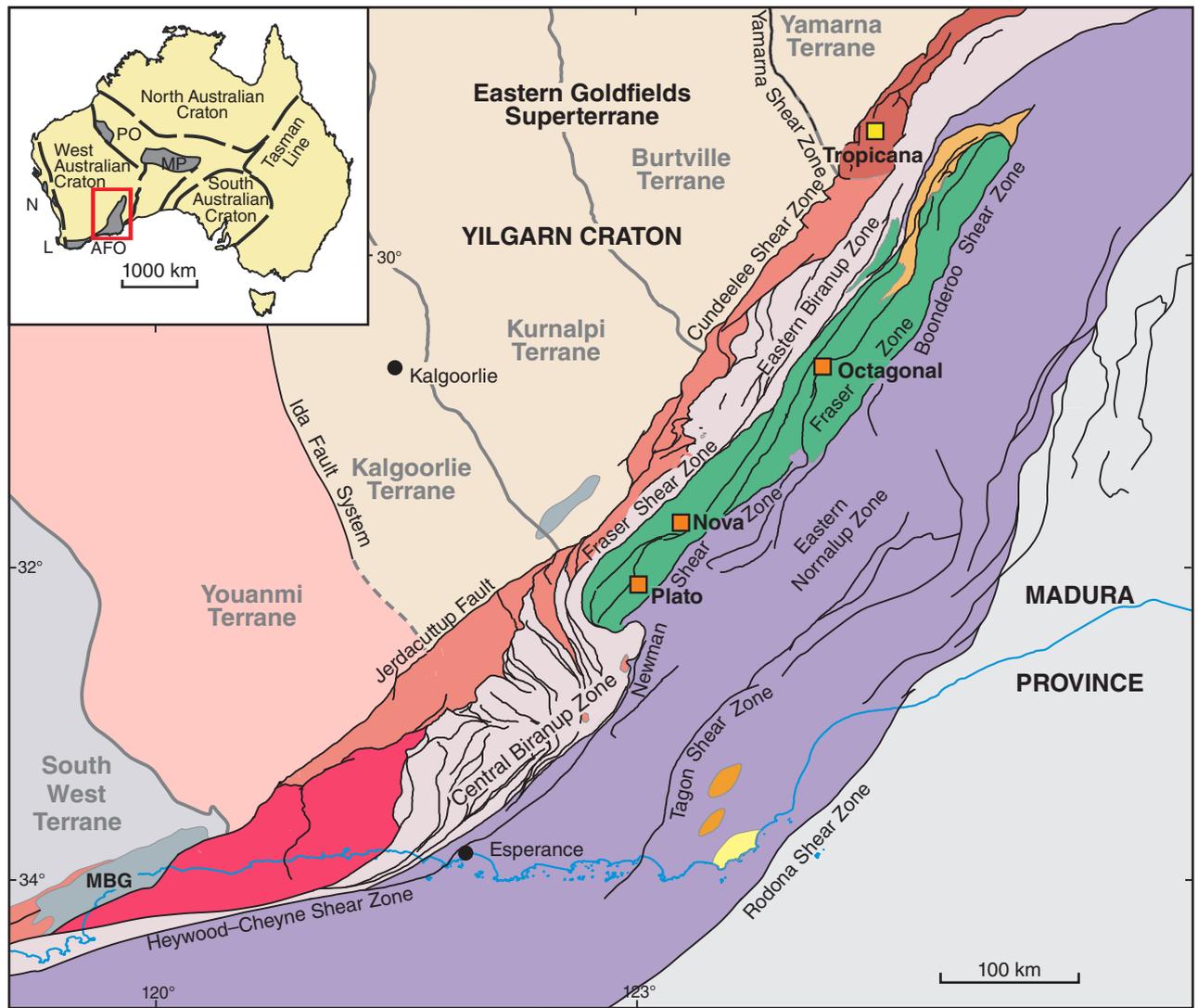
Vienna Canyon Diablo Troilite, VCDT). Mantle-derived sulfur, such as the minimal sulfur content found within a typical mantle-derived melt, characteristically has a $\delta^{34}\text{S}$ isotopic signature between -2 and 2 ‰. Concurrent assimilation of sulfur-bearing crustal material during magmatic emplacement drives the $\delta^{34}\text{S}$ isotopic signature of the magma towards a value between the initial $\delta^{34}\text{S}$ signatures of both the melt and the assimilated sulfur, depending on the degree of assimilation. By identifying the sulfur isotopic signatures of both mineralized and unmineralized magmatic bodies and crustal sulfur sources, we can identify the sulfur sources involved in mineralization, estimate the degree of assimilation of external sulfur involved in mineralized bodies and potentially highlight unexplored areas in which similar mineralization is likely to be present. Furthermore, sulfur isotope systematics also allow fingerprinting of Archean sulfur. Differences in the Archean atmosphere, relative to present conditions, facilitated mass-independent fractionation of sulfur isotopes via photochemical processes that can be identified by non-zero $\Delta^{33}\text{S}$ sulfur isotopic signatures. The presence of mass-independent fractionation within a sulfur source would indicate the presence of an Archean sulfur component, and provide further information on the origin of sulfur-hosting crustal material.

With regard to sulfur isotopes, this study aims to address the following questions: 1) which sulfur isotope ranges characterize the magmatic and sedimentary geology of the Fraser Zone; 2) are these signatures related to (or the absence of) mineralization; and 3) can an Archean sulfur component be identified in the Fraser Zone, as previous radiogenic studies indicate limited evolved Archean input into melts (Kirkland et al., 2011; Smithies et al., 2013). In this work, we present new $\delta^{34}\text{S}$ (Fig. 2) and $\Delta^{33}\text{S}$ data from weakly mineralized (Plato) through to strongly mineralized (Octagonal) prospects using in situ sulfur isotope measurements from several sulfide phases. Magmatic sulfides from both prospects were analysed, in addition to metasedimentary material from Octagonal to characterize local sulfur sources in the Fraser Zone.

Distinct sulfur isotopic signatures at each of the mineral prospects indicate variable degrees of assimilation of local metasedimentary rocks. Analysis of two samples of sulfide-bearing metasedimentary rock from Octagonal provide a mean sedimentary $\delta^{34}\text{S}$ signature of 6.07 ± 1.86 ‰. A near mantle (1.05 ± 0.85 ‰) $\delta^{34}\text{S}$ isotopic signature characterizes rocks from Plato

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ALBANY-FRASER OROGEN

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|---|---|---|---------------------|
|  | Mount Ragged Formation |  | Major faults |
|  | Fraser Zone (1305–1290 Ma) |  | Terrane boundary |
|  | Gwynne Creek Gneiss |  | Geological boundary |
|  | Malcolm Metamorphics |  | Coastline |
| } Arid Basin | |  | Town |
|  | Normalup Zone (1800–1650 Ma); Recherche (1330–1280 Ma) and Esperance (1200–1140 Ma) Supersuites (undivided) |  | Au |
|  | Biranup Zone (1800–1650 Ma) and Archean remnants |  | Ni |
|  | Barren Basin (undivided) | | |
|  | Tropicana Zone (2720–1650 Ma) | | |
|  | Munglinup Gneiss (2800–2660 Ma) | | |
|  | Northern Foreland, undivided | | |

Figure 1. Simplified geological map of the Albany–Fraser Orogen (modified after Spaggiari et al., 2015). Abbreviations: AFO, Albany–Fraser Orogen; L, Leeuwin Province; MBG, Mount Barren Group; MP, Musgrave Province; N, Northhampton Province; PO, Paterson Orogen

(Fig. 2), which likely reflects minimal assimilation of external sulfur by Plato parental magmas. In contrast, Octagonal exhibits a more positive $\delta^{34}\text{S}$ mean signature of $4.31 \pm 0.80\text{‰}$ (Fig. 2), indicating a greater degree of sedimentary assimilation and mixing between magmatic and sedimentary sulfur sources. These results highlight a coupling between variable assimilation of external sulfur by Fraser Zone magmas and the mineralization present at the prospects studied — sulfides from more mineralized material possess more positive $\delta^{34}\text{S}$ sulfur isotopic signatures. However, sulfur contents within mineralized samples exceed the concentrations possible solely through assimilation processes and likely require the involvement of additional processes such as tenor upgrading.

There is no indication of an Archean sulfur component within the material analysed. However, this is at odds with evidence from other isotopic systems and geochemical modelling that strongly suggest an Archean component to the Fraser Zone. Two-component mixing models indicate this discrepancy is unlikely to be due to dilution of Archean sulfur within the parental magmas. Hence, we advocate a decoupling of the sulfur-bearing component from the majority of the Archean sedimentary material incorporated into the Fraser Zone magmas via a process operating in the surface weathering and erosion cycle, where more reactive sulfide phases are removed in preference to resistant minerals such as zircon.

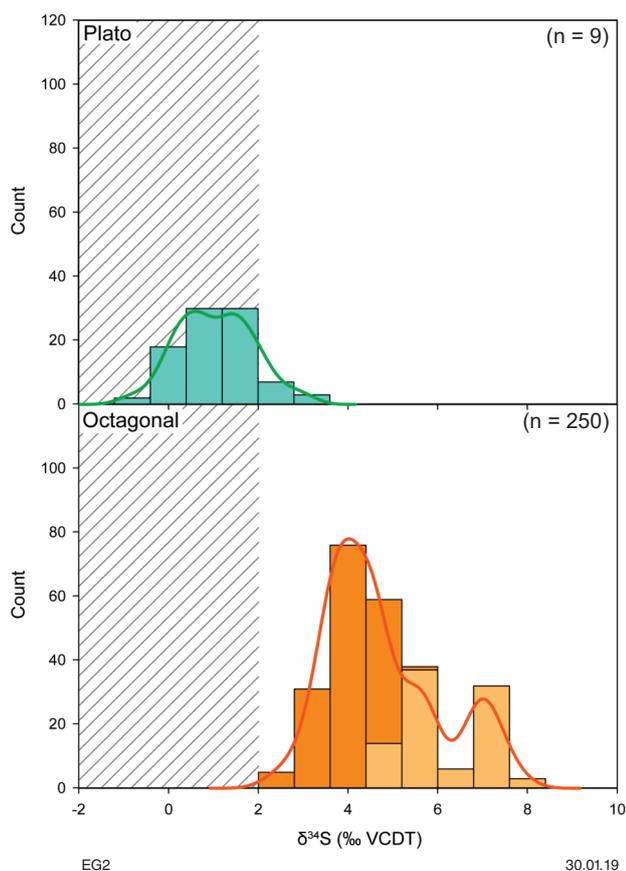


Figure 2. Histograms illustrating distributions of $\delta^{34}\text{S}$ values in samples analysed from the Plato and Octagonal prospects (Kernel Distribution Estimate overlaid). Octagonal magmatic analyses are shown in darker orange and sedimentary analyses in lighter orange. Hashed area indicates accepted range of values for mantle-derived sulfur

Laser ablation mapping of multiple sulfide phases

Magmatic sulfide deposits concentrate a range of metals beyond those of economic interest (primarily Ni, Cu, Co). Many processes involved in the formation of a deposit affect the partitioning of metals between the constituent sulfide minerals. Characterization of elemental partitioning between sulfides provides insight into the processes occurring during the formation of a deposit. Hence we sought to identify the partitioning of metals between magmatic sulfides by laser ablation mapping, and couple these spatial observations to those processes involved in magmatic sulfide mineralization in the Fraser Zone.

Laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) and Tescan Integrated Mineral Analysis (TIMA) were used to map elemental concentrations across sample surfaces composed of multiple sulfide phases. Elemental mapping highlighted Mn concentrations within later, magnetite-infilled fracture networks (Fig. 3) with only minimal levels of Mn within the sulfide material surrounding fractures. The presence of Mn is attributed to transport via fluids within the fracture network during formation. The observation of apparent co-localization between Mn and fracture material provided an excellent opportunity to apply a novel, quantitative statistical analysis to quantify the strength of this spatial relationship.

Application of co-localization analysis to elemental maps

Co-localization requires both co-occurrence and correlation — co-occurrence is the spatial overlap of two datasets, whereas correlation is not only overlap but co-distribution of datasets in proportion to one another within and between structures (Dunn et al, 2011). Co-occurrence and correlation were assessed using Mander's Colocalization Coefficient (MCC) and Pearson's Correlation Coefficient (PCC), respectively. Analysis was undertaken on spatial datasets describing distributions of elements and fracture networks on two samples of magmatic sulfide breccia from the Octagonal prospect. A range of elements exhibiting different distributions was selected to test the robustness of the technique. Our analysis reveals a statistically significant relationship between the distribution of fractures and the distribution of Mn, in which Mn is co-localized with the fracture material. Fluid flow and consequent remobilization of metals via fracture networks syn/post-mineralization within a deposit is a means by which metal tenor may be upgraded. Alternatively, pervasive and prolonged fluid alteration might also destroy a deposit, with remobilization stripping and dispersing metal content from once-economic horizons.

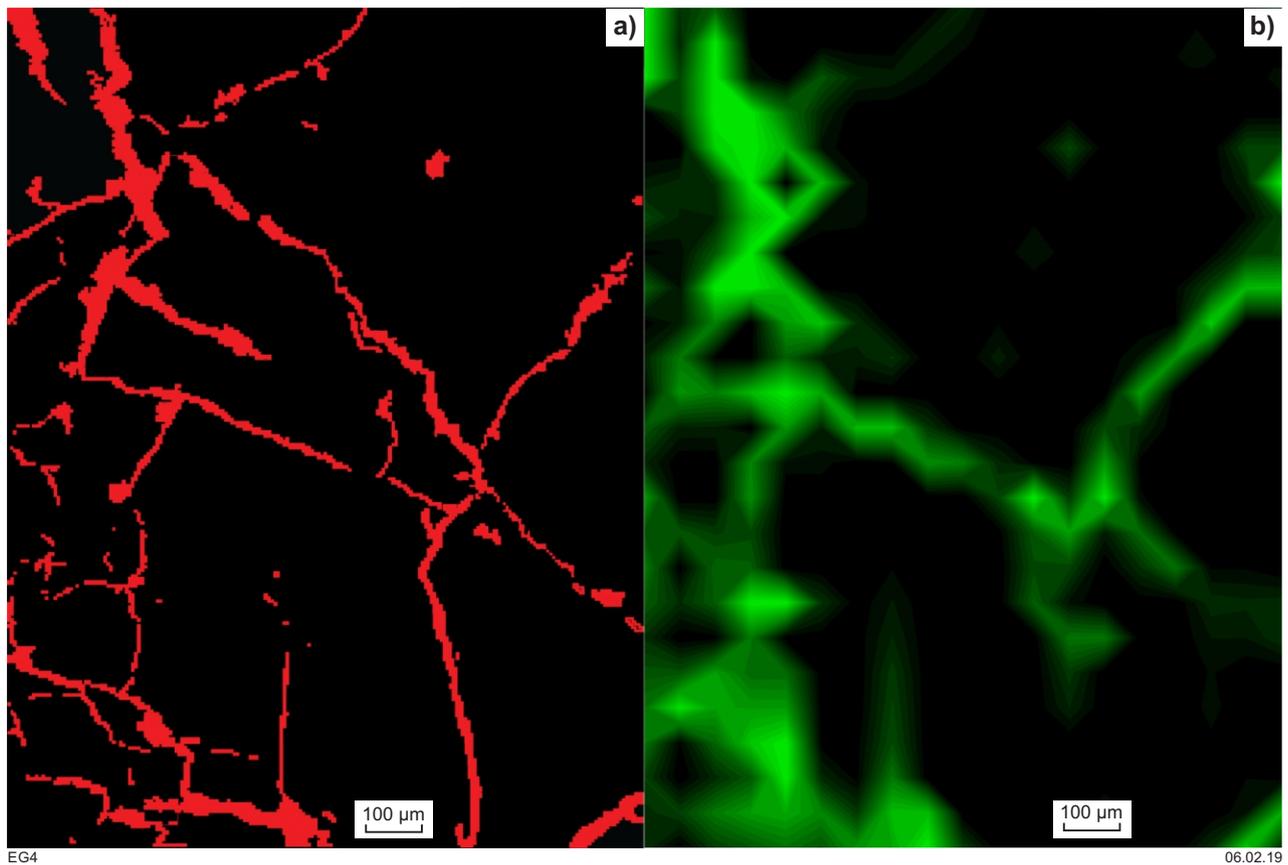


Figure 3. Elemental mapping images: a) the fracture network (in red) across the analysed surface of sulfide breccia GSWA 219070; b) elemental map illustrating the distribution of Mn across the sample surface. Higher green intensity indicates higher Mn concentrations. Images were overlaid for Mn co-localization analysis

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