Olivine and S Isotope Systematics of Ore-Bearing Intrusions at Noril'sk, Siberia

C. Li[1], E. M. Ripley[1] and A. J. Naldrett[2]
[1] Department of Geological Sciences, Indiana University, Bloomington, IN 47401, USA
[2] Department of Geology, University of Toronto, Toronto, Ontario, M5S 3B1 Canada
E-mail: cli@indiana.edu

Introduction

The Ni-Cu-PGE ore-bearing intrusions of the Noril'sk area such as the Noril'sk I and the Main and NW Talnakh intrusions have been recognized to be comagmatic with the voluminous Permo-Triasic Siberian Traps flood basalts (Lightfoot et al., 1992; Naldrett et al., 1992; Czamanske et al., 1994; Fedorenko, 1994). These intrusions contain at least 50 times more sulfides than the magmas represented by their rocks could have dissolved (Naldrett et al., 1992). Although there is a common consensus that much of the sulfides and their metals were possibly derived from the associated lavas as well as the intrusive rocks, opinions as to where the sulfide segregation took place are still divided. Naldrett et al. (1995, 1996), Lightfoot and Hawkesworth (1997) and Naldrett and Lightfoot (1999) have proposed that the ore-bearing intrusions were volcanic feeders in which immiscible sulfide liquids segregated and reacted with continuous surges of magmas *en route* to the surface. Others have suggested that the ore-bearing intrusions are blind sills formed by sulfide-laden magmas derived from a dynamic staging magma chamber (Naldrett et al., 1992; Brügmann et al., 1993; Naldrett and Lightfoot, 1993; Lightfoot et al., 1994) or a series of staging magma chambers (Fedorenko, 1994). This study is concerned with the systematic variations of olivine and S isotopic compositions that can be used to discriminate these two competing genetic models.

Types of olivine and their compositional variations

Olivines from the ore-bearing intrusions occur as (1) inclusions in augite and plagioclase oikocrysts (Fig. 1); (2) discrete grains with granular or subpoikilitic pyroxenes and plagioclase, and interstitial sulfides; and (3) poikilitic crystals enclosing pyroxenes and plagioclase. There is a special type of olivine that occurs as olivine-rich schlieren and masses referred to as "olivinites" by many Russian geologists.

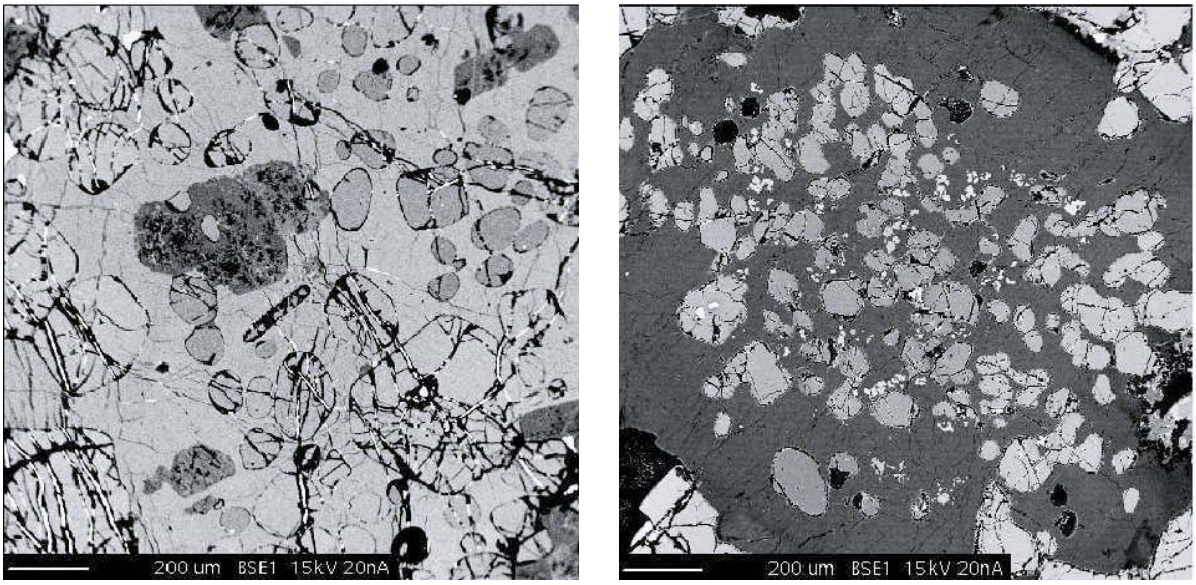

Figure 1. *BSE images showing olivine inclusions in augite (left) and plagioclase (right)*

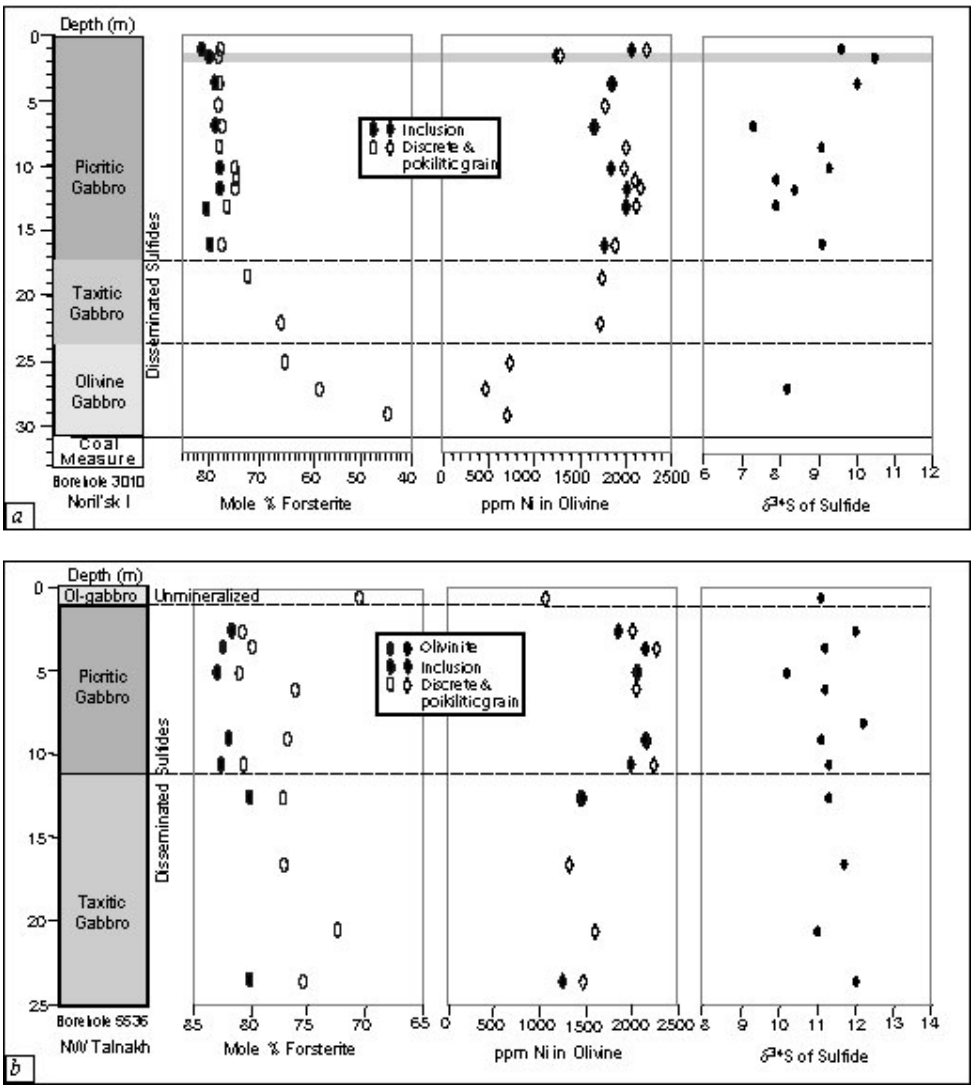

Figure 2. *Stratigraphic variations of olivine and S isotopic compositions at Noril'sk (a) and Talnakh (b).*

.

The compositional relationships between olivine inclusions and coexisting discrete olivines are different in sulfide-poor (<0.3 wt.% S) and sulfide-bearing samples. In sulfide-poor samples, olivine inclusions contain higher Fo and Ni than coexisting discrete olivines, consistent with the results of fractional crystallization. In sulfide-bearing samples, discrete olivines also have lower Fo contents than coexisting olivine inclusions. However, the Ni contents of the discrete olivines are higher instead of lower. In addition, the discrete olivines together define an inverse Ni-Fo relationship that apparently has resulted from subsolidus re-equilibration of olivine with trapped sulfide liquid. The difference in olivine composition between an olivinite and its sulfide-bearing gabbroic host is similar to the difference between olivine inclusions and coexisting discrete olivines in the sulfide-bearing samples.

The main points inferred from the compositional variations of different types of olivine are summarized below: (1) olivine inclusions were early cumulus crystals that have been largely protected by their host oikocrysts from re-equilibration with trapped silicate and/or sulfide liquids; (2) olivinites were either cognate inclusions of early olivine cumulates or they represent *in situ* segregation of cumulus olivine aggregates; and (3) discrete and poikilitic olivines crystallized later and their compositions were variably modified by trapped silicate and/or sulfide liquids.

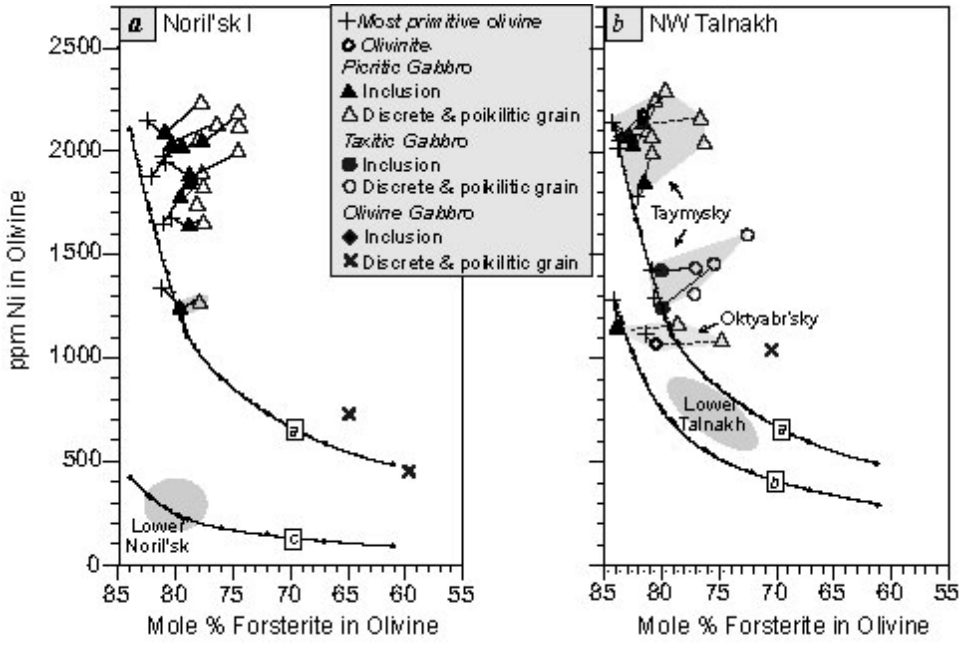

Figure 3. *Modeling of olivine fractionation. a. Noril'sk I and Lower Noril'sk intrusions. b. NW Talnakh and Lower Talnakh intrusions. See text for discussions.*

Stratigraphic variations of S isotopic and olivine compositions

Fig. 2a illustrates the stratigraphic variations of olivine and S isotopic compositions in borehole 3010 in the northern part of the Noril'sk I intrusion. The Fo contents of olivines from the olivine gabbro unit decrease downward from 67 mole % to less than 45 mole %. In the overlying taxitic gabbro unit, the Fo contents of olivines are slightly higher and appear to extend the trend of the gabbro unit. But the Ni contents of olivine in the taxitic gabbro unit are much higher, varying between 1700-1900 ppm. In the picritic gabbro, olivine inclusions contain Fo up to 81 mole %. The Fo variations of olivine inclusions from this unit are rather small, mostly less than 3 mole %. The Fo contents of discrete olivines are several mole % less than coexisting olivine inclusions. The contents of Ni in both olivine inclusions and coexisting discrete olivines display an inverse correlation with their Fo contents. Olivines from a sample close to the top of the unit have much lower Ni contents than others from this unit, which may be related to lower Ni content in the sulfide. The content of Ni in the bulk sulfide of this sample is 7 wt%. The contents of Ni in other samples of this unit vary mostly between 9 and 12 wt%. The $\delta^{34}S$ values of the samples from this borehole vary between 7.9 and 10.5 ‰. Within the picritic gabbro unit, the sample with low Ni content in olivine has a higher $\delta^{34}S$ value than other samples.

The stratigraphic variations of olivine and S isotopic compositions in borehole 5536 located at the Taymysky Mine in the northern part of the NW Talnakh intrusion is shown in Fig. 2b. The $\delta^{34}S$ values of sulfides from different rock units in this borehole are similar, varying between 10.2 and 12.2 ‰. In contrast, olivines from different units have distinctly different compositions. Olivines from the picritic gabbro unit are the most primitive and have the highest Ni contents. Olivines from the underlying taxitic gabbro unit have slightly lower Fo contents and significantly lower Ni contents. Olivines from the top olivine gabbro unit are the most evolved and have the lowest Ni contents.

In summary, there are significant discontinuities of olivine compositions, particularly Ni contents, at the contacts of different rock units in the Noril'sk I and Talnakh intrusions. In contrast, the stratigraphic variations in S isotopic compositions are only subtle or minor. This is only explicable if multiple magmas with distinctly different Ni contents and similar S isotopic compositions were involved in the development of the intrusions.

Comparison of different intrusions

The compositions of olivine from different intrusions are compared in Fig. 3. The model curves represent the compositional variations of the olivines expected to crystallize from magmas with variable initial Ni contents and the same major element com-

positions during fractional crystallization. The model lines labeled *a*, *b* and *c* represent initial Ni contents of 300, 180 and 60 ppm, respectively. The major element compositions are from the average values of the Noril'sk-type sills given by Zen'ko and Czamanske (1994). The simulation of crystallization was performed for 1 kb at the QFM buffer using the silicate liquid model MELTS of Ghiorso and Sack (1995). Olivine is predicted to crystallize at 1230 ^{o}C. Plagioclase starts to join olivine at 1198 ^{o}C, and clinopyroxene starts to join both olivine and plagioclase at 1175 ^{o}C. This crystallization sequence is in good agreement with petrographic observation. Nickel fractionation was calculated assuming that D^{Ni} for olivine, clinopyroxene and plagioclase are 7, 1 and 0, respectively.

Olivine inclusions from the Noril'sk I intrusion have Fo contents similar to the same type of olivine from the Lower Noril'sk intrusion, but have much higher Ni contents and thus require a much higher initial Ni content in magma (300 ppm, line *a* versus 60 ppm, line *c*). It is seen that 5% crystallization in accordance with the model of 300 ppm initial Ni in magma accounts well for the most primitive olivines from the Noril'sk I intrusion, except for one sample which has a much lower Ni content and falls closer to the model line at >20% of crystallization. The displacement of the coexisting discrete olivines to the right can be attributed to reaction with trapped silicate liquid and/or sulfide liquid. Olivines from the olivine gabbro unit of the Noril'sk I intrusion are broadly consistent with the modeled compositions after >50% crystallization.

Compared to the Noril'sk I intrusion, the contents of Fo in olivine inclusions from the picritic gabbro unit of the NW Talnakh intrusion at Taymysky are slightly higher (Fig. 5b). Most of the olivine inclusions from this unit fall closer to the model of 300 ppm initial Ni in magma at <5% crystallization. The olivine inclusions from the taxitic gabbro unit of the NW Talnakh intrusion at Taymysky are more fractionated and fall near the model line at 10-12 % crystallization. Olivine inclusions from the picritic gabbro unit of the NW Talnakh intrusion at Oktyabr'sky have significantly lower Ni contents than the same type of olivine from the same type of rock unit at Taymysky, and require a much lower initial Ni content in magma (180ppm, line *b*). Olivines from the olivinites have compositions similar to the olivine inclusions from the same rock units. Similar to the Noril'sk I intrusion, there are notable displacements to the right for the discrete olivines from the NW Talnakh intrusion, possibly due to re-equilibration with trapped silicate liquid and/or sulfide liquid. Olivines from the Lower Talnakh intrusion plott slightly to the right of the model *b* fractionation trend (180 ppm initial Ni content in magma).

Lower Ni contents in olivine from the Oktyabr'sky mine than from the Taymysky mine are coupled with lower Ni, Cu and PGE contents in their associated sulfide ores. At Oktyabr'sky, the bulk sulfide ores of the picritic gabbro unit contain 2.0-3.6 wt% Ni, 5.2-9.4 wt% Cu and 8-19 ppm Pd (Naldrett et al., 1996). At Taymysky, the bulk sulfide ores of the same rock unit intercepted by borehole 5536 contain 3.6-9.3 wt% Ni, 7.1-11.5 wt% Cu and 15-28 ppm Pd. It seams that a higher R-factor would explain the higher chalcophile element contents in the sulfide ores at Taymysky. But this is not supported by the similar sulfur isotopic compositions at both locations. Similarly, the disseminated sulfides in the different rock units at Taymysky are also not related to each other by different R-factors. The content of Pd in the bulk sulfide of a sample from the olivine gabbro unit is <4ppm, which is >3 times less than the contents of Pd in the bulk sulfides of the underlying picritic gabbro unit. The $\delta^{34}S$ values of the sulfides from these two units however, are similar and all close to ~11 ‰.

The main conclusions from the proceeding discussions are summarized below: (1) with respect to major element compositions, the parental magmas of the picritic gabbro units of the Noril'sk and Talnakh intrusions were similar; (2) with respect to Ni contents, however, the parental magma of the picritic gabbro unit at Oktyabr'sky was significantly depleted in Ni as compared to that of the same type of rock unit at Taymysky and Noril'sk (180 versus 300 ppm); and (3) the disseminated sulfides in the same type of rock units in different intrusions, as well as in different rock units of a single borehole, were often not related to each other by different *R*-factors. Rather, compositional differences appear to be related to emplacement of multiple magmas that contained sulfide liquids with similar S isotopic compositions but significantly different chalcophile element concentrations.

Summary

Our S isotopic and olivine data are more consistent with the interpretation that sulfide segregation occurred in staging chambers. The sulfide liquids were then episodically upgraded in their chalcophile element concentrations by new surges of magmas into the chambers. Some of these sulfide magmas were simultaneously transported by the episodic surges of magmas to higher levels to form the composite sills of the ore-bearing intrusions.