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Effects of paleoweathering and supergene activity on volcanogenic massive sulfide (VMS) mineralization in the Penokean Volcanic Belt, northern Wisconsin, Michigan and east-central Minnesota, USA: Implications for future exploration

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ABSTRACT

Three cycles of paleoweathering and supergene activity have been identified within the Penokean Volcanic Belt (PVB) of northern Wisconsin, Michigan and east-central Minnesota, USA. These cycles are responsible for significant subaerial weathering, erosion, oxidation and most importantly local supergene Au, Ag and Cu enrichment that has a major economic impact upon volcanogenic massive sulfide (VMS)-style mineralization within the PVB. The paleoweathering profile (regolith-saprolite) that developed on the exposed PVB surface now marks an angular unconformity with stratigraphically overlying, late Paleoproterozoic Baraboo Interval quartzites and late Cambrian sandstones.

Differential uplift of the PVB surface is a direct result of the ~1850 Ma compressional tectonic event that occurred during the Penokean orogeny. The uplifted PVB paleosurface experienced its first weathering cycle in the mid to late Paleoproterozoic. VMS mineralization near the paleosurface was exhumed and affected during this protracted cycle which ceased upon deposition of Baraboo Interval quartzites (1788–1714 Ma). Further uplift and subsequent unroofing of the quartzites during the Mazatzal orogeny (~1650–1630 Ma) initiated a second paleoweathering cycle that culminated within the Neoproterozoic – Cambrian transition. During this cycle of accelerated and uninterrupted paleoweathering, new and surviving supergene Au-Ag-Cu-enriched profiles geochemically matured over exhumed mineralized sections in terrains with favorable fault block movements. Supergene systems that developed during both cycles were highly acidic environments. Low protolith reactivity and high hypogene pyrite concentrations promoted acidity of supergene fluids thus facilitating enhanced Cu, Au and Ag mobility. In those systems that lacked sufficient carbonate, Zn and Pb were lost to surrounding aqueous regimes.

The second paleoweathering cycle ended with the deposition of overlying late Cambrian sandstone (497–485.4 Ma). Erosional retreat of the overlying Paleozoic sequence exposed many of these supergene deposits to a third, possibly brief paleoweathering cycle before the onset of Quaternary continental glaciation. VMS profiles not protected by sandstone outliers or within down-dropped fault blocks were glacially eroded.

Of the 14 or more known VMS deposits and occurrences in the belt, four have preserved or partially preserved paleoweathering profiles. The most significant are at the Flambeau and Back Forty deposits where Au-Ag-enriched indigenous gossans with extensive or local underlying supergene-enriched Cu sulfide zones have developed over hypogene massive sulfide horizons. These profiles demonstrate efficient cumulative or multicyclic Au, Ag and Cu-enrichment to ore grades.

Although commonly small (≤2 million tonnes), such supergene-enriched deposits are generally shallow, allowing for development by low cost open pit methods and production of exceptionally high-grade, direct shipping copper and/or gold ores. As such, the buried PVB unconformity is considered a prime exploration target that is highly prospective for new discoveries of commercially viable, supergene-enriched VMS resources.

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1. Introduction

The successful operation and closure of the Flambeau copper-gold mine in the 1990s coupled with the discovery of the large Back Forty zinc-gold deposit in 2001, repeal of Wisconsin's mining moratorium, and a recovery of metal prices have renewed economic interest in the Paleoproterozoic Penokean Volcanic Belt. Past exploration efforts by numerous major mining companies and junior explorers since the discovery of Flambeau in 1967 have identified over 150 million tonnes of volcanogenic massive sulfide (VMS) base and precious-metal mineralization, containing nearly 4.5 million ounces of gold, in 14 or more deposits/occurrences of which 4 are considered potentially economic (DeMatties, 2007). Exploration campaigns conducted by these companies generated voluminous amounts of geologic and geophysical data, which combined with limited academic field studies, were the basis of establishing a geologic framework. This tentative working model assisted further exploration within this poorly exposed but highly productive greenstone belt (LaBerge, 1996; DeMatties, 1994, 1996, 1997). A detailed treatise of PVB geology and mineralization is presented by LaBerge (1996). More recent academic studies of the belt have been completed by Quigley et al. (2016) involving reinterpretation of regional magnetic and gravity data supported by major and trace element geochemical analyses and high precision U-Pb dating of selected outcrop and mineralized drill core samples.

One outstanding characteristic of this belt is that known VMS deposits and occurrences have been affected to various degrees by paleoweathering and cumulative supergene enrichment. Preservation of supergene profiles over VMS deposits is very rare in the extensively glaciated Canadian Shield. Secondary enrichment can produce high-grade, direct shipping gold and copper ores, as was the case at Flambeau (Flambeau Mining Corporation, 1976; Flambeau Mining Inc., 1990). Although commonly small (≤ 2 million tonnes) in tonnage, these elusive but highly profitable and environmentally benign deposits are regarded by most geologists who have worked in the belt as premier exploration targets. Generally considered more politically and socially acceptable, such deposits have a more than reasonable chance of successful mine development under today's strict regulatory permitting system.

This contribution reviews the geologic framework of the Paleoproterozoic Penokean Volcanic Belt and attempts to characterize

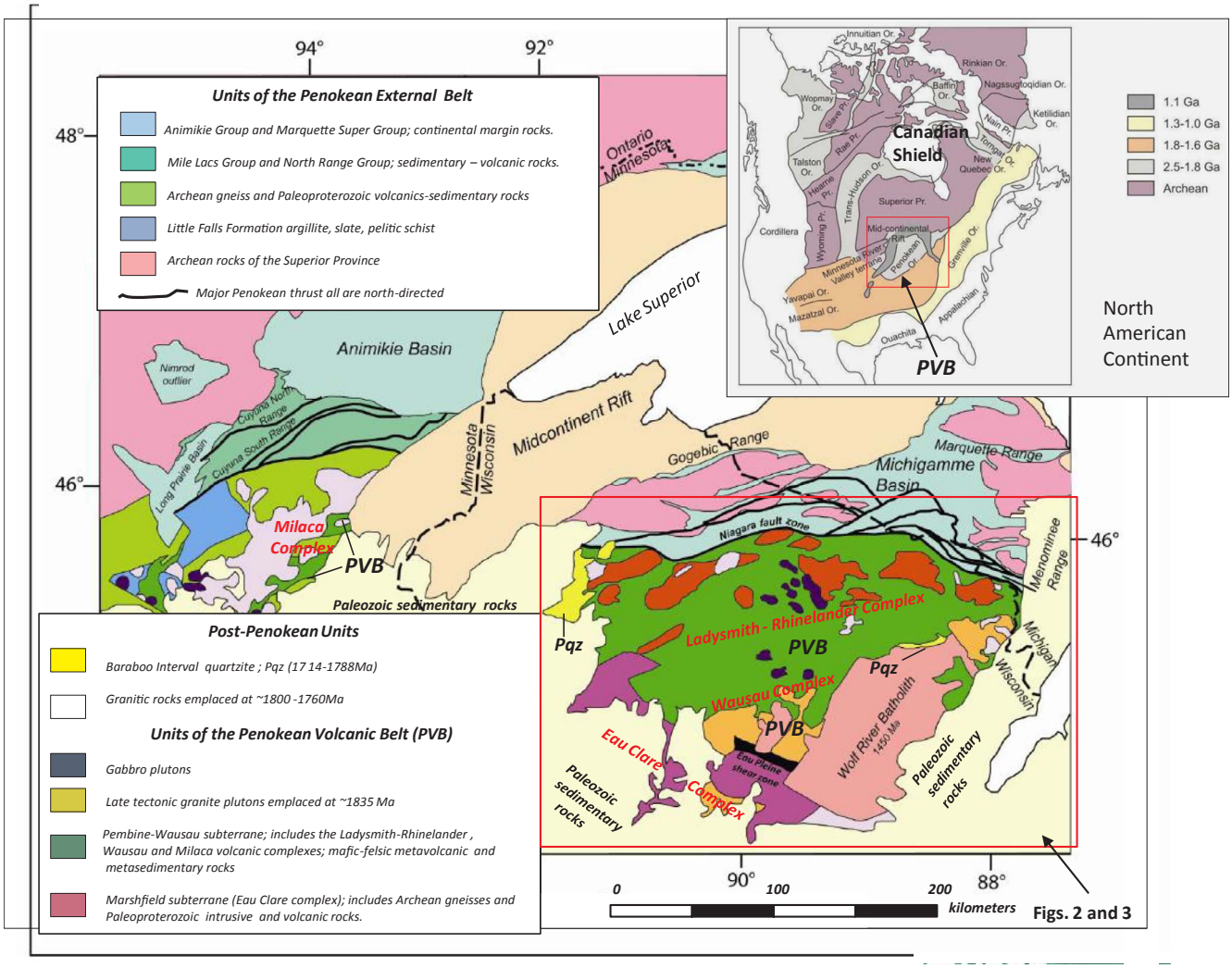

Fig. 1. General geologic location maps of the Penokean orogeny and Penokean Volcanic Belt (modified from Hoffman, 1989; Schultz and Cannon, 2007).