Geochemistry and petrography of the volcanic strata hosting the Flambeau Cu-Zn-Au Deposit in Rusk County, WI: A re-examination of Wisconsin's only past-producing Volcanogenic Massive Sulfide mine

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Introduction

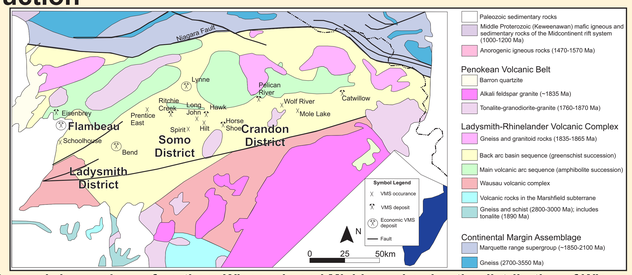


Figure 1: Precambrian geology of northern Wisconsin and Michigan showing the distribution of Wisconsin Volcanogenic Massive Sulfides.

This project aims to understand the stratigraphy, geochemistry, petrography, and alteration of the poorly understood Cu-Zn-Au Flambeau volcanogenic massive sulfide deposit. The Flambeau deposit is hosted by the Wisconsin Magmatic Terrane of the Penokean Orogen which is a 1.8-1.9 billion year old volcanic arc sequence consisting of volcanic and sedimentary rocks, and associated mafic and felsic plutonic rocks (DeMatties, 1994; Schulz and Cannon, 2007). The Wisconsin Magmatic Terrane hosts many Cu-Zn-Au deposits but their geological and economic significance has not been examined in any detail.

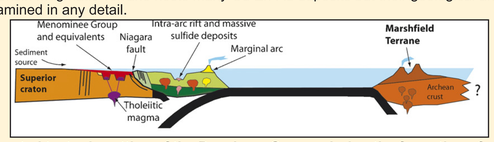


Figure 2: Reconstructed tectonic setting of the Penokean Orogen during the formation of metallic ore deposits in northern Wisconsin.

The tectonic framework and evolution of the Penokean Orogeny has recently been synthesized (Schulz and Cannon, 2007) and will provide a regional context and history of deformation to help unravel the complex geology of this terrane. This reconstruction is on a regional scale and provides little information on the scale of individual ore deposits. Therefore, understanding the geochemistry, stratigraphy, and alteration of the rocks hosting the Flambeau ore body is essential to obtaining a more detailed understanding of the tectonic history of Wisconsin. Studies of individual ore deposits will also contribute important scientific information regarding controversial metallic sulfide ore bodies and their potential impact on the economy and environment.

Volcanogenic Massive Sulfides (VMS)

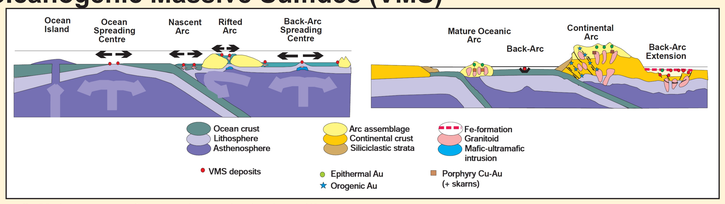


Figure 3: Metallogeny of volcanic arc tectonic settings.

VMS deposits produce a diverse suite of base and precious metals and are major sources of Cu, Zn, Pb, Au, and Ag. They are associated with extensional tectonic settings—however, only submarine rifted arcs and back arcs are present in the ancient rock record because they are preserved and uplifted during subduction and orogenesis (Galley et al, 2007). These settings can be identified in ancient rocks by comparing trace element geochemistry with modern tectonic settings.

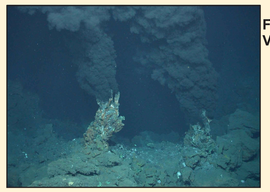


Figure 4: Black smokers on the sea floor are modern analogs for ancient VMS deposits.

VMS deposits precipitate metalliferous sediments near volcanically-active submarine rifts via “black smokers.” Seawater is heated by synvolcanic intrusions lower in the crust and fluids reach temperatures in excess of 300°C. These hydrothermal fluids concentrate ores at the vent site.

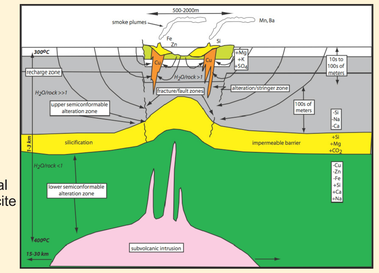


Figure 5: Hydrothermal alteration results in element mobilization in host rocks.

The same process that concentrates ore minerals also mobilizes many major elements (e.g. Na, Mg, Fe, Ca, Si, K). This hydrothermal alteration creates predictable mineralogical changes in the rock and forms assemblages of chlorite, sericite and quartz (silicification). Geochemical indices based on the abundances of elements gained and lost can theoretically predict the degree of alteration and proximity to ore lenses.

Study Area

Figure 6: The Flambeau Cu-Au deposit near Ladysmith is Wisconsin’s only past-producing VMS deposit.

Despite the Flambeau deposit being the only partially extracted VMS deposit in Wisconsin, because of its short mine life, little geoscience research was produced. Due to the scarcity of exposed bedrock in the region, our research is focused on Flambeau drill cores from the Wisconsin Geological and National History Survey.

Stratigraphy of the Flambeau VMS

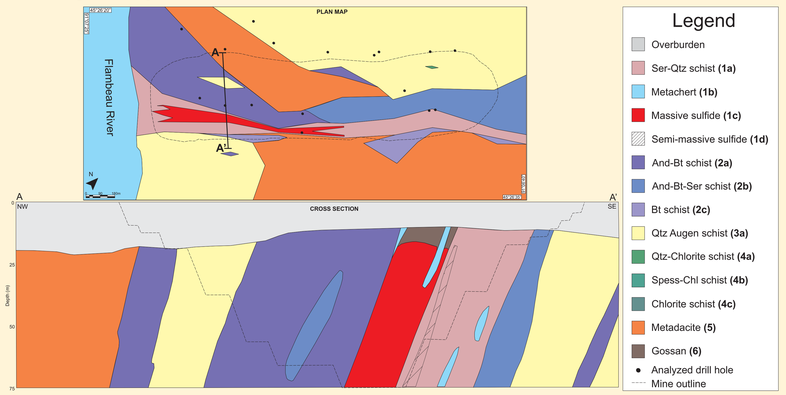


Figure 7: Geology and stratigraphy of the Flambeau deposit.

The Flambeau VMS ore body is a steeply dipping, near tabular lense that has previously been interpreted to be overturned (May and Dinkowitz, 1996). The mined portion of the Flambeau ore body is a gossan and supergene enriched zone. The volcanic stratigraphy that hosts the Flambeau deposit is subdivided based on their lithological characteristics (each were given a unique mine code), rather than protoliths. Each of these units are described below in Figure 8.

Figure 8A: Sericite Quartz schist (1A).
A light gray, very well foliated, sericitic and variably silicified unit commonly found within the ore horizon and often associated with semi-massive stringer-type mineralization. Minor amounts of chlorite, andalusite and biotite are present.

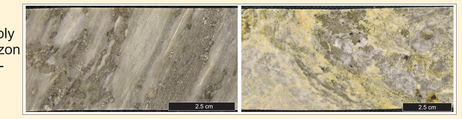


Figure 8B: Andalusite-Biotite±Sericite schist (2B).
A strongly foliated and metamorphosed hydrothermal alteration assemblage. Geochemistry indicates both mafic and intermediate volcanic protoliths. It is variably mineralized and associated with more sericite-rich zones.

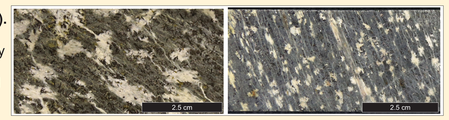


Figure 8C: Quartz Augen schist (3A).
A felsic quartz-crystal ignimbrite distinguished by bluish quartz porphyroclasts ranging in size from 1-10 mm. These units have a variable texture with some homogenous layers and some containing obvious lapilli fragments.

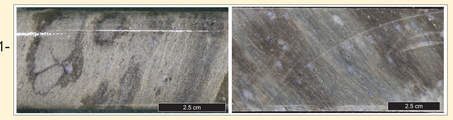


Figure 8D: Chlorite schist (4b/4c).
A well foliated, generally homogenous alteration unit. Variable abundance of stringer mineralization and spessartine garnets. Generally interlayered with the metadacite unit (5). Geochemically, this unit has mafic to intermediate volcanic protoliths.

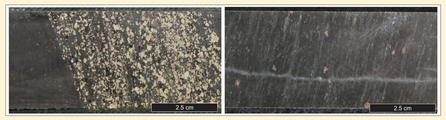
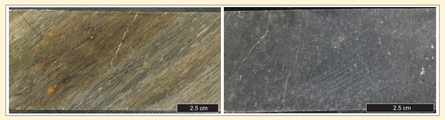


Figure 8E: Metadacite (5).
A green to purple colored, massive, variably foliated unit. Despite the name given by mine geologists, the protoliths consist of andesitic flows, tuff flows and lapilli tuffs.



Characteristics of Alteration

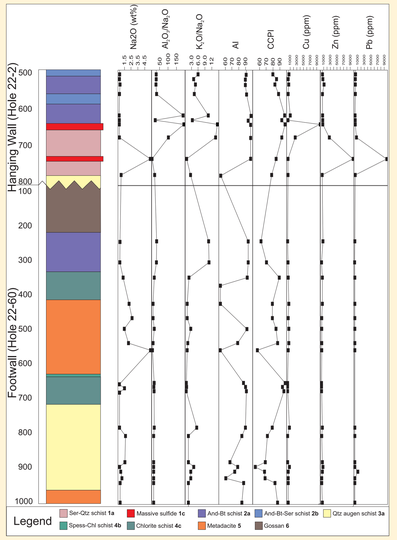
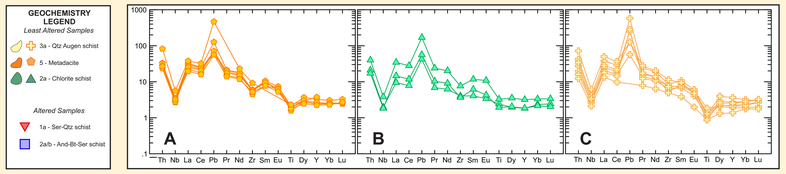


Figure 9: Downhole profiles of alteration indices for Flambeau host rocks.
Using a variety of geochemical alteration proxies and indicies (AI: Ishikawa, 1976; CCPI: Large et al., 2001) throughout the compiled stratigraphy, a thorough understanding of the temporal evolution of the hydrothermal system was possible. These indicies imply high levels of mobilization of various elements. The Ishikawa index measures the presence of K and Mn versus the mobility of Na and Ca and therefore the intensity of sericite and chlorite alteration. The Chlorite-Carbonate-Pyrite index measures the presence of Mn and Fe versus the mobility of Na and K and therefore the intensity of chlorite and carbonate alteration. Peaks in multiple geochemical alteration indicies may highlight potential additional ore horizons. The intense alteration found in the Flambeau hanging wall suggests sustained hydrothermal activity after the deposition of ore body.

Figure 10: Primitive mantle-normalized trace element diagrams for least altered units.
Normalized data (using values from Sun & McDonough, 1989) reveals an arc-dominated geochemical signature in mafic units (B) with prominent LREE enrichment, negative Nb and Ti anomalies, and enriched Th/La values. Felsic and intermediate units (A, C) have moderately enriched HREE and modest La/Yb ratios, characteristic of FII-type felsic suites.



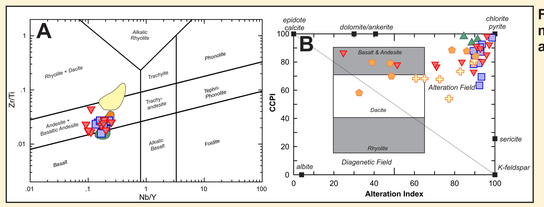


Figure 11: Classification of pre-metamorphic protoliths and alteration assemblages of rocks
(A) Classification plot (from Pearce, 1996) showing that altered samples appear to be compositionally similar to mafic-intermediate volcanic rocks. (B) Alteration assemblage plot (from Large et al., 2001) showing that volcanic rocks are dominated by chlorite-pyrite and sericite alteration assemblages.

Conclusions

Previous phases of geochemical analyses have shown that the Flambeau VMS deposit formed within a rifting arc geodynamic setting where a submarine volcanic arc was developing a back-arc rift center (Zens et al., 2015). However, stratigraphic context to the units and more historical compilation was needed.

After additional core logging and analyses, a comprehensive understanding of the stratigraphy of the Flambeau host rocks, their protoliths, and mineralization assemblages has been gained. Flambeau alteration and mineralogy assemblages are largely hosted in mafic-intermediate phases consistent with a rift setting. The majority of stringer mineralization downhole from the massive sulfide suggests that stratigraphy is upright and makes the original overturned hypothesis of May and Dinkowitz (1996) questionable. Additionally, the ore horizon appears to cross-cut stratigraphy. This suggests that the main ore horizon formed from sub-seafloor replacement rather than as a sulfide mound.

Acknowledgements

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