Characterization of country-rock hosted sulfide textures within the vicinity of the Eagle Ni-Cu-PGE Deposit, Upper Peninsula, Michigan

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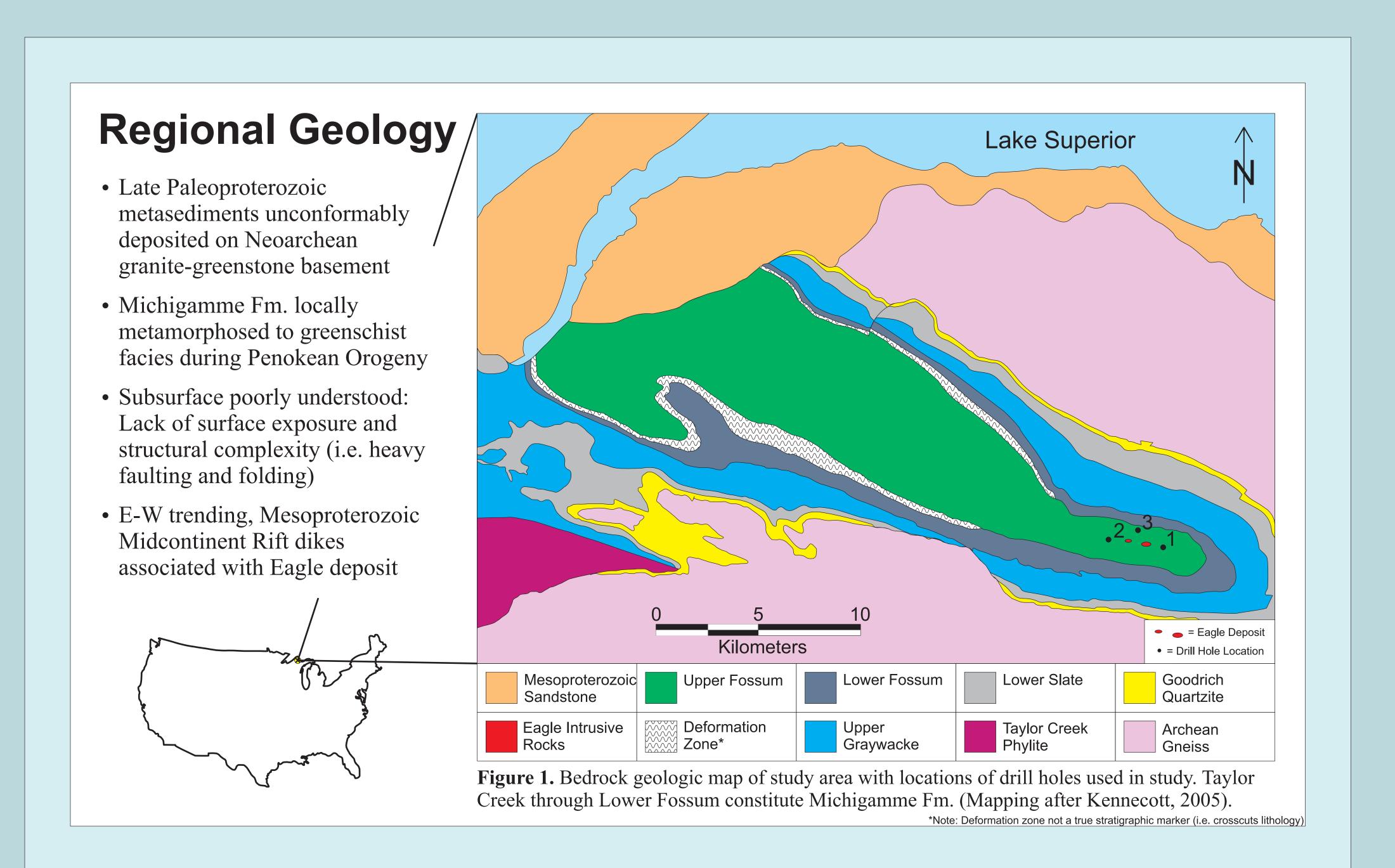
Abstract

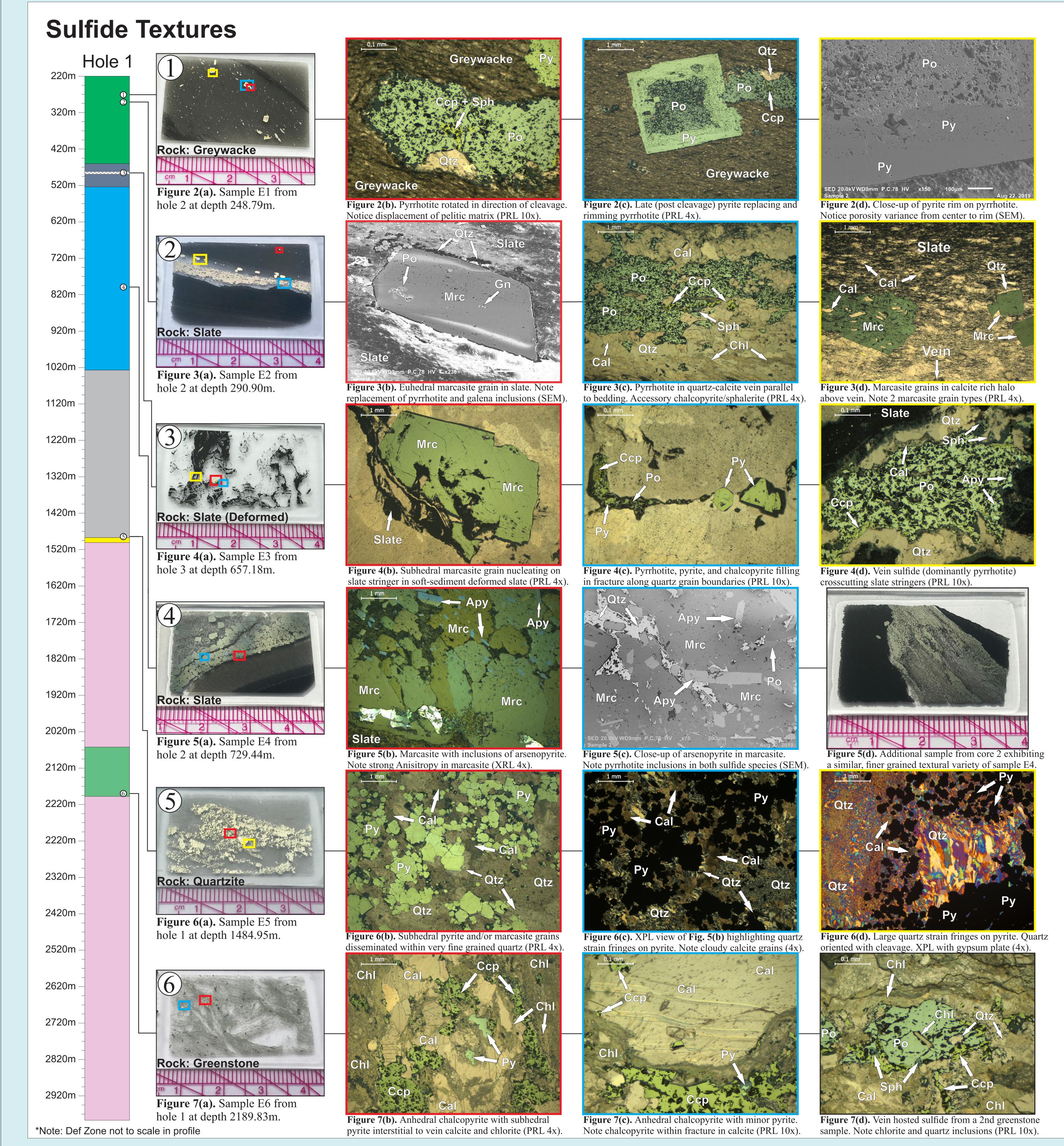
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The Eagle deposit, hosted within the Baraga Basin on Michigan's Upper Peninsula, is a highgrade, conduit style, magmatic Ni-Cu-PGE deposit considered to be related to early stage, Midcontinent Rift magmatism. The Baraga Basin is a structural basin largely comprised of ~1.85 Ga Michigamme Formation metapelites, metagraywacke, and iron formation, conformably overlying lesser amounts of basal Goodrich Quartzite. Underlying the basin is the ~2.7 Ga granite-greenstone terrain of the Northern Complex which is comprised largely of granite, granitic-gneiss, and greenstone. Within the vicinity of the Eagle deposit, the Michigamme and Goodrich Quartzite contain up to 10 and 5 percent sulfide respectively, while sulfide in the basement rocks is disseminated and rare.

Multiple authors have suggested contamination of mafic magma by country rock derived sulfur is a critical factor in the genesis of magmatic-sulfide ore deposits. While the mechanisms by which country rock sulfur is incorporated into magma are not well understood, evidence from case studies support claims that externally-derived sulfur contributes to sulfide mineralization. Over the last decade, studies conducted on the Eagle deposit have unearthed evidence suggesting that a significant quantity of ore-forming sulfur was derived from Baraga Basin metasediments and the underlying Archean basement.

In this study, we characterize several modes of sulfide occurrence within the country rocks of the Eagle deposit using a combination of reflected and refracted light petrography and SEM w/ EDS. Along with enhancing descriptions of previously recognized textures, we report several new sulfide textures and comment on their origins. While typical sulfide assemblages consist of pyrite, pyrrhotite and minor chalcopyrite, trace amounts of other sulfides also exist. Sulfides range from disseminated, very fine-grained pyrite to massive, pyrrhotite-pyrite bands and lenses usually indicating hydrothermal influence. Other observations include occurrences of sulfide zonation, complex emplacement structures, and epitaxial overgrowths. The exceptional textural variety of sulfides preserved in these rocks record a complex diagenetic and metamorphic history further complicated by mobilization and re-emplacement by later hydrothermal fluids.





Sulfide Texture Types

Classification & Description of Sulfide Textures

 Various modes of sulfide occurrence are observed within the country rocks surrounding the Eagle deposit. These occurrences can be grouped into 3 broad categories: 1. Vein hosted, 2. Layered/lens type, and 3. Disseminated.

Vein Hosted Sulfides

- Vein hosted sulfides are defined by their occurrence in distinctive sheets, fractures, or bands which display definitively different texture, fabric, composition, and/or mineralogy than that of the host rock. Textural varieties include:
- Massive*, banded, sulfide, roughly parallel to bedding which commonly displays rough, pyrrhotite-arsenopyrite rich centers (Fig. 5(a), upper-left corner) with marcasite rimming and replacing pyrrhotite (e.g. Sample E4; Fig. 5(b) & 5(c)).
- Anhedral pyrrhotite, with accessory anhedral chalcopyrite, sphalerite, and arsenopyrite within chlorite-quartz-calcite veins crosscutting graphite-rich, locally deformed, slate (e.g. Sample E2; Fig. 3(c) and sample E3; Fig. 4(d)).
- Anhedral chalcopyrite, with very low amounts of pyrrhotite, sphalerite, or pyrite (subhedral to anhedral) in chlorite-calcite rich veins and fractures in greenstone (e.g. Sample E6; Fig. 7(b), 7(c), & 7(d)).
- Anhedral aggregates to massive pyrite and/or marcasite hosted within either sub mm sized veinlets or breccia fill comprised almost exclusively of carbonate. Texture occurs more often than not at depths typically shallower than ~350 meters.

by volume and lens/layered type sulfides where the lens/layer appears to be composed essentially of sulfide.

Layered/Lens Type

- Layered/lens type sulfides are defined by their lens-like appearance, apparent spatial discontinuity, and lack of a veinnetwork association. Textural varieties include:
- Lenses of massive sulfide (pyrite and/or pyrrhotite) present parallel to bedding. Sulfide is typically oriented/remobilized in the direction of cleavage and warps bedding, except where cleavage is oriented parallel to bedding.

Disseminated Sulfides

- Disseminated sulfides are defined by their occurrence typically as either individual grains or grain aggregates hosted directly within the rock matrix. Disseminated grains may be either ubiquitous or sparsely occurring. Textural varieties include:
- Ubiquitous euhedral to subhedral epitaxial pyrite and marcasite surrounding anhedral sulfide cores (typically pyrrhotite but occasionally pyrite). Sulfide rims typically exhibit very low porosity and overprint foliation while cores display a generally patchy texture indicative of sulfide dissolution (e.g. Sample E1; Fig. 2(c) & 2(d)).
- Finely disseminated, typically <1mm sized anhedral porphyroblasts of pyrrhotite with accessory, anhedral chalcopyrite, sphalerite, and occasional subhedral to euhedral arsenopyrite inclusions (e.g. Sample E1; Fig. 2(b)). Grains typically display evidence of grain deformation, as visible in cross-polarised light, displace bedding, and are rotated in the cleavage direction.
- Bands of loosely concentrated, finely disseminated, sub mm sulfide (typically euhedral to subhedral pyrite) parallel to bedding.

Key Observations, Interpretations, and Implications

Key Observations and Interpretations

- Most sulfides appear along bedding planes and typically display evidence of ductile deformation (e.g. deformed crystals, preferential grain orientations, etc.)
- Layered/Lens type sulfides and disseminated sulfides typically displace bedding and are oriented in the principle cleavage direction which corresponds to the ~1.85 Ga Penokean Orogeny. Strain fringes (pressure shadows) adjacent to much of the pyrite/marcasite found within the Michigamme Fm. (e.g. Fig. 3(b), 3(d), 6(c) & 6(d)) suggest some pyrite/marcasite may have precipitated during or even prior to the timing of cleavage
- Pyrite-marcasite overgrowths appear to overprint cleavage, suggesting they post date cleavage, but may have precipitated during late-stage hydrothermal events or retrograde metamorphism.

Potential Source of Sulfur/Sulfides

- In general, many of the sulfides observed thus far appear to be either pre- or syn-metamorphic in origin. Sulfide sulfur likely originated as a result of bacterial sulfate reduction which was later mobilized and re-emplaced during metamorphism.
- Previous work has demonstrated significant isotopic variability of sulfide sulfur in the country rocks of the Eagle deposits (Ding et al., 2012; Hinks, 2016; Thakurta et al., 2019).
- Emplacement of the Eagle and East Eagle intrusions likely resulted in mixing and exchange of country-rock derived sulfur with magmatic-hydrothermal sulfur. Therefore, determining the origin, timing of emplacement, and the mechanisms responsible for the isotopic variations observed in the country-rock sulfides is pertinent to understanding the significance and extent of mixing between the Eagle Deposit and the surrounding Paleoproterozoic and Neoarchean country rocks.

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Acknowledgements

- The WMU Department of Geological and Environmental Sciences and the Graduate College for their generous financial support
- Lundin Mining and Bob Mahin for allowing access to their drill core
- The kind and helpful exploration geologists at the Eagle exploration offices for their valuable input and help with core sampling
- Tyler Norris and Christ Remero for their aid in sample collection
- Katharine G. Rose for her support and numerous, engaging discussions