Geochemistry and Petrography of the Strata Hosting the Flambeau Cu-Zn-Au Deposit: Revisiting Wisconsin's only Past-producing Volcanogenic Massive Sulfide Mine

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Introduction

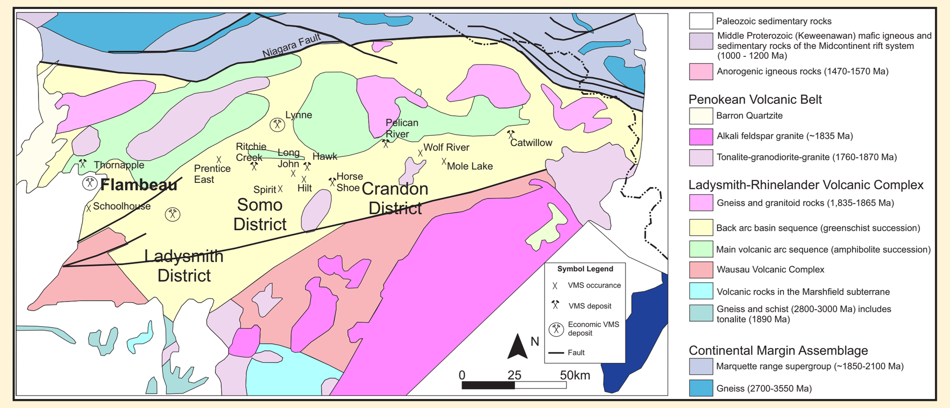


Figure 1: Precambrian geology of northern Wisconsin and Michigan showing the distribution of Cu-Zn-Au mineralization and major ore deposits.

The primary objective of this project is to complete a geochemical and petrographic study of the poorly understood Cu-Zn-Au mineralization hosted in Precambrian volcanic assemblages in northern Wisconsin. These deposits and their regional geological and economic significance have not been examined in any detail, despite almost 20 years of advancement in the fields of economic geology, geochemistry, and tectonics. These metallic mineral deposits are hosted in the Wisconsin Magmatic Terrane of the Penokean Orogen (DeMatties, 1994): a 1.8-1.9 billion year old volcanic arc sequence consisting of volcanic and sedimentary rocks, and associated mafic and felsic plutonic rocks.

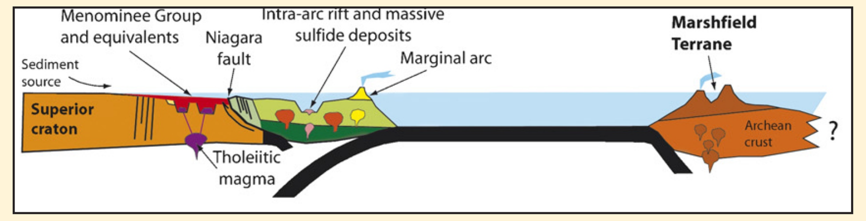


Figure 2: Reconstructed tectonic setting of the Penokean Orogen during the formation of metallic ore deposits in northern Wisconsin.

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 based on broadly collected geological data and provides little information on individual ore deposits. The spatial variation of geological and geochemical characteristics of the ore deposits and their host rocks will also provide a more detailed understanding of the tectonic history of Wisconsin and will contribute important information regarding the controversial metallic sulfide ore bodies and their potential impact on the economy and environment.

Volcanogenic Massive Sulfides (VMS)

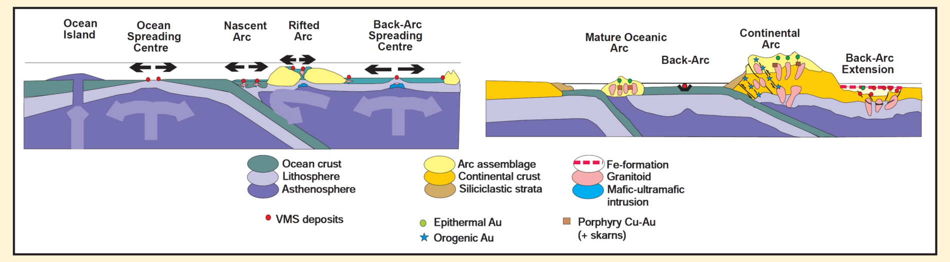


Figure 3: Metallogeny of volcanic arc tectonic settings.

VMS deposits are important sources of base and precious metals such as Cu, Zn, Pb, Au, and Ag and are associated with extensional tectonic settings. Extensional settings that host VMS deposits are those that are preserved during subduction and subsequent orogenesis: rifted submarine volcanic arcs and back-arcs (e.g. Galley et al., 2007). These settings can be identified in ancient rocks by comparing trace element geochemical characteristics with modern tectonic settings.

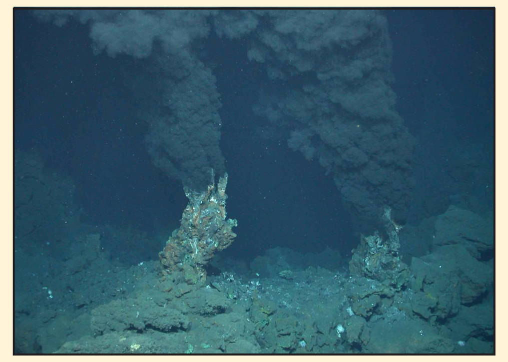


Figure 4: Black smokers on sea floor are modern analogs for ancient VMS deposits.

"Black smokers" near volcanically-active submarine rifts precipitate metalliferous sediments on or near the sea floor. Seawater is heated by synvolcanic intrusions lower in the crust and fluids reach temperatures in excess of 300°C. These fluids concentrate ores at the vent site.

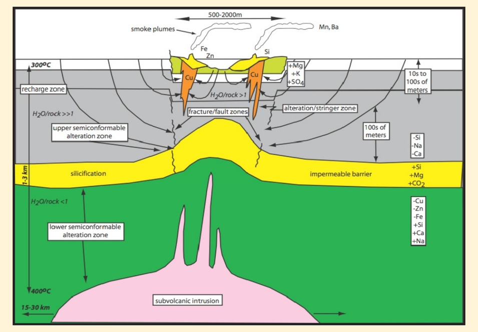


Figure 5: Hydrothermal fluids result in mobilization of elements in host rocks.

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 ores.

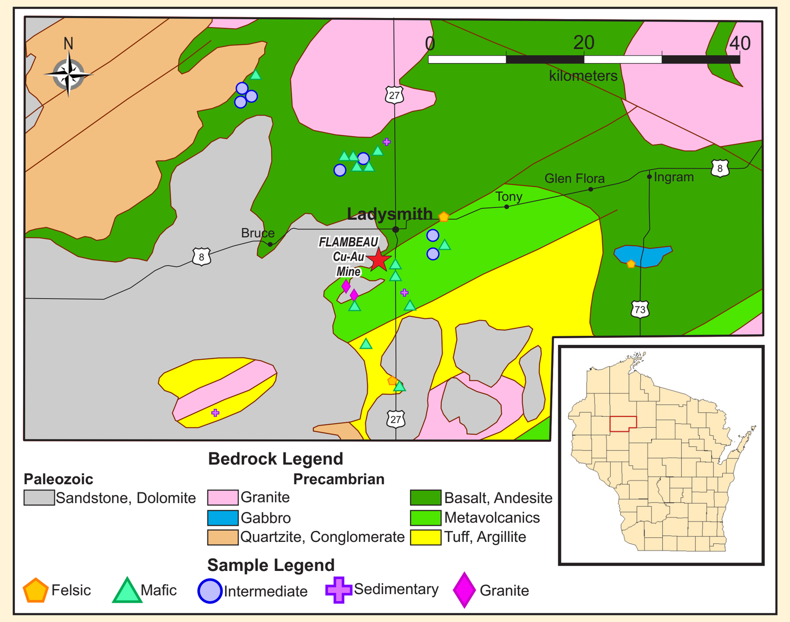
Study Area and Methods

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

The Flambeau deposit was mined between 1993 and 1997. Despite the fact that the Flambeau deposit was the only VMS in Wisconsin to have been extracted, a short mine life coupled with limited exposed bedrock yielded very little geoscience research. Because exposed outcrop in the region is rare, our research focused on drill cores obtained during exploration and mine development. Drill cores allowed for the development of a more complete stratigraphic model. These cores are held by the Wisconsin Geological and Natural History Survey in Mount Horeb, WI.

Major and trace element geochemistry of sampled cores were obtained from X-ray Flourescence analysis. Volatile amounts were measured using a Vulcan 3-550 for Loss on Ignition (LOI) tests.

Bedrock Geology of Rusk County



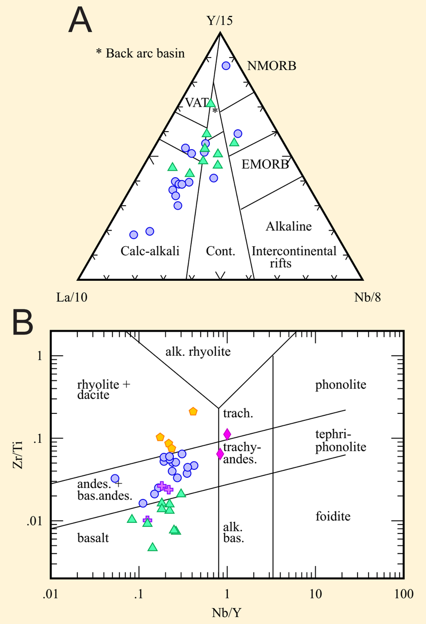


Figure 7: Regional bedrock geology of Rusk County, WI, showing location and composition of samples collected from drill core.

Rusk County has very limited Precambrian bedrock outcrops and the regional geological context of the Flambeau Mine is poorly constrained. Previous maps were completed using geophysical data and limited exposed rock. Using samples from drill core obtained during mineral exploration, an improved and more detailed geological map is being developed. This will provide a better understanding of the Precambrian geology of the region despite a cover of thick glacial sediments and younger sedimentary rocks.

Figure 8: Geochemical plots showing tectonic discrimination and rock classification for rocks collected from Rusk County.

(A) Plot showing variable tectonic affinities for mafic rocks throughout Rusk county. Trace element data for basalt and basaltic andesites show variation from arc-like ratios to rift- and ridge-like ratios. These affinities will be geospatially constrained to determine their regional tectonic significance. (B) Plot showing trace element classification of rocks.

Figure 9A: Felsic Volcanic Rocks

These rocks vary from quartz- and feldispar-phyric tuff and lapilli tuff. Texturally, they are variably foliated and are locally heavily hydrothermally altered to sericite.

Figure 9B: Intermediate Volcanic Rocks

These rocks consist of moderately foliated, bedded tuff to lapilli tuff that are locally altered to sericite. Minor chlorite-pyrite "stringers" indicate proximity to VMS.

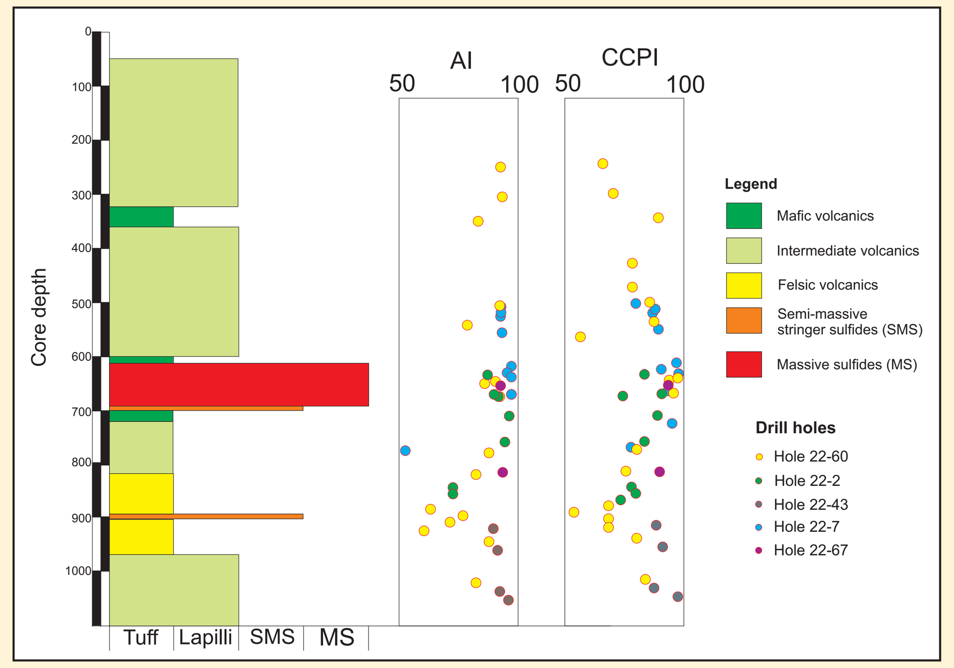
Figure 9C: Mafic Volcanic Rocks

These rocks include variably altered basalts, defined by deformed phenocrysts, spare/thin veins, and occasional spherical amygdules.

Figure 9D: Sedimentary Rocks

These rocks are defined by thinly bedded and laminated fine sandstones and siltstones. Sedimentary structures include load structures and graded bedding.

Geology of the Flambeau VMS deposit



Ishikawa (AI)

$$\frac{MgO + K_2O}{MgO + K_2O + Na_2O + CaO}$$

CCPI

$$\frac{MgO + FeO}{MgO + FeO + Na_2O + K_2O}$$

Figure 10: Stratigraphic representation of the Flambeau VMS deposit, showing how alteration varies with depth and between different cores.

With lithological and geochemical data, a stratigraphic column representing the average geology and alteration intensity of the Flambeau VMS deposit was developed. Two alteration indeces were used: the Ishikawa Alteration Index (AI; Ishikawa, 1976) and the Chlorite-Carbonate-Pyrite index (CCPI; Large et al., 2001). The AI measures the addition of Mg and K as chlorite and sericite and the depletion of Ca and Na by the destruction of feldspars. The CCPI measures addition of Fe and Mg as chlorite and pyrite and depletion of Ca and Na by destruction of feldspars. Because higher alteration indicates proximity to ore bodies, these indeces provide an exploratory model of the VMS deposit. Additionally, a plot of AI versus CCPI allows for the discrimination between different types of diagenetic and hydrothermal alteration.

Figure 11A: Felsic Volcanic Rocks

These rocks are light gray to green in color and have euhedral quartz phenocrysts. Volcanic facies vary from tuff to lapilli tuff with variable alteration.

Figure 11B: Intermediate Volcanic Rocks

These rocks are gray to green in color with rare quartz phenocrysts. They vary from tuff to lapilli tuff with chlorite and sericite alteration.

Figure 11C: Mafic Volcanic Rocks

These rocks are dark green to black. Mafic rocks were generally massive flows. Rocks are intensely chlorite and biotite altered with minor pyrite.

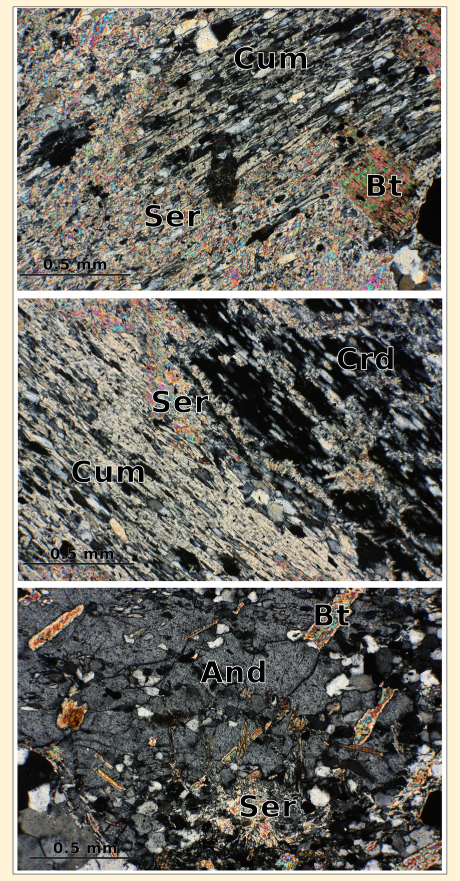


Figure 12A: Alteration of Felsic rocks

Felsic rocks in the immediate footwall to the ore deposit have been altered to sericite (Ser), cummingtonite (Cum), and porphyroblastic biotite (Bt).

Figure 12B: Alteration of Mafic rocks

Strongly altered mafic rocks contain porphyroblastic cordierite (Crd), cummingtonite (Cum), and sericite (Ser) mineral assemblages.

Figure 12C: Effects of Metamorphism

Primary hydrothermal alteration assemblages have basic major element geochemistry similar to pelitic rocks. When metamorphosed, mineral assemblages can include poikioblastic andalusite (And) with biotite (Bt) and sericite (Ser).

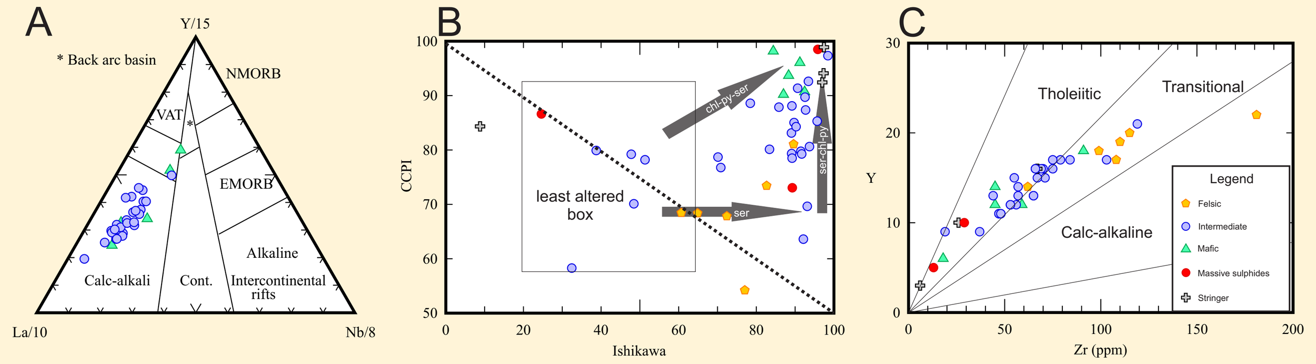


Figure 13. Geochemistry plots for tectonic discrimination and alteration characterization for rocks collected from the Flambeau deposit.

(A) Plot including only intermediate to mafic rocks (Pearce, 1996) showing the evolution from calc-alkalic (representing early arc-rifting) to back-arc basin (representing transitional to mature rifting). (B) Alteration plot discriminating between diagenetic (lower left corner) and hydrothermal (upper right) alteration and showing volcanic rocks with increasing sericite-chlorite-pyrite alteration. (C) Magmatic affinity classification showing evolution from arc-like, transitional affinity to rift-type, tholeiitic affinity.

Ore geology

Figure 14: Massive sulfides

Massive sulfide units are characterized by layered pyrite, sphalerite, galena, and chalcopyrite with chlorite and silica gangue.

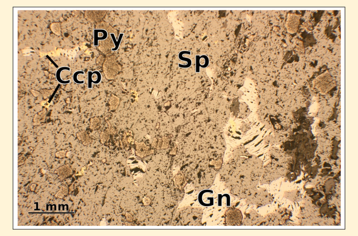


Figure 15: Ore minerals

Crystals of calcopyrite (Ccp), pyrite (Py) and galena (Gn) in a sphalerite (Sp) matrix all under reflected light.

Despite the Flambeau mine mainly producing Cu and Au, the primary, non-supergene ores observed in this study were Zn-rich. Future work will include Scanning Electron Microscopy to characterize the nature of host mineral assemblages for gold.

Conclusions

Geochemical data shows that the Flambeau VMS deposit formed under a rifting arc geodynamic setting where a submarine volcanic arc was developing a back-arc rift center. Alteration indices reveal that ore-forming sericite-chlorite-pyrite alteration was the dominant alteration process during the formation of the Flambeau orebody. The alteration chemostratigraphy indicates that ore-forming processes were not restricted to a singular VMS deposit but instead suggests the presence of several stacked deposits. Future work will involve examination of additional drill core from the Flambeau deposit to better constrain litho- and chemostratigraphy.

The study of the regional geology of Rusk County is evolving with additional core studies and field investigations planned for this summer to increase the amount of lithological and geochemical data across Rusk County. This additional work will significantly improve the knowledge of the ore-forming volcanic system that formed the Flambeau deposit and other VMS prospects in this part of Wisconsin during the Precambrian. Future research may reveal which portions of Wisconsin contain ore resources which are economical to obtain.

Acknowledgements

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