Introduction

The focus of current debate on the genesis of Ni-Cu-PGE sulfide ores in several subvolcanic intrusions, including the Kharaelakh intrusion in the Noril’sk-Talnakh region, Siberia, is on the contributions of chalcophile elements from the coeval flood basalts. A research group led by Naldrett (Naldrett, 1992; Naldrett et al., 1992, 1996; Naldrett and Lightfoot, 1999) proposed a conduit model that emphasizes a direct link between the ore-bearing intrusions and a specific suite of the coeval lavas (i.e., the Nadezhdinsky suite) that is depleted in chalcophile elements including Ni, Cu, Au, and platinum-group elements (PGE; Brügmann et al., 1993; Lightfoot and Keays, 2005). The various versions of the conduit model have been criticized by other researchers because of differences between the intrusive and extrusive rocks shown by liquidus phase relationships (Latypov, 2002), S isotopes (Ripley et al., 2003), and Sr-Nd isotopes plus trace elements (Wooden et al., 1993; Czamanske et al., 1995; Arndt, 2005; Arndt et al., 2003, 2005). To explain some of these differences Arndt and coworkers (Arndt, 2005; Arndt et al., 2003, 2005) proposed that the ore-bearing intrusions were not the conduits of the chalcophile element-depleted lavas and that the depleted lavas lost their chalcophile elements to sulfide liquid that segregated and remained in a deep staging chamber, not to the sulfide ores in the ore-bearing intrusions. The different genetic models render different implications for global mineral exploration. In this communication we propose a new genetic model that can explain the combination of elevated δ34S values and high PGE concentrations in the sulfide ores that have not been explained by the previous models, and the occurrence of magmatic anhydrite-sulfide assemblages in the Kharaelakh intrusion (Li et al., 2009). To avoid confusion that may arise from the presence of anhydrite of different origins in the intrusion, a detailed description of anhydrite textures will be given first.

Geologic Background

U-Pb zircon dating has indicated that the ore-bearing intrusions in the Noril’sk-Talnakh region, Siberia, are contemporaneous with the voluminous Late Permian continental flood basalts in the region (Kamo et al., 1996, 2003). The most important ore-bearing intrusions are the Noril’sk-I, Talnakh, and Kharaelakh intrusions (Fig. 1a). The Kharaelakh intrusion was also called the northwestern Talnakh intrusion by some researchers (Naldrett, 1992; Naldrett et al., 1992, 1996; Li et al., 2003). All mine geologists now refer to it as the Kharaelakh intrusion. In both the Noril’sk and Talnakh areas, weakly mineralized intrusions are also present. Although the ore-bearing (e.g., Kharaelakh) and weakly mineralized (e.g., Lower Talnakh) intrusions are spatially close to each other...
of their S isotope compositions as well as their radiogenic isotopes and trace elements are different. The mineralized intrusions have δ34S values from 6 to 12 per mil, whereas the weakly mineralized intrusions have δ34S values that are generally <6 per mil (Grinenko, 1985). In the Talnakh area the ore-bearing intrusions occur in both the Devonian evaporate-bearing sedimentary strata and the overlying coal-bearing sedimentary strata (Fig. 1b). In the Noril’sk area all ore-bearing intrusions are above the Devonian evaporate-bearing sedimentary strata. The internal structures of the ore-bearing intrusions, including the Kharaelakh intrusion, have been described by Czamanske et al. (1995). These intrusions all comprise multiple rock units that are suggestive of multiple magma injections (Czamanske et al., 1995; Li et al., 2003). The studies of the overlying basaltic sequence by Brügmann et al. (1993) and Lightfoot and Keays (2005) indicated that the lower and middle parts of the Nadezhdinsky suite (Nd1-2) are significantly depleted in chalcophile elements compared to the overlying Morongovsky suite. The Nd1-2 lavas and the weakly mineralized intrusions, which are considered to have predated emplacement of the ore-bearing intrusions (Zen’ko and Czamanske, 1994; Czamanske et al., 1995), are characterized by high Th/Nb and γOs, and low εNd, suggesting that the assimilation of old granitoid crust or sedimentary rocks derived from old granitoid crust (Lightfoot et al., 1990, 1993; Wooden et al., 1993; Walker et al., 1994; Hawkesworth et al., 1995; Horan et al., 1995; Fedorensko et al., 1996, Arndt et al., 2003). The trace element ratios of the ore-bearing intrusions are significantly different from those of the Nd1-2 lavas but broadly similar to those of the overlying Morongovsky lavas (Naldrett et al., 1992, 1996). However, the Morongovsky lavas and ore-bearing intrusions are different in estimated parental magma compositions (Latypov, 2002), 87Sr/86Sr, εNd (Arndt, 2005), and S isotopes (Ripley et al., 2003).

Samples and Analytical Methods
Two (K53, K58) of the samples used in this study are from drill core P5536 which is located in the eastern part of the Kharaelakh intrusion. The mineralogical and S isotope variations in this drill core are given in Li et al. (2003). Another sample (KH-2) is from drill cores M690 that is located in the western part of the intrusion. Sample K53 is a taxitic gabbro (Fig. 2a) and samples K58 and KH-2 (Fig. 2e) are picritic gabbros. Taxitic and picritic gabbros are Russian terms; they correspond to variable-textured and olivine gabbros in western

(Fig. 1a), their S isotope compositions as well as their radiogenic isotopes and trace elements are different. The mineralized intrusions have δ34S values from 6 to 12 per mil, whereas the weakly mineralized intrusions have δ34S values that are generally <6 per mil (Grinenko, 1985). In the Talnakh area the ore-bearing intrusions occur in both the Devonian evaporate-bearing sedimentary strata and the overlying coal-bearing sedimentary strata (Fig. 1b). In the Noril’sk area all ore-bearing intrusions are above the Devonian evaporate-bearing sedimentary strata. The internal structures of the ore-bearing intrusions, including the Kharaelakh intrusion, have been described by Czamanske et al. (1995). These intrusions all comprise multiple rock units that are suggestive of multiple magma injections (Czamanske et al., 1995; Li et al., 2003). The studies of the overlying basaltic sequence by Brügmann et al. (1993) and Lightfoot and Keays (2005) indicated that the lower and middle parts of the Nadezhdinsky suite (Nd1-2) are significantly depleted in chalcophile elements compared to the overlying Morongovsky suite. The Nd1-2 lavas and the weakly mineralized intrusions, which are considered to have predated emplacement of the ore-bearing intrusions (Zen’ko and Czamanske, 1994; Czamanske et al., 1995), are characterized by high Th/Nb and γOs, and low εNd, suggesting that the assimilation of old granitoid crust or sedimentary rocks derived from old granitoid crust (Lightfoot et al., 1990, 1993; Wooden et al., 1993; Walker et al., 1994; Hawkesworth et al., 1995; Horan et al., 1995; Fedorensko et al., 1996, Arndt et al., 2003). The trace element ratios of the ore-bearing intrusions are significantly different from those of the Nd1-2 lavas but broadly similar to those of the overlying Morongovsky lavas (Naldrett et al., 1992, 1996). However, the Morongovsky lavas and ore-bearing intrusions are different in estimated parental magma compositions (Latypov, 2002), 87Sr/86Sr, εNd (Arndt, 2005), and S isotopes (Ripley et al., 2003).

Samples and Analytical Methods
Two (K53, K58) of the samples used in this study are from drill core P5536 which is located in the eastern part of the Kharaelakh intrusion. The mineralogical and S isotope variations in this drill core are given in Li et al. (2003). Another sample (KH-2) is from drill cores M690 that is located in the western part of the intrusion. Sample K53 is a taxitic gabbro (Fig. 2a) and samples K58 and KH-2 (Fig. 2e) are picritic gabbros. Taxitic and picritic gabbros are Russian terms; they correspond to variable-textured and olivine gabbros in western
literature (e.g., Li et al., 2003). Sample KM-1 is from the aureole of the Kharaelakh intrusion at the Komsomolsky mine. Anhydrite in the samples was identified using transmitted and reflected light microscopy, followed by backscattered electron imagery and wavelength dispersive analysis using a CAMECA SX50 electron microprobe.

**Textures of Anhydrite**

There are three types of anhydrite in the Kharaelakh intrusion: (1) xenoliths, (2) hydrothermal, and (3) magmatic. The first two types were reported previously by Gorbachev and Grinenko (1973). Anhydrite-bearing evaporite xenoliths up to 0.5 m in thickness are most common in the western part of the intrusion. The second type is also called metasomatic anhydrite by many Russian geologists (e.g., Gorbachev and Grinenko, 1973). This type of anhydrite occurs within the intrusion as well as in the aureole of the intrusion (Fig. 2b). It is not known whether or not the different occurrences are related to the same hydrothermal activity. Magmatic anhydrite was not reported in the western literature until recently by Li et al. (2009).

Hydrothermal anhydrite in the Kharaelakh intrusion occurs as irregular patches up to ~1 cm in diameter, commonly bounded by microfractures, and surrounded by secondary hydrous silicates (Fig. 2a). The hydrous silicates include hydrogrossular, pectolite, prehnite, thomsonite, and xonotlite. Their compositions determined by electron microprobe analysis are listed in Table 1. Minor calcite, pyrite, chalcopyrite, and magnetite are present within some of the secondary hydrous silicate assemblages.

Magmatic anhydrite is hard to recognize in hand specimens due to its small size and similar color to plagioclase which is
ubiquitous in the rocks. For example, in a picritic gabbro (sample KH-2) from the Kharaelakh intrusion, rare magmatic anhydrite crystals are found in thin sections under microscopic observation but are not visible in split drill core specimens (Fig. 2c). Li et al. (2009) reported the typical textures of magmatic anhydrite in the Kharaelakh intrusion such as planar grain boundaries between anhydrite, olivine, and augite, and inclusions of anhydrite in augite and vice versa. Here we report the textures of magmatic anhydrite in association with magmatic sulfides in the Kharaelakh intrusion. Figure 3a and b illustrates a typical magmatic anhydrite-sulfide assemblage in a thin section under both reflected and transmitted light. In this assemblage anhydrite crystals occur as randomly oriented crystals and form a framework; sulfides (pyrrhotite, pentlandite, and chalcopyrite) occur in the interstices. Elongated anhydrite crystals at the margins of the assemblage have sharp contacts with granular augite crystals. In some cases sulfides in the assemblage are completely isolated from silicate minerals by anhydrite crystals (Fig. 3c).

Figure 3d through f illustrates the textures of hydrothermal anhydrite assemblages in the Kharaelakh intrusion. In relatively large alteration patches anhydrite commonly occurs as needles with other secondary hydrous silicates and calcite (Fig. 3d). In relatively small alteration patches finer grained anhydrite crystals occur intergrown with secondary hydrous silicates (Fig. 3e). In this type of assemblage backscattered electron image (Fig. 3f) and energy dispersive X-ray spectrum are needed for mineral identification.

### Origin of High $\delta^{34}S$ Values

With the exception of two sulfide-poor gabbroic samples ($<500$ ppm S) which have $\delta^{34}S$ values between 1.5 and 3.6 per mil, all sulfide-mineralized samples from the Kharaelakh intrusion analyzed to date yield $\delta^{34}S$ values from 10 to 12 per mil (Grinenko, 1985; Li et al., 2003, 2009). The positive correlation between S content and $\delta^{34}S$ value indicates a link between sulfide saturation-segregation and contamination with $^{34}S$-enriched S. However, some Russian geologists (e.g., Godlevsky and Likachev, 1986) have proposed that the high $\delta^{34}S$ values are of mantle origin rather than being related to crustal contamination. Anomalously high $\delta^{34}S$ values have not been found in the coeval basalts to date (Ripley et al., 2003). The $\delta^{34}S$ values in the basalts are similar to those of the two sulfide-poor gabbroic samples from the Kharaelakh intrusion. The significant difference between the basalts and the sulfide-mineralized intrusive rocks is inconsistent with the hypothesis of anomalously high $\delta^{34}S$ values in the mantle beneath the Siberian platform.

Degassing may affect S isotope compositions in volcanic and subvolcanic systems (e.g., Mandeville et al., 2009). Ripley et al. (2003) discussed the possible effects of degassing on the S isotope compositions of volcanic rocks in the Noril'sk area. During degassing the S isotope compositions of magma is critically dependent on the temperature, pressure, the mass of the vapor lost, the composition of the vapor, and the $f_{O_2}$ condition which controls speciation in the melt and vapor. At $f_{O_2}$ conditions where sulfate is the predominant species in the magma the loss of a vapor can lead to $^{34}S$ enrichment in the magma. However, Ripley et al. (2003) showed that the vast majority of volcanic rocks in the Noril'sk region are characterized by $\delta^{34}S$ values less than 5 per mil. Abundant sulfide ores in the Kharaelakh intrusion indicate that the ore-bearing intrusive rocks have certainly not degassed to the extent of the relatively low $\delta^{34}S$ coeval lavas. It is therefore extremely unlikely that the elevated $\delta^{34}S$ values found in the sulfide ores of the Kharaelakh intrusion are a result of degassing.

Grinenko (1985) proposed assimilation of sulfur in sour gas as the cause of elevated $\delta^{34}S$ values in the sulfide ore-bearing

### Table 1. Compositions of Secondary Silicates in the Kharaelakh Intrusion

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Hydrograssular</th>
<th>Pectolite</th>
<th>Prehnite</th>
<th>Thomsonite</th>
<th>Xonotlite</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO$_2$</td>
<td>31.37</td>
<td>53.92</td>
<td>43.67</td>
<td>37.51</td>
<td>50.13</td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>0.04</td>
<td>0.00</td>
<td>0.02</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>25.92</td>
<td>0.18</td>
<td>25.79</td>
<td>31.30</td>
<td>0.10</td>
</tr>
<tr>
<td>MgO</td>
<td>0.27</td>
<td>0.00</td>
<td>0.00</td>
<td>0.04</td>
<td>0.00</td>
</tr>
<tr>
<td>CaO</td>
<td>37.58</td>
<td>33.20</td>
<td>26.82</td>
<td>13.10</td>
<td>46.03</td>
</tr>
<tr>
<td>MnO</td>
<td>0.03</td>
<td>0.26</td>
<td>0.00</td>
<td>0.06</td>
<td>0.00</td>
</tr>
<tr>
<td>FeO</td>
<td>1.29</td>
<td>0.06</td>
<td>0.00</td>
<td>0.92</td>
<td>0.02</td>
</tr>
<tr>
<td>Na$_2$O</td>
<td>0.04</td>
<td>9.16</td>
<td>0.00</td>
<td>3.78</td>
<td>0.00</td>
</tr>
<tr>
<td>K$_2$O</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.03</td>
<td>0.01</td>
</tr>
<tr>
<td>H$_2$O$^1$</td>
<td>not calc.</td>
<td>2.09</td>
<td>4.41</td>
<td>13.40</td>
<td>4.08</td>
</tr>
<tr>
<td>Total</td>
<td>96.55</td>
<td>98.88</td>
<td>100.72</td>
<td>100.16</td>
<td>100.35</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cation</th>
<th>$24O$</th>
<th>$24O$</th>
<th>$24O$</th>
<th>$80O$</th>
<th>$24O$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Si</td>
<td>4.58</td>
<td>7.76</td>
<td>5.94</td>
<td>25.75</td>
<td>7.36</td>
</tr>
<tr>
<td>Ti</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.04</td>
<td>0.00</td>
</tr>
<tr>
<td>Al</td>
<td>4.47</td>
<td>0.03</td>
<td>4.14</td>
<td>9.90</td>
<td>7.25</td>
</tr>
<tr>
<td>Mg</td>
<td>0.06</td>
<td>0.00</td>
<td>0.00</td>
<td>0.03</td>
<td>0.00</td>
</tr>
<tr>
<td>Ca</td>
<td>5.89</td>
<td>5.12</td>
<td>3.91</td>
<td>5.11</td>
<td>0.00</td>
</tr>
<tr>
<td>Mn</td>
<td>0.00</td>
<td>0.03</td>
<td>0.00</td>
<td>0.54</td>
<td>0.00</td>
</tr>
<tr>
<td>Fe</td>
<td>0.02</td>
<td>0.01</td>
<td>0.00</td>
<td>0.03</td>
<td>0.00</td>
</tr>
<tr>
<td>Na</td>
<td>0.01</td>
<td>2.56</td>
<td>0.00</td>
<td>0.03</td>
<td>0.00</td>
</tr>
<tr>
<td>K</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>67.49</td>
<td>14.63</td>
</tr>
<tr>
<td>Total</td>
<td>15.03</td>
<td>15.50</td>
<td>13.99</td>
<td>67.19</td>
<td>14.63</td>
</tr>
</tbody>
</table>

$^1$ Calculated by stoichiometry.
intrusions in the Noril’sk region. However, sulfur in sour gas commonly occurs as reduced species such as H₂S. It is extremely unlikely that addition of reduced S species into a mantle-derived magma can drive magma to sulfate saturation, as indicated by the presence of magmatic anhydrite in the Kharaelakh intrusion (Li et al., 2009). Therefore, we support the hypothesis made previously by many other authors (e.g., Naldrett et al., 1992, 1996; Li et al., 2003, 2009) that assimilation of anhydrite-bearing evaporite country rocks is responsible for the elevated $\delta^{34}S$ values of sulfide ores in the intrusion. Because the melting temperature of anhydrite (>1,400°C) is significantly higher than the temperature of a basaltic magma (1,200°C–1,300°C), it is unlikely that the magma of the Kharaelakh intrusion could have assimilated anhydrite by melting. Chemical dissolution by magma that was originally unsaturated with anhydrite is a more plausible mechanism.

---

**Fig. 3.** Microphotographs of magmatic and hydrothermal anhydrites in the Kharaelakh intrusion. (a), (b), and (c). Magmatic anhydrite-sulfide assemblages. (d), (e), and (f). Hydrothermal anhydrite. Anh = anhydrite, Cp = chalcopyrite, Cpx = clinopyroxene, Hgs = hydrograssular, Pn = pentlandite, Po = pyrrhotite.
Mass-Balance Constraints

The $\delta^{34}$S value of sulfide ores in the Kharaelakh intrusion vary mostly between 10 and 12 per mil (Li et al., 2003). The $\delta^{34}$S values of anhydrite country rocks in the region are ~20 per mil (Gorbachev and Grinenko, 1973). The content of sulfur in mantle-derived magmas in continental rift settings such as the Deccan magmas is estimated to be ~0.14 wt percent based on the analysis of melt inclusions in olivine phenocrysts (Self et al., 2008). To produce a contaminated magma with a $\delta^{34}$S value of 12 per mil, the magma needs to assimilate 0.89 wt percent anhydrite if the content of S in the uncontaminated magma is 0.14 wt percent and the $\delta^{34}$S value of the uncontaminated magma is 0 per mil. The amount of anhydrite assimilated increases to 0.96 wt percent if the content of S in the uncontaminated magma is 0.15 wt percent. The relationship between $\delta^{34}$S values in contaminated magmas and the amounts of anhydrite assimilated by the magmas are illustrated in Figure 4.

Anhydrite assimilation by magma will increase $f_{O_2}$ in the magma through the following equilibria:

$$CaSO_4^{solid} \Leftrightarrow CaSO_4^{melt},$$ (1)

and

$$CaSO_4^{melt} + 9FeO^{melt} \Leftrightarrow FeS^{melt} + 4Fe_2O_3^{melt} + CaO^{melt}. \quad (2)$$

Equation (2) can be used to calculate the increase of $Fe_2O_3/FeO$ in the magma due to anhydrite assimilation. The increase of $f_{O_2}$ in the contaminated magma can be calculated using the MELTS program of Ghiorso and Sack (1995) in which the $f_{O_2}$-$\langle FeO/Fe_2O_3 \rangle$-$T$ relationship is implemented. Figure 5 illustrates the change of $f_{O_2}$ due to anhydrite assimilation by a magma with composition similar to the average composition of the Noril’$k$-type sills (Zen’ko and Czamanske, 1994) and initial $f_{O_2}$ at 2 log units below the buffer of fayalite-magnetite-quartz (i.e., FMQ-2). The assumed original oxidation state is within the range of midocean ridge basalt.

$$\delta^{34}S = 12\%e$$

Contaminated magma

$\delta^{34}S = 10\%e$

$\delta^{34}S = 8\%e$

$\delta^{34}S = 12\%e$

$\delta^{34}S = 0\%e$

$\delta^{34}S = 12\%e$

$\delta^{34}S = 10\%e$

$\delta^{34}S = 8\%e$

$\delta^{34}S = 12\%e$

$\delta^{34}S = 10\%e$

$\delta^{34}S = 8\%e$

$\delta^{34}S = 12\%e$

$\delta^{34}S = 10\%e$

$\delta^{34}S = 8\%e$

$\delta^{34}S = 12\%e$

$\delta^{34}S = 10\%e$

$\delta^{34}S = 8\%e$

$\delta^{34}S = 12\%e$

$\delta^{34}S = 10\%e$

$\delta^{34}S = 8\%e$

$\delta^{34}S = 12\%e$

$\delta^{34}S = 10\%e$

$\delta^{34}S = 8\%e$

$\delta^{34}S = 12\%e$

$\delta^{34}S = 10\%e$

$\delta^{34}S = 8\%e$

$\delta^{34}S = 12\%e$

$\delta^{34}S = 10\%e$

$\delta^{34}S = 8\%e$

$\delta^{34}S = 12\%e$

$\delta^{34}S = 10\%e$

$\delta^{34}S = 8\%e$

$\delta^{34}S = 12\%e$

$\delta^{34}S = 10\%e$

$\delta^{34}S = 8\%e$

$\delta^{34}S = 12\%e$

$\delta^{34}S = 10\%e$

$\delta^{34}S = 8\%e$

$\delta^{34}S = 12\%e$

$\delta^{34}S = 10\%e$

$\delta^{34}S = 8\%e$

$\delta^{34}S = 12\%e$

$\delta^{34}S = 10\%e$

$\delta^{34}S = 8\%e$

$\delta^{34}S = 12\%e$

$\delta^{34}S = 10\%e$

$\delta^{34}S = 8\%e$

$\delta^{34}S = 12\%e$

$\delta^{34}S = 10\%e$

$\delta^{34}S = 8\%e$

$\delta^{34}S = 12\%e$

$\delta^{34}S = 10\%e$

$\delta^{34}S = 8\%e$

$\delta^{34}S = 12\%e$

$\delta^{34}S = 10\%e$

$\delta^{34}S = 8\%e$

$\delta^{34}S = 12\%e$

$\delta^{34}S = 10\%e$

$\delta^{34}S = 8\%e$

$\delta^{34}S = 12\%e$

$\delta^{34}S = 10\%e$

$\delta^{34}S = 8\%e$

$\delta^{34}S = 12\%e$

$\delta^{34}S = 10\%e$

$\delta^{34}S = 8\%e$

$\delta^{34}S = 12\%e$

$\delta^{34}S = 10\%e$

$\delta^{34}S = 8\%e$

$\delta^{34}S = 12\%e$

$\delta^{34}S = 10\%e$

$\delta^{34}S = 8\%e$

$\delta^{34}S = 12\%e$

$\delta^{34}S = 10\%e$

$\delta^{34}S = 8\%e$

$\delta^{34}S = 12\%e$

$\delta^{34}S = 10\%e$

$\delta^{34}S = 8\%e$
balance calculations (see Figs. 4, 5) indicate that after point increases with increasing anhydrite assimilation due to decrease
the second part from point et al., 2003), we envision that the process from point
immiscible sulfide liquid due to anhydrite assimilation. In the closed system case no magma leaves the system after anhydrite assimilation. The R factors for these

figure represents the increase of total S with increasing amounts of anhydrite assimilation by a magma with initial S content of 0.14 wt percent and oxidation state of FMQ-2. During the early stages of anhydrite assimilation (from point e-g), the contaminated magma becomes sulfide saturated, and immiscible sulfides develop within it. However, further assimilation of anhydrite (after point g) drives the contaminated magma below S saturation. The S saturation history of the contaminated magma can be further divided into two parts: the first part from point e to f during which the R factor decreases with increasing anhydrite assimilation, and the second part from point f to g during which the R factor increases with increasing anhydrite assimilation due to decreasing amount of immiscible sulfide liquid. The results of mass-balance calculations (see Figs. 4, 5) indicate that after point f the δ34S values of the contaminated magmas are higher than 12 per mil. Since the majority of the sulfide ores in the Kharaelakh intrusion and other ore-bearing intrusions in the region have δ34S values below this value (Grinenko, 1985; Li et al., 2003), we envision that the process from point f to g was not important for the formation of the deposits. The R factors from point e to f for both open and closed systems have been calculated and are illustrated in Figure 7. In the open system case the contaminated magma is withdrawn from the system after segregation of immiscible sulfide liquid due to anhydrite assimilation. In the closed system case no magma leaves the system after anhydrite assimilation. The R factors for these
two different systems vary from 100 to 400. These values are likely the maximum values because the content of S in the magma before anhydrite assimilation may be higher than the assumed value of 0.14 wt percent due to higher FeO content. For example, the sulfur content at sulfide saturation in a magma with composition similar to the average composition of the Noril’sk-type sills (Zen’ko and Czamanske, 1994) under the conditions of 4 kbars and FMQ-2, calculated using the empirical equation of Li and Ripley (2005) in conjunction with the MELTS program of Ghiorso and Sack (1995) for the estimation of liquid temperature, is 0.16 wt percent. The R factors of 100 to 400 (Fig. 7) are one order of magnitude lower than R factors estimated based on the Pt tenors of the sulfide ores in the Kharaelakh intrusion and initial magma Pt content similar to the value in the coeval, most undepleted lavas (~10 ppb Pt; Naldrett et al., 1996). The Pt tenors in the sulfide ores in the Kharaelakh intrusion vary between 2 and 8 ppm (Naldrett et al., 1996). To form the sulfide liquids with such high Pt concentrations and R factors of <400 the parental magmas must contain Pt >60 ppb (Fig. 8), which is six times the value of the coeval, most undepleted lavas that have been analyzed to date (Brügmann et al., 1993; Lightfoot and Keays, 2005).

Sulfide Resorption

The most effective way to form a PGE-enriched magma is by resorption of PGE-rich sulfide liquid (Kerr and Leitch, 2005). Among the lavas that are coeval with the Kharaelakh intrusion, the Nd1-2 lavas are most depleted in PGE, an indication of sulfide segregation at depth (Brügmann et al., 1993; Lightfoot and Keays, 2005). The Nd1-2 lavas are also characterized by high La/Sm, high SiO2, and low εNd, which indicate contamination with granitoid crust (Lightfoot et al., 1993; Lightfoot and Hawkesworth, 1997). Sulfide saturation in these lavas at depth was thought to be due to contamination with granitic crustal materials in a deep staging chamber.
perhaps in the lower parts of the upper crust (Lightfoot et al., 1993; Lightfoot and Hawkesworth, 1997; Arndt et al., 2005). The results of numerical modeling by Lightfoot and Keays (2005) suggest that the overlying Morongovsky lavas may have equilibrated with sulfide liquid with Pt content in excess of 200 ppm. When a new, S-unsaturated magma from the mantle entered the staging chamber, it would have dissolved FeS from the sulfide liquids. Nickel, Cu, and especially PGE would have stayed with the remaining sulfide liquid because of their much higher sulfide liquid/magma partition coefficients relative to Fe. As magma replenishment continued, the sulfide liquid would have become progressively more PGE (and Ni and Cu) enriched. Since the magma flowing through the chamber remained in equilibrium with the sulfide liquid present there, it would also have become PGE enriched, eventually acquiring a much higher PGE content than the original magma. As an example, Figure 9 illustrates the results of such a process based on a two-component mass balance on Pt and the parameters given in the figure. In our mass-balance calculations we used the maximum sulfide/magma D^Pt given by Stone et al. (1990) and Fleet et al. (1999). The initial Pt content in the sulfide liquid is within the range of values for the sulfide liquids in equilibrium with the Morongovsky magma given by Lightfoot and Keays (2005). The Pt content in the mantle-derived, S-unsaturated magma was fixed at 10 ppb and is similar to the values in the relatively PGE undepleted lavas above the Nadezhdinsky suite (Lightfoot and Keays, 2005). Our calculations indicate that Pt content in the magma will exceed 60 ppb after nearly complete resorption of sulfide liquid in the staging chamber.

A New Model

In light of the mass-balance constraints given above, we propose a new model for the formation of Ni-Cu-PGE sulfide ores in the Kharaelakh intrusion. The key aspects of the model are illustrated in Figure 10 and summarized here. Early sulfide segregation took place in a deep staging chamber due to contamination with granitic crustal materials in the lower parts of the upper crust, as suggested previously by other researchers (Naldrett et al., 1992, 1996; Naldrett and Lightfoot, 1999; Arndt et al., 2003, 2005). The magma then rose to form the weakly mineralized intrusions and erupted to the surface to form the Nd1-2 lavas, leaving a sulfide liquid with relatively low tenors of Ni, Cu, and PGE in the staging chamber. The PGE-poor sulfide liquid in the chamber was then upgraded in chalcophile elements (PGE, Ni, and Cu) by the Morongovsky magma from the mantle to form a PGE-rich sulfide liquid. The PGE-rich sulfide liquid remained in the staging chamber while the Morongovsky magma erupted to form the Morongovsky lavas (Fig. 10a). New, S-unsaturated magma from the mantle continued to enter the chamber, progressively dissolved the PGE-rich sulfide liquid in the chamber to form a PGE-enriched magma. The PGE-enriched magma then rose to the upper parts of the upper crust where it reacted with anhydrite-bearing evaporite country rocks and became sulfide saturated, thereby producing immiscible sulfide liquid with high PGE concentrations as well as high δ^34S values (Fig. 10b). The sulfide liquid became lodged in the hydraulic traps of the plumbing system at Kharaelakh (Fig. 10c).

According to Zen'ko and Czamanske (1994), the weighted average sulfide content (calculated as FeS) in the Noril'sk ore-bearing intrusion and its peripheral sills intercepted by drilling to date is ~0.17 wt percent, which is within the values for the closed system case described above. The weighted average sulfide content in the Kharaelakh-Talnakh ore-bearing intrusions and their peripheral sills intercepted by drilling to date is ~1.6 wt percent, which is 60 percent higher than the maximum value for the closed system case (~1 wt %) described above. In other words, ~40 percent of the magma

![Fig. 8. Relationships between Pt content in sulfide liquid, R factor, and Pt content in initial magma.](image)

![Fig. 9. S-unsaturated magma interacting with sulfide liquids in a conduit or sill would dissolve FeS from the sulfide liquids. Nickel, Cu, and especially PGE would stay with the remaining sulfide liquids because of their much higher sulfide liquid/magma partition coefficients relative to Fe. Repetitive batches of magma passing through a system, dissolving out FeS, would steadily upgrade the Ni, Cu, and PGE contents of the residual sulfide liquid. As the sulfide liquids became more PGE enriched, the flowing magma itself would also become PGE enriched, eventually having a much higher PGE content than the original magma.](image)
involved in the formation of the Kharaelakh-Talnakh deposits has not been accounted for by the host intrusions and their peripheral sills intercepted by drilling to date. It is possible that more peripheral sills in the Kharaelakh-Talnakh ore-forming system may have not been found due to a lack of drilling beyond the orebodies. Alternatively, the missing magma with elevated $\delta^{34}S$ values may have erupted to the surface but have not been identified due to insufficient sampling. However, the difference in the estimated parental magma compositions between the intrusive and extrusive rocks (Latypov, 2002) makes the second scenario less likely. Although the above mismatch may be explained by shallow-level processes such as contamination and fractional crystallization that took place after the magma left the intrusions.
and flowed onward toward the surface, the shallow-level processes cannot explain lower Rb/Sr, 87Sr/86Sr, and ɛNd in the erupted lavas than in the ore-bearing intrusions (Arndt, 2005).

With slight modification our model can also be applied to other Ni-Cu-PGE deposits in the region, including the Noril’sk-I deposit which occurs several hundred meters above the evaporite strata. In this case anhydrite assimilation needed to take place before the magma reached the hydraulic trap of the plumbing system at Noril’sk-I. The sulfide ores of the Noril’sk-I deposit generally have higher Pt tenor (up to 12 ppm; Naldrett et al., 1996) and lower δ34S values (8–10‰; Li et al., 2003) than the Kharaelakh deposit, which is consistent with less amounts of anhydrite assimilation and thereby higher R factors for the resultant sulfide liquids.

Concluding Remarks

Our new model adequately explains why the Nd1:2 lavas, which provided much of the PGE to the sulfide ores in the ore-bearing intrusions, have S isotopes, Sr-Nd isotopes, and trace element ratios different from the ore-bearing intrusions (Lightfoot et al., 1990, 1993; Wooden et al., 1993; Arndt et al., 2003, 2005; Ripley et al., 2005). This is because the Nd1:2 lavas and the ore-bearing intrusions were not directly linked (Arndt, 2005; Arndt et al., 2003, 2005). Chalcopyrite element depletion in flood basalts as an exploration tool for important Ni-Cu-PGE deposits in coeval subvolcanic intrusions, which was proposed previously by Naldrett and coworkers (Naldrett, 1992; Naldrett and Lightfoot, 1999) based on different approaches, remains valid according to our new model.

Acknowledgments

We thank Viktor Radko of the Noril’sk Nickel Company and the chief geologist of the Komsomolsky mine for supplying some of the samples used in this study, and Nick Arndt for thoughtful review of the manuscript. This research was supported by the Natural Science Foundation of China (40534020), Project-111 from the Ministry of Education of China (B07011), and the Natural Science Foundation of the United States (EAR 0710910).

December 3, 2008; February 13, 2009

REFERENCES

Lightfoot, P.C., Naldrett, A.J., Gorbačev, N.S., Doherty, W., and Fedorenko, V.A., 1990, Geochemistry of the Siberian trap of the Noril’sk area, USSR, with implications for the relative contributions of crust and mantle to flood


