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Contents

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Forward/Context

Targeted Geoscience Initiative Phase 6 (TGI-6) is a five-year (2020-25) research program of Natural Resources Canada to conduct national, collaborative research, with the aim to provide the Canadian mineral industry with the next generation of geoscience knowledge, innovative techniques, and predictive models that will result in more effective targeting of buried mineral deposits. Specific program objectives are: 1) generate geoscience knowledge to enhance the understanding of the processes that formed Canada's mineral deposits, including critical minerals, and identify and develop novel indicators and parameters to guide exploration in emerging and existing mining areas; and 2) improve mineral exploration effectiveness by developing next-generation geological knowledge, as well as leading edge tools, innovative techniques, and predictive models.

The former objective aims to clarify the processes that formed various ore deposits with a focus on elements that are critical to Canada's transition to a green and digital economy. Volcanogenic massive sulfide (VMS) and other massive sulfide deposits (e.g., magmatic sulfide, skarns, Mississippi Valley-type, and sediment-hosted lead-zinc) host several metals important to this transition, grouped under the term "critical minerals", but in many cases the specific sulfide minerals hosting these metals are not well known. Furthermore, the effect of deformation and metamorphism on the (re)distribution of these metals is generally poorly constrained. The results presented here form part of TGI-6 research investigating how deformation and metamorphism affect the distribution of critical minerals, such as cobalt, copper, zinc and germanium, in VMS deposits.

Summary

This report presents 35 microstructural maps of sulfides from the Windy Craggy VMS deposit, located in the Alexander Terrane in northwestern British Columbia, Canada. These microstructural maps were generated by Electron Backscatter Diffraction (EBSD) and will be used to determine how the sulfides were remobilized or otherwise modified during deformation and/or metamorphism. In addition, the microstructural maps will be combined with quantitative compositional data from laser ablation – inductively coupled plasma – mass spectrometry (LA-ICP-MS), to determine which elements within which sulfides may have been remobilized during deformation and/or metamorphism, and to link element mobility to specific sulfide modification mechanisms. Windy Craggy was used as a case study because it and the enclosing host rocks (basalt flows, basalt sills, and argillites) experienced folding and highly localized shearing under greenschist-facies metamorphic conditions (Peter, 1989), such that both deformed and relict undeformed sulfides are present and can be compared.

The samples were collected in 1988 and 1989 by Jan Peter during his Ph.D. research on the Windy Craggy deposit (Peter, 1992). Microstructural mapping was conducted by Tarryn Cawood and Matthew Polivchuk in 2022-2023, with funding from the TGI-6 program. A description of the analytical methods used, a summary of the main results, and some preliminary observations and interpretations are provided below. The results (raw data) are provided in this .zip Open File package as 35 .h5oina files (Pinard et al., 2021), along with a summary of figures showing this data (Fig. 1-14).

Analytical Methods

For this study, >400 hand samples (along with ~200 associated polished thin sections) were observed to identify mineralization styles and sulfide textures. From these, 13 samples were selected because they display the complete spectrum of representative sulfide textures. Polished thin sections of these were made and investigated with standard petrographic methods, and specific examples of different sulfide textures were identified for microstructural mapping. Microstructural mapping was conducted using EBSD, which determines the crystallographic orientation at each point in a raster (map) (Prior et al., 2009). EBSD uses a specific detector

attached to a scanning electron microscope (SEM; see, for example: www.ebsd.com/ebsd-techniques/ebsd-detectors).

For EBSD analysis, standard polished thin sections were further polished for 30 minutes using 0.06 µm colloidal silica. A 5 nm thick carbon coat was then applied. Mapping was conducted with an Oxford Instruments Nordlys Nano detector attached to a TESCAN Mira3 XMH field emission scanning electron microscope. Analyses were performed using an accelerating voltage of 20 kV, working distance of 18 mm, and beam current of approximately 5 nA with the sample surface tilted at 70 degrees towards the detector, and a step size of between 0.08 and 3.5 µm. EBSD camera settings included a 4x4 frame binning and 24 ms exposure time with a combined static and dynamic background removal. The Kikuchi patterns were indexed in Oxford Instruments' AZtec software using a Hough transform resolution of 70 and requiring a minimum of 6 and maximum of 11 detected bands. Elemental analyses using X-ray energy dispersive spectroscopy (EDS) were conducted simultaneously using an X-Max 80 silicon drift detector, and phases with similar Kikuchi patterns were discriminated based on their chemistry using the software's TruPhase function.

Oxford Instrument's AZtec Crystal software was used to generate various types of microstructural maps. No clean up or post-processing has been applied to the data, as pyrite, pyrrhotite, and sphalerite typically indexed well (with typically >95% of points correctly indexed). Chalcopyrite typically indexed poorly (≤80%), possibly because it tends to tarnish (oxidize) rapidly. Storing freshly polished thin sections in dehumidified conditions helped somewhat.

Grain boundaries are defined as boundaries with >10° angular misorientation across them, whereas 2-10° was used for subgrain boundaries.

Results

The resulting microstructural data for each mapped area are provided as raw .h5oina files, which can be opened, visualized, cleaned/processed, and interrogated using Oxford Instrument's Aztec Crystal software (www.ebsd.com/ois-ebsd-system/azteccrystal-processing-software), as well as with the MTEX toolbox in Matlab (https://mtex-toolbox.github.io/). The H5OINA file format is based on Hierarchical Data Format 5 (HDF5) and has been designed to exchange microanalysis data within the Oxford Instruments' AZtec ecosystem as well as with third-party software and libraries.

These microstructural data can be visualized in various ways to show different aspects of the analyzed areas, including the distribution of different mineral phases; their crystallographic orientations; grain boundaries and subgrain boundaries; grain size; grain shape; and internal distortion within grains. For example, maps can be generated that show grain reference orientation deviation (GROD), which uses a colour scale to show the deviation from the mean crystallographic orientation of each grain, and thus highlights misorientations or distortion within individual grains. Maps can also be colour-coded by the inverse pole figure (IPF), which uses different colours to represent which crystallographic direction is oriented parallel to the observer's point of view.

Figures 1 to 14 (see attached .pdf file) provide a reflected light photomicrograph for each sample, showing the various minerals (asp = arsenopyrite; cc = calcite; ccp = chalcopyrite; chl = chlorite; po = pyrrhotite; mgt = magnetite; py = pyrite; sid = siderite; sp = sphalerite; qz = quartz), together with the mapped regions (white rectangles); followed by three maps for each of these regions. The maps each show a combination of several data types: 1) BC + GB + GROD-Ang maps, which show band contrast (BC, an indication of the quality of the EBSD data) overlain by grain boundaries (GB) and colour-coded for grain reference orientation deviation; 2) BC + IPF + GB maps, which again show band contrast and grain boundaries, colour-coded by the inverse pole figure; and 3) BC + Ph maps, which show band contrast and the different mineral phases (Ph) analyzed.

Preliminary Observations and Interpretations

The presence of internal lattice misorientations, best observed in the IPF and GROD maps as colour variations within single grains (e.g., Fig. 3B), is analogous to undulose extinction seen in translucent minerals like quartz and is indicative of mechanical solid-state deformation by dislocation glide (McClay and Ellis, 1983; Passchier and Trouw, 2005).

Most analyzed samples of pyrite show little to no internal misorientation (e.g., Fig. 1, 2, 8), indicating that these grains do not record internal deformation. This could be because these samples come from areas within the Windy Craggy deposit that escaped the localized shearing; because deformed pyrite was subsequently annealed; and/or because pyrite behaves in a more competent manner (i.e., it is less ductile) than the surrounding minerals (typically pyrrhotite or gangue minerals including calcite, siderite, and chlorite). Some pyrite grains, however, do show internal misorientation (e.g., Fig. 3), showing that in these cases the pyrite was affected by deformation. Some coarse (~0.5-1 mm diameter), euhedral pyrite grains are partially replaced by aggregates of smaller pyrite crystals (Fig. 9). This represents a typical core-and-mantle structure and suggests that pyrite experienced dynamic recrystallization during deformation (McClay and Ellis, 1983; Passchier and Trouw, 2005), with the coarse parent grain being progressively recrystallized around the outer edges to form new, finer grains. Pyrite also displays cataclastic textures (Fig. 11), indicating it also locally experienced brittle deformation.

All the analyzed pyrrhotite-rich areas comprise pyrrhotite with some amount of internal misorientation (e.g., Fig. 3), and several pyrrhotite-rich samples are strongly foliated, with the foliation defined by elongate pyrrhotite grains (e.g., lower part of Fig. 4A). This suggests that pyrrhotite is weaker than pyrite and behaved in a ductile manner to accommodate a significant portion of the deformation at Windy Craggy. This strength contrast between more-competent pyrite and less-competent pyrrhotite is supported by the presence of pyrite as porphyroclasts, wrapped by a matrix of foliated pyrrhotite (Fig. 3, 9). Microstructurally, pyrrhotite varies from coarse, anhedral grains with minor internal misorientation (e.g., Fig. 14), through coarse grains with moderate to major internal misorientation (e.g., lower part of Fig. 3C), to significantly smaller grains with a strong crystallographic preferred orientation (CPO), visible in IPF maps as many grains exhibiting similar colours/orientations (e.g., Figs. 4C, 5D). The internal misorientation and development of a CPO indicates that pyrrhotite was deformed by dislocation glide (Kübler, 1985; Passchier & Trouw, 2005). In addition, subgrain structures are visible in some coarse-grained pyrrhotite (e.g., the lower area of Fig. 3D), and the similar size of these subgrains and adjacent fine-grained pyrrhotite suggests that coarse pyrrhotite grains experienced dynamic recrystallization by subgrain rotation (SGR, White, 1977), to form the finer grains.

Chalcopyrite varies from coarse, subhedral polycrystalline masses with little internal misorientation (Fig. 10) to very fine-grained masses, occurring as asymmetric tails on pyrite porphyroclasts wrapped by foliated, recrystallized pyrrhotite (Fig. 9) and in the necks between chlorite boudins, again hosted by foliated pyrrhotite (Fig. 5). Note that in this case, chlorite is relatively more competent than the surrounding pyrrhotite, which enabled it to become boudinaged. The presence of chalcopyrite in low-strain regions such as porphyroclast tails and boudin necks suggests that it was mobile in a fluid phase during deformation. It may have been locally remobilized by coupled dissolution-reprecipitation (e.g., Putnis, 2002), or introduced by syn-deformational fluids.

Sphalerite typically occurs as small, scattered grains (e.g., Fig. 12), from which little can be deduced. One sample, however, contains coarse grained polycrystalline sphalerite with abundant twinning and internal misorientation, that is locally cut by a narrow zone in which the sphalerite displays a significantly reduced grain size (Fig. 6). As with pyrrhotite, the presence of internal strain within sphalerite grains, subgrain structures, and the small size of the new grains (Fig. 6C) suggests that this sphalerite accommodated deformation by local dislocation creep and dynamic recrystallization by SGR.

Magnetite occurs as medium- to fine-grained polycrystalline aggregates with some internal misorientation, intermixed with similarly medium- to fine-grained pyrrhotite (Fig. 13). Although it is not certain, this may indicate that magnetite experienced dislocation creep, dynamic recrystallization, and phase mixing with pyrrhotite during deformation.

In addition, coarse, anhedral pyrrhotite, chalcopyrite and lesser sphalerite, along with euhedral pyrite, occur in the fold hinges of folded, fine grained, polysulfide rock (Fig. 7). This suggests that all these minerals were also remobilized in the fluid phase during deformation, and dissolved from high-strain areas and re-precipitated into low strain areas like fold hinges. Pyrite veins and veinlets (e.g., Fig. 1, 11) similarly show that pyrite was precipitated from a fluid. In some cases (e.g., Fig. 1) these veins are texturally early and were likely emplaced during hydrothermal activity. In others (e.g., Fig. 11) the pyrite veins may be late deformational.

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