Stable Isotopic Constraints on the Nature of Fluids that Affected Stratiform PGE Mineralization in the Sonju Lake Intrusion, Northeastern Minnesota

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The Sonju Lake intrusion (SLI) is located in northeastern Minnesota, and is part of the Beaver Bay Complex which formed during the development of the ~1.1 Ga Midcontinent Rift system. In the 9 km^2 area where it is exposed the SLI is 1200 m in thickness, and consists of a layered series of well-foliated mafic cumulates that is enclosed between a lower contact zone of melatroctolite and an upper zone of olivine monzodiorite. Five units are distinguished within the layered series on the basis of successive cumulus arrivals of olivine (dunite), plagioclase (troctolite), augite (gabbro), Fe-Ti oxides (Fe-Ti oxide gabbro), and apatite (apatite olivine diorite). Smooth cryptic variations in the compositions of both olivine and augite formed during continuous primocryst mineral accumulation at the floor of the magma chamber. The data suggest that the SLI did not experience significant episodes of recharge, eruption, or assimilation (Miller and Ripley, 1996; Miller, 1999). The top of the SLI shows a gradational contact with the Finland granite, and may reflect partial melting of country rock along the roof zone of the intrusion (see below).

Geochemical data reported by Miller (1999) indicate that sharp increases in Cu, Pd, and Pt occur near the middle of the Fe-oxide gabbro (Fig. 1). As is the case in other tholeiitic intrusions that show reef-style Pt-Pd enrichments, the peaks in Pd and Pt concentrations fall just below that of Cu. The peak in S concentration (Fig. 1) occurs from 100 to 150 m above that of Cu. Miller (1999) suggested that the enrichment in Pt, Pd, and Cu occurred due to fractional crystallization and the attainment of sulfide saturation in the magma. The offset in S relative to Cu was thought to be the result of S dissolution via a deuteric fluid. An alternative mechanism would be the chromatographic accumulation of PGE and base metals via reaction between crystallized minerals and a fluid phase percolating upward in the crystal pile (Boudreau and Meurer, 1999).

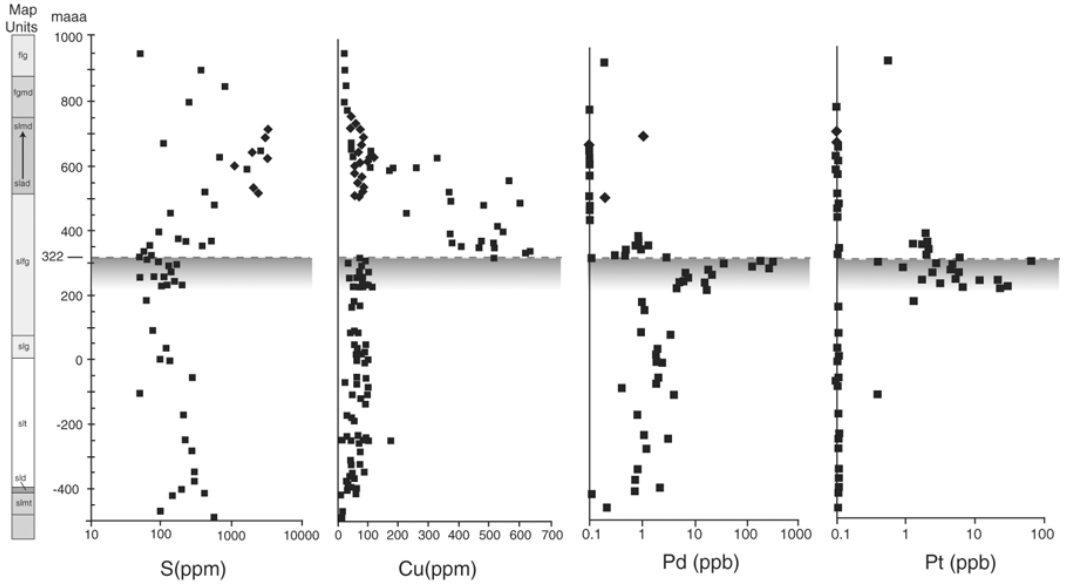

Figure 1. *Pd, Pt, S and Cu concentrations in the Sonju Lake Intrusion. Abbreviations: slmt – melatroctolite; sld – dunite; slt – troctolite; slg – gabbro; slfg – Fe-oxide gabbro; slad – apatitic olivine diorite; slmd – monzodiorite; fgmd – Finland quartz monzodiorite; flg – Finland granite. After Miller (1999).*

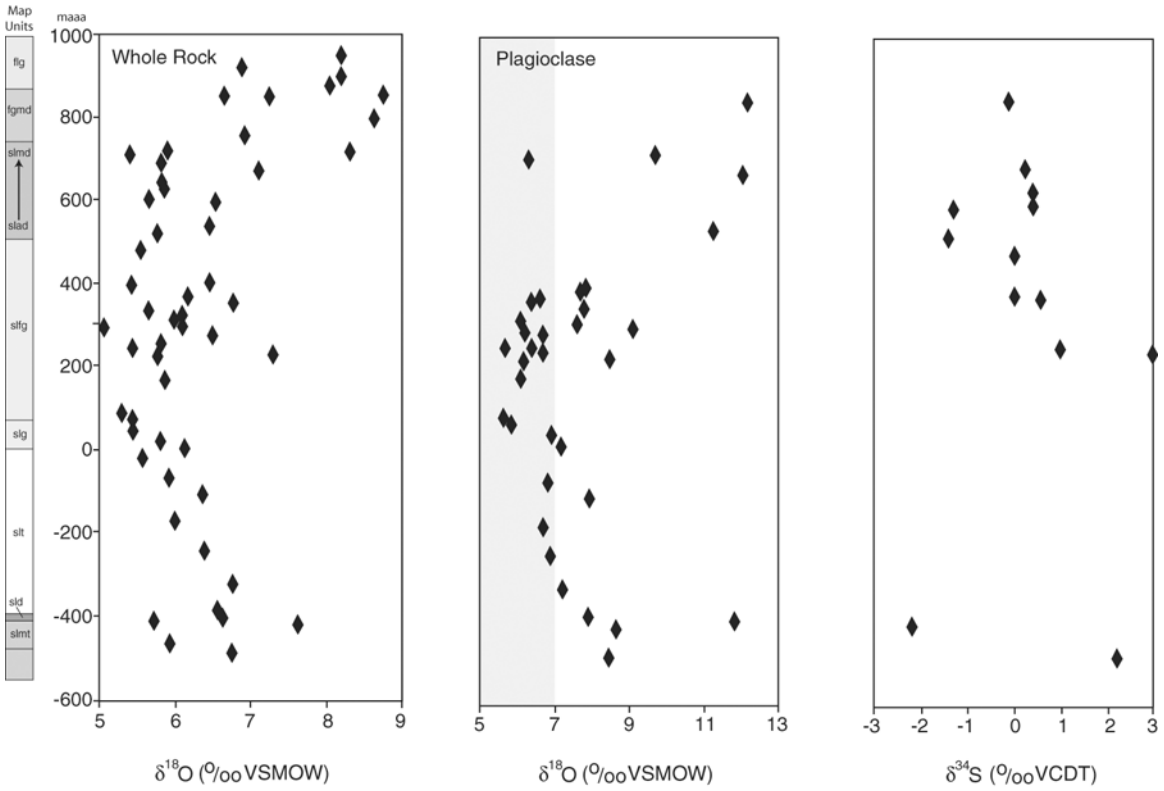

Figure 2. *$\delta^{18}O$ - whole rock, $\delta^{18}O$ - plagioclase, and $\delta^{34}S$ in the Sonju Lake Intrusion.*

Stable isotopic studies of the SLI were initiated to investigate possible variations in $\delta^{18}O$ values related to crystal fractionation and incompatible element enrichment, as well as to evaluate the possible importance of a fluid phase in the Cu-Pt-Pd enrichment observed in the SLI. $\delta^{34}S$ values of sulfide minerals in the SLI range from -2.2 to +3.0‰, and are in the range of mantle-derived sulfur. The values differ strikingly from those of Cu-Ni mineralization in basal troctolitic sheets of intrusions in the Duluth Complex where the external addition of S is strongly indicated. Sulfur isotopic compositions lend support to the interpretation that the SLI represents near closed system crystallization of a mantle-derived magma without significant crustal contamination.

Whole rock $\delta^{18}O$ values of the SLI range from 4.7 to 8.3‰, and those from the Finland granite range from 6.6 to 9.8‰ (Fig. 2). SLI whole rock $\delta^{18}O$ values in excess of 7‰ occur near top or bottom contacts of the intrusion, or near monzodioritic dikes. These values could reasonably be attributed to interaction with high-^{18}O country rocks. Whole rock values between 5 and 6.5‰ are not atypical for rocks that have crystallized from mantle-derived mafic magma. However, $\delta^{18}O$ values of plagioclase separates from all units of the SLI show ^{18}O-enrichment, and range from 5.6 to 12.0‰. Plagioclase $\delta^{18}O$ values tend to be highest near the margins of the intrusive (Fig. 2). The elevated $\delta^{18}O$ values are indicative of interaction with an externally derived fluid of relatively low-^{18}O content. At temperatures less than ~300^{N}C elevated plagioclase $\delta^{18}O$ values are possible by exchange with a fluid of $\delta^{18}O$ less than ~3.5‰. Park and Ripley (2001) determined that a fluid with $\delta^{18}O$ between 3 and 6‰ interacted with lavas of the nearby North Shore Volcanic Group. Whole rock $\delta^{18}O$ values tend to lie in the "normal" mantle range because of the presence of low ^{18}O minerals such as Fe-Ti oxides, or because of the low modal abundance of plagioclase (e.g. as an interstitial mineral in dunite).

Although oxygen isotopic values of plagioclase clearly indicate that subsolidus exchange with a low-temperature fluid of probable meteoric origin has occurred, it unfortunately remains difficult to evaluate the competing hypotheses for PGE enrichment in the SLI. In the

area of the reef the offsets between Cu, S, and Pt+Pd may be due to secondary, subsolidus processes related to interaction with a low-temperature, externally-derived, fluid. Local enrichments in pyrite within the reef zone, which is itself partially converted to goethite, suggests that the SLI may have experienced multiple stages of secondary processes and interaction with extern-ally-derived fluids. Clearly, cryptic variations in the cumulus silicate minerals suggest that these minerals may have escaped any chemical alteration as a result of such interaction. Therefore it remains feasible that the offsets observed between Pt + Pd and Cu record a primary process. This may not be the case for the offset between S and Cu. Additional petrographic and isotopic studies are in progress to further evaluate the PGE and isotopic anomalies exhibited by the SLI.

References

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