

# The Evolution of Troctolitic and High Al Basaltic Magmas in Proterozoic Anorthosite Plutonic Suites and Implications for the Voisey's Bay Massive Ni-Cu Sulfide Deposit

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## Abstract

The Voisey's Bay massive Ni-Cu sulfide deposit is contained within troctolitic (plagioclase + olivine) intrusions of the 1.34 to 1.29 Ga Nain Plutonic Suite, coastal Labrador, Canada, and represents a new setting for magmatic sulfide deposits. Proterozoic anorthosite plutonic suites consist of vast quantities (as much as 20,000 km<sup>2</sup>) of cumulate anorthosite-leucotroctolite-leuconorite, intrusions of troctolite and Fe-enriched dioritic rocks, and large granitic batholiths. Crystallization ages span nearly 1,200 m.y. within the Middle Proterozoic (2.12–0.92 Ga). Many Proterozoic anorthosite plutonic suites were emplaced into relatively young Proterozoic crust and some were intruded along Archean-Proterozoic boundaries (e.g., Nain, Labrador; Laramie, Wyoming; Korosten, Ukraine). Nearly all of the largest plutonic suites contain significant areas (thousands of km<sup>2</sup>) of plagioclase-rich cumulate rocks that are olivine bearing (olivine anorthosite-leucotroctolite). Troctolitic rocks (20–30% modal olivine) occur in Proterozoic anorthosite plutonic suites, principally as cumulates in layered or massive intrusions (e.g., Kiglapait, Hettasch, Jonathon–Nain) intruded into anorthositic rocks. With the notable exception of the Voisey's Bay deposit, nearly all troctolitic rocks crystallized late in the evolution of individual plutonic suites. Many of the troctolitic intrusions have fine-grained olivine-rich marginal rocks that closely represent parental magma compositions. Numerous fine-grained olivine-normative dikes with high Al basaltic compositions also occur within many plutonic suites (Nain, Harp Lake, Laramie, Adirondack) and share compositional characteristics with the troctolitic magmas. These olivine-normative high Al basaltic magmas record the least evolved compositions in Proterozoic anorthosite plutonic suites (Mg# = 0.43–0.64; An = 45–60), have high Al<sub>2</sub>O<sub>3</sub> (15–19 wt %) and FeO<sub>total</sub> (9–15 wt %) contents, and typically show the least contaminated Sr and Nd isotope compositions in a given plutonic suite. Many dikes and marginal rocks have strong positive Eu anomalies, a feature of the melt composition that is not related to plagioclase accumulation. Except at Laramie, the least evolved troctolitic magmas appear to have about 8 wt percent MgO and corresponding Ni and S concentrations between 100 to 150 ppm and 0.02 to 0.05 wt percent, respectively. Based on closed-system fractionation in the Kiglapait intrusion, sulfide saturation occurs late in the crystallization history of troctolitic magmas, after Ni concentrations have been severely depleted by protracted olivine fractionation. The optimal conditions for formation of a Ni-Cu sulfide deposit associated with a Proterozoic anorthosite plutonic suite require a relatively high MgO parental magma that has not crystallized much prior olivine and an external source of S to promote early sulfide saturation, probably through desulfurization reactions as hot troctolitic magmas ascend through the crust. An economically important massive Ni-Cu sulfide deposit on the scale of Voisey's Bay clearly requires large volumes of magma, probably involving continuous replenishment of relatively Ni rich, unfractionated parental magma in staging chambers or mixing between magmas in conduits during ascent. A model for the formation of troctolite-associated massive Ni-Cu sulfide deposits is proposed. Depending on the relative degrees of sulfide saturation and fractionation of the mixed magmas, mixing between troctolitic magmas in a conduit or magma chamber may either poison the system, stopping sulfide segregation, or enhance sulfide segregation.