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Chemical Evolution and Origin of Nickel Sulfide Mineralization in the Sudbury Igneous Complex, Ontario, Canada

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Abstract

The Sudbury Igneous Complex is widely believed to be the result of melt generation due to meteorite impact, and the Ni and Cu ores associated with the sublayer and offsets of the complex are considered to be a consequence of this event. The noritic and granophyric rocks of the main mass have similar yet elevated ratios of large ion lithophile elements (LILE) and light rare earth elements (LREE) relative to high field strength elements (HFSE) and heavy rare earth elements (HREE). This indicates that the magma was homogenized in terms of the incompatible trace element ratios and had a large chemical and isotopic contribution from an upper crustal source. Through the mafic and felsic norite there is an upward decline in MgO (14.6–4.4 wt %) and a small increase in incompatible element abundance (Ce = 35–50 ppm). The granophyre becomes slightly more evolved from the top toward the base (MgO = 0.6–2 wt %; Ce = 90–120 ppm). Some of these variations may be due to differentiation, but we believe that the crystallization of the original melt took place from the base upward and the top downward; this implies that the melt sheet was fundamentally density stratified into noritic and granophyric layers. Estimates of the bulk composition of the melt sheet are within the range of quartz diorite from the different Sudbury offsets, and we believe that all of these rocks are the products of impact-triggered melting of upper crustal rocks of the Sudbury region.

Mafic norite from the base of the Sudbury Igneous Complex has 1 to 5 modal percent pyrrhotite, plus chalcopyrite and elevated Ni (40–1,000 ppm) and Cu (40–1,140 ppm); this is overlain by felsic norite, which contains trace pyrite, and low Ni (15–40 ppm) and Cu (7–40 ppm). For a similar range of MgO, the upper portion of the felsic norite unit has 5 to 10 times lower Ni and Cu than within-plate basalts and crustal rocks. There is an increase in Ni (1–5 wt %) and Cu (1–5 wt %) tenor of sulfide toward the base of the norite sequence. The depletion of the upper part of the felsic norite in Ni, Cu, and platinum group elements (PGE) is most likely due to equilibration of the magma with magmatic sulfide and accumulation of the dense sulfide liquid to the base of the melt sheet. The parental magmas giving rise to these disseminated sulfides contained ~210 ppm Ni and 109 ppm Cu based on realistic partition coefficients and magma/sulfide ratio; the process of sublayer and offset ore formation did not entirely strip the Ni, Cu, and PGE from the main mass.

About 40 percent of the total Ni-Cu-PGE inventory of the Sudbury Igneous Complex is related to quartz diorite in offset dikes and Sudbury breccia belts. The marginal sulfide-free quartz diorite of the Worthington offset has a Ni and Cu abundance that is similar to crustal rocks over the same range in MgO content (3–6 wt % MgO). We believe that the quartz diorite initially formed from an S-undersaturated magma that was injected downward away from the melt sheet. The Worthington offset quartz diorite averages 83 ppm Ni and 98 ppm Cu, which is similar to sulfide-poor quartz diorite from the other offsets (Lightfoot et al., 1997b). Saturation of the melt sheet in S was achieved shortly after the injection of the quartz diorite magmas but before the center of the offset had entirely crystallized. The presence of immense resources of magmatic sulfides in the Copper Cliff offset, with sulfide metal tenors of ~13 wt percent Cu, ~6 wt percent Ni, ~18 ppm Pt, and high Pd/Ni, indicates that these sulfides formed early and from a parental magma with a Ni/Cu ratio of ~1. The parental magma is calculated to have contained 310 ppm Ni and 311 ppm Cu, and this is not characteristic of the bulk crustal melt. Presumably density segregation accompanied or predated sulfide saturation in the melt sheet, and this mechanism provides a way to produce a more metal-rich parental magma with a Ni/Cu ~1.

The formation of the geologically complex and heavily contaminated sublayer is believed to either accompany or postdate offset formation. The sublayer at the Whistle and Creighton mines occupies embayment structures at the base of the Sudbury Igneous Complex, which are directly connected to small

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offsets. Ores from the Creighton embayment have sulfide metal tenors of ~7 wt percent Cu, ~5 wt percent Ni, and a lower Pd/Ni than the offset ores. Calculated parental magmas would have 265 ppm Ni and 172 ppm Cu, which indicates that the metals were not all removed by the formation of offset ores.

Mass-balance calculations show that there is more than enough Ni and Cu in the initial melt sheet to produce all of the known sulfide deposits at Sudbury. In this model there is no requirement for metal contributions from mantle sources or from protores. The mineral potential of offset and embayment structures appears to be empirically linked to the thickness of the overlying noritic rocks, and this is consistent with our model.