

Melting of the Siberian mantle plume

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Abstract. The Putorana basalts, comprising ~90% of the Siberian Traps (ST), have had their chemistry modified from primary tholeiitic picritic magmas by ~12% crystallization of olivine. Major-trace element ratios, and Nd isotopes of these lavas are consistent with their origin from a relatively undepleted plume by 12-16% rapid decompressional melting at ~50-80 km depths within the lithosphere.

Introduction

An outstanding problem in magma genesis is the identification of primary liquid, specifically whether erupted lavas are close to the original melt formed in the mantle, or modified during ascent by complex crystallization and melting processes. The connection between hotspots and continental flood basalts has been interpreted as sudden decompressional melting of a plume, causing large volumes of basalts to erupt within a short period of time [e.g. *Richards et al.*, 1989, *Renne and Basu*, 1991]. These observations and recent advances in experimental-theoretical petrology of major element variations during mantle melting [e.g., *Klein and Langmuir*, 1987; *Langmuir et al.*, 1992; *Baker and Stolper*, 1994; *White and McKenzie*, 1995; *Asimow et al.*, 1997], have encouraged this study of the Siberian Traps. The ST erupted through old cratonic lithosphere and constitute one of the largest continental flood basalt provinces. Here we provide assessments of the roles of fractional crystallization, mantle source composition, degree and nature of melting of the peridotite source, and the initial magma composition in the development of this large ($>3 \times 10^6 \text{ km}^3$) plateau basalt province within one million years [*Renne and Basu*, 1991].

A composite volcano-stratigraphy of the ST is shown in Figure 1 with the relative locations and the data sources of the 55 samples used in this study. There are 31 samples from the Putorana section, which is believed to constitute 90 percent of the entire volume of the ST; other 24 samples represent the Noril'sk section. The samples are divided into three groups: i) basalts with $\text{MgO} < 6 \text{ wt.}\%$, ii) basalts with $\text{MgO} > 6 \text{ wt.}\%$, and iii) picrites with $\text{MgO} > 12 \text{ wt.}\%$. Noril'sk and the lower portion of Putorana exhibit a wide range of ϵ_{Nd} values and

highly variable Sm/Nd ratios (Figure 2), reflecting a variety of sources. The volumetrically significant and younger Putorana basalts generally have more uniform ϵ_{Nd} values and Sm/Nd ratios. This is consistent with the main volume of the ST being derived from a relatively undepleted mantle plume with $\epsilon_{\text{Nd}} \sim 0$ and a near chondritic Sm/Nd ratio. High $^3\text{He}/^4\text{He}$ ratios ($R_A = 13$) have been recorded in the ST lavas [*Basu et al.*, 1995] to the east of Putorana, indicating a lower mantle plume source for the ST.

Major Element Variations

Both Na_2O and MgO exhibit a considerable range of variation in Figure 3. It is clear that the lavas with $< 6 \text{ wt.}\%$ MgO have been modified by fractional crystallization, while major and trace elements indicate that the basalts with $\text{MgO} > 6 \text{ wt.}\%$ have not suffered substantial fractional crystallization except for minor (10-15%) olivine fractionation. These rocks could not have suffered substantial plagioclase and/or clinopyroxene fractionation because i) the Ca/Al ratio in the basalts is relatively constant and close to chondritic (Figure 6), ii) the samples have relatively flat chondrite-normalized rare earth element patterns with no Eu-anomalies. The Ni concentration in the basalts with $> 6 \text{ wt.}\%$ MgO is 100-200 ppm; thus the samples could only have suffered 10-15% olivine crystallization. Hence, further consideration of primary magma is based on lavas with $> 6 \text{ wt.}\%$ MgO . The picrites

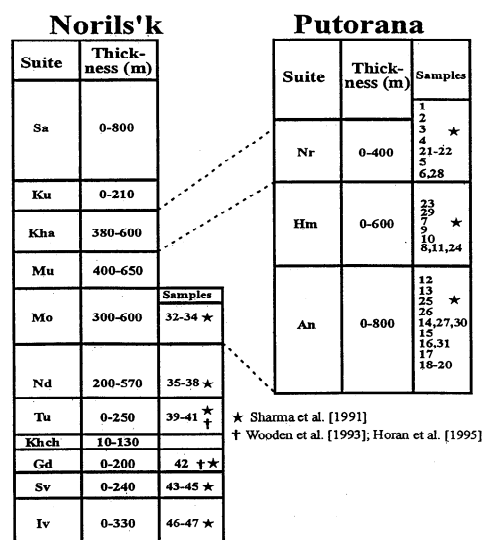


Figure 1. Volcano-stratigraphy of the ST, showing the samples of this study. Suite names as in *Sharma et al.* [1991].

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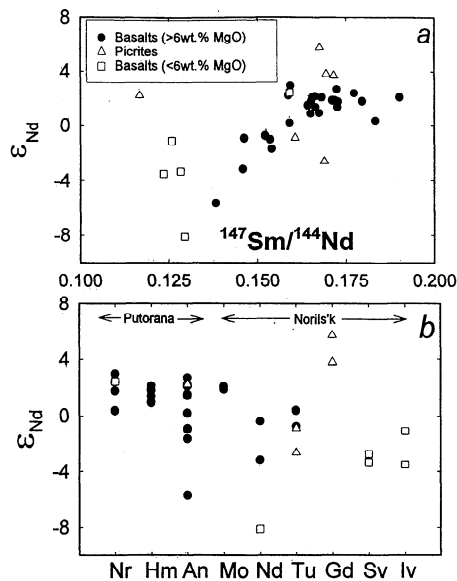


Figure 2. (a) Initial ϵ_{Nd} vs. $^{147}Sm/^{144}Nd$ showing that most of the basalts with >6 wt.% MgO have $^{147}Sm/^{144}Nd$ ratios slightly lower than the chondritic value. (b) Initial ϵ_{Nd} versus lava suites (same as Figure 1), showing the Putorana basalts having ϵ_{Nd} mostly in the range 0 to +2. Suites are oldest on the right (Iv) and youngest (Nr) on the left.

have 400 to 1200 ppm Ni, positively correlated with MgO content. Thus, some of the picrites with the lowest Ni and MgO may be close to primary magmas, while the samples with the highest Ni and MgO may have suffered olivine accumulation. As discussed later the ST picrites have more complex chemical signatures than the basalts with MgO >6 wt.%. It is possible that picrites that have Na_2O , Ni and MgO values close to those expected for primary magmas are in fact differentiated magmas that acquired an apparent primary signature by olivine accumulation. Different degrees of melting of the mantle source causes large variations in Na_2O and MgO of primary melts. The incompatible element Na strongly prefers the melt to the residual solid during mantle melting, while Mg is compatible during melting. The concentration of Na_2O in the melt is roughly inversely proportional to the degree of melting [Langmuir et al., 1992;

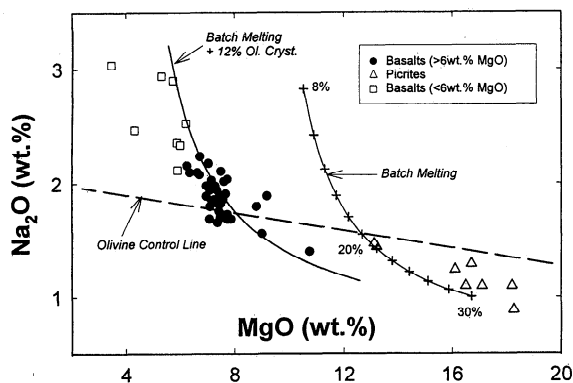


Figure 3. Na_2O vs. MgO variation in Siberian lavas. Curves for batch melting and a dashed line for adding or removing olivine ($F_{0.87}$) are shown as olivine control line.

Baker and Stolper, 1994]. The hyperbolic trend observed for Na_2O and MgO for the ST (Figure 3) may primarily be due to variable degrees of partial melting.

Plume Melting and Source Composition

We consider melting of a relatively undepleted mantle source with $Na_2O = 0.33$ wt.%, and $MgO = 38$ wt.%. Such a source defines a linear relationship with a slope of 0.135 and an intercept of -0.0326 in a Na_2O/MgO versus Na_2O diagram (line labeled $D_{Mg}^0 = 4$ in Figure 4) for a batch melting process. Experimental investigations of partial melting of fertile mantle [Baker and Stolper, 1994] document monotonic decrease of TiO_2 and Na_2O during increasing degree of partial melting. Many recent models assume basalt generation under adiabatic conditions [e.g., Klein and Langmuir, 1987; Langmuir et al., 1992; White and McKenzie, 1995] and quantify the effects of the degree of melting on melt composition. Melt segregation in the mantle is a complex process to model in detail; however, the batch partial melting equation [Shaw, 1970] may be sufficient for a first order understanding of element variations during mantle melting. We note that the batch melting equations also apply to some of the more complex melt segregation models if equilibrium is maintained [Spiegelman and Kenyon, 1992]. This mass balance equation describes the enrichment of an element in the melt (C_m) relative to the value in the initial source (C^0): $\{C_m/C^0 = 1/(D + F(1-D))\}$ where F is the mass fraction of melt and $D = C_r/C_m$ is the bulk distribution coefficient between the element in the solid residue (C_r) and the melt. The D -value may be a function of F as source minerals contribute different fractions to the melt. This may be expressed as: $D(F) = (D^0 - FP)/(1 - F)$, where D^0 is the initial bulk distribution coefficient and P is the distribution coefficient weighted by the liquid fractions contributed by each solid phase in the source [Shaw, 1970]. It is well known that by combining the above equations for two elements, in our case Na and Mg, and by eliminating F , one obtains a linear relationship: $C_{Na}/C_{Mg} = aC_{Na} + b$ in a plot of the Na/Mg ratio versus Na if both D^0 and P are constant

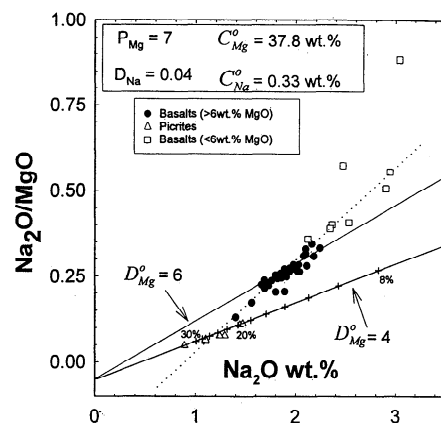


Figure 4. Na_2O/MgO vs. Na_2O variation in Siberian lavas. The dotted line fits the basalt data with a slope = 0.258 and an intercept = -0.225 . This slope and intercept yield unrealistically high D_{Mg}^0 and Na/Mg values, respectively, for the mantle source. The line with tick marks is consistent with parameters for melting an undepleted mantle source.

[Minster and Allegre, 1978; Sims and DePaolo, 1997]. The slope (a) and intercept (b) are:

$$a = [D_{Mg}^o - D_{Na}^o(1 - P_{Mg}) / (1 - P_{Na})];$$

$$b = (C_{Na}^o / C_{Mg}^o) \cdot ((1 - P_{Mg}) / (1 - P_{Na})).$$

Experimental determinations of D_{Na} are in the range 0.03 – 0.07 and we use a value $D_{Na} = 0.04$ for all F. However, it is clear that D_{Mg} varies with F. We fitted the results of Baker and Stolper [1994] to above equations and obtained $P_{Mg} = 7$ and $D_{Mg}^o = 4$. This is consistent with D's on mineral melt partitioning as function of P and T as well as the general relationships between F, T and P as discussed by Langmuir et al. [1992] for mantle melting.

Figure 4 also shows Na_2O/MgO ratio versus Na_2O for the Siberian basalts. The picrites plot close to the primary magma trend in this diagram, while other samples plot above this trend. The basalts with $MgO > 6$ wt.% plot on a line corresponding to $D_{Mg}^o = 6$. Such a high value is inconsistent with experimental data, requiring a very low melting temperature [Langmuir et al., 1992]. However, minor olivine crystallization can cause the shift above the line for $D_{Mg}^o = 4$. Using these parameters we calculated the trend for 8% to 30% batch melting (Figure 3). The effect of 12% equilibrium crystallization of olivine is also shown in figure 3. The olivine control line in this diagram shows addition or subtraction of olivine. These results mean that the basalts with >6 wt.% MgO are partial melts of a relatively undepleted mantle, and modified by about 12% olivine crystallization. The picrites appear closer to primitive melts, possibly due to olivine addition. The close similarity of the observed Na_2O and MgO variations and calculated curves (Figure 3) provides evidence for ~12 – 18 % melting of the Siberian plume as the primary cause for the elemental variations in the basalts.

The basalts with $MgO > 6$ wt.% show a negative trend in a plot of total Fe versus MgO (Figure 5). This trend is different from experimental [Baker and Stolper, 1994] or calculated trends for batch and fractional melting [Klein and Langmuir, 1987; Langmuir et al., 1992;], which show positive slopes in this diagram. The trend indicates that Fe is incompatible during melting just like Na. One possible explanation is that Fe^{3+} is incompatible similar to Al during melting, while Fe^{2+} is compatible. Figure 5 shows the effect of 15% of the Fe in

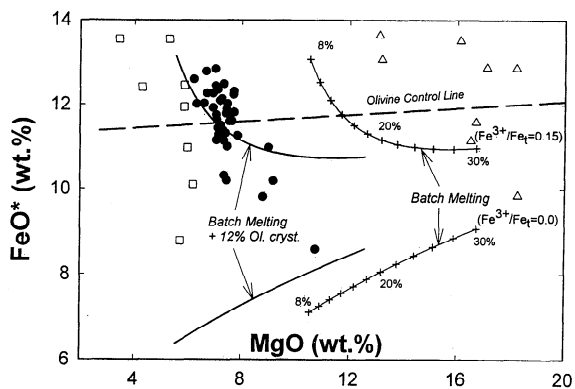


Figure 5. FeO vs. MgO variation in lavas. Batch melting calculations treating all iron as Fe^{2+} and also treating 15% of total Fe as Fe^{3+} are shown. The results are consistent with inferences from Figure 3.

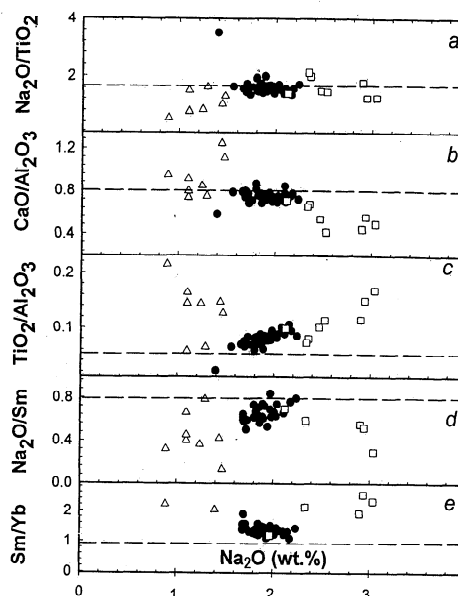


Figure 6. Several elemental ratios versus Na_2O for the ST. Basalts with $MgO > 6$ wt. % plot close to the Bulk Silicate Earth ratio [McDonough and Sun, 1995] shown by the dashed lines. Data symbols same as in Figures 2-5.

the trivalent state compared to all the Fe as divalent. As shown this gives the negative trend in the basalts. Batch melting with 12% olivine crystallization and an olivine control line for $Fe_{0.7}$ are also shown. The batch melting curves in this diagram have the same D_{Mg}^o and P_{Mg} values as in Figures 3 and 4 and a bulk $D_{Fe^{2+}}/D_{Mg} = 0.3$ similar to the value for olivine and melt [Langmuir et al., 1992]. For trivalent iron we used $D_{Fe^{3+}} = 0.1$, similar to the inferred D-value for Al [Baker and Stolper, 1994]. As shown in Figure 5, the $MgO-FeO$ variations of Siberian basalts cannot be due to olivine accumulation. The bulk of the data cluster at values of $FeO = 11.5$ wt. % and $MgO = 7.5$ wt.%. Only about 12 % equilibrium crystallization of olivine is necessary to explain the samples in this diagram. Thus the FeO^*-MgO variations in the basalts are consistent with batch melting followed by about 12% olivine crystallization. The picrites in Figure 5 are consistent with variable olivine accumulation. In the above evaluation, we considered an undepleted mantle source for the ST, although major element ratios can not always distinguish between depleted and undepleted sources. However, as shown below, this consideration is justified for the bulk of the basalts with $MgO > 6$ wt.% as their Sm/Nd , Nd -isotopic, Na_2O/Sm and Na_2O/TiO_2 ratios strongly indicate an undepleted source. It is unlikely that such ratios could have resulted from complex processes of mixing, melting and fractional crystallization. We do not test in this short paper alternative scenarios of fractional melting or polybaric melting as the isobaric batch melting curves fit the data reasonably well. We also note that the effect of pressure on the partitioning of Fe, Mg and Na may not be significant because the ST magmas are known to have erupted rapidly by melting at shallow depths in the lithosphere, as discussed below.

We compare several other incompatible elements, Ti, Ca, Al, Sm and Yb relative to Na. These incompatible element ratios are plotted versus Na_2O (proportional to $1/F$) in Figure

6. The basalts with MgO > 6 wt. % plot close to bulk silicate Earth (BSE) values, while the other two groups show considerable variability. The ST basalts plot in a cluster with a distinctly flat slope with Na₂O/TiO₂ of approximately 1.6, identical to the BSE value, and Na₂O ranging between 0.86 to 3.04 wt. % (Figure 6a). Experimental melting of a fertile peridotite gives D_{Ti} and D_{Na} [Baker and Stolper, 1994] in the range 0.01 to 0.07 for 12 – 18 % melting, consistent with a slope of ~0 in Figure 6a. The basalts with Mg > 6 wt.% all have CaO/Al₂O₃ slightly below the BSE value of 0.8; the TiO₂/Al₂O₃ ratio in these basalts is slightly higher than the chondritic ratio (Figure 6a,b). These features are consistent with melting experiments of spinel peridotite [Baker and Stolper, 1994]. The Na₂O/Sm ratio is slightly lower than the BSE ratio, consistent with a relatively primitive source for the ST basalts. Finally, the Sm/Yb ratio is slightly higher than chondritic for the basalts with MgO > 6 wt.% while it is substantially higher for the picrites and the basalts with MgO < 6 wt.%. This suggests that the picrites and the fractionated basalts formed from a source with a substantial amount of garnet. However, the Sm/Yb ratios effectively rule out garnet as a major component in the source of the basalts with MgO > 6 wt.%. In fact the Putorana basalts have Sm/Nd and Sm/Yb ratios similar to some of the least fractionated basalts in the upper part of the Noril'sk section. Modeling of rare earth element patterns [White and McKenzie, 1995] is consistent with production of such magmas by decompressional melting primarily of spinel lherzolite at 50-80km depths. Our results demonstrate that this applies to the main volume of the Siberian lavas and not just the top of the Noril'sk section. This requires the emplacement of the plume to shallow levels within the lithosphere and consequent rapid magma generation by decompressional melting.

Conclusions

Based on major element and Nd isotopic data the ST falls into three groups: i) Relatively unfractionated tholeiitic basalts with MgO in the range 6 to 11 wt.%, with approximately 12 % fractional crystallization of olivine. The primary tholeiitic picritic magmas for these lavas had 11.5 – 13 wt. % MgO, 1.5 – 2.2 wt. % Na₂O and 9.5 – 13 wt. % FeO*. The Na₂O versus MgO relations for these lavas imply that they formed by about 12 to 18 % partial melting of a relatively undepleted mantle source. Most of these lavas are from the Putorana subprovince, the most voluminous of the ST, and typically have ε_{Nd} values of 0 to +2, and element ratios consistent with derivation primarily in the spinel peridotite facies from an undepleted lower mantle derived plume. ii) Picrites with 13-18 wt.% MgO. Most of these lavas are from Noril'sk and appear to have olivine accumulation in melts with a more complex chemical and isotopic evolution than the basalts above. The isotopic data on these lavas require contributions from depleted asthenospheric mantle as well as ancient enriched lithospheric mantle. They are not parental magmas to the upper units and have both different composition and sources compared to the inferred picritic parental magmas of the bulk of the ST lavas. iii) Highly fractionated basalts with less than 6 wt.% MgO, mostly from Noril'sk, appear to have varied source materials, including lithospheric mantle. Thus, the ST data are consistent with the bulk of the basalt

generation by decompressional melting within the Siberian lithosphere of an undepleted lower mantle-derived plume.

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