Evaluation of different models for the origin of the Siberian Traps

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ABSTRACT

Various types of evidence, including the size and volume of the Siberian Traps, the timing and duration of eruptions, paleotectonic and paleogeographic reconstructions, lithospheric structure, heatflow, and the trace-element and radiogenic isotope compositions of lava, are reviewed in this chapter. The major evidence may be summarized as follows. The Siberian Traps erupted in a number of brief volcanic events from the Late Permian until the end of the Middle Triassic. They occupied a vast region (~7 × 10^6 km^2) in a back-arc tectonic setting. The overall volume of erupted rocks was as much as ~4 × 10^6 km^3, with most of the volume erupted within the Tunguska syncline. This syncline experienced long-term subsidence before initiation of the volcanism, and the region is now underlain by a very thin lithosphere, which is ~180 km thick. Two types of trace-element patterns are observed in the Siberian Traps: subordinate high-Ti ocean island basaltic-like patterns and dominant low-Ti island arc basaltic-like patterns. In radiogenic isotope and trace-element coordinates, mixing trends between these two types of magma are absent, or at least not evident. Some volcanic rocks contain primary magmatic mica. These are considered in light of different models. Each model can explain, or was thought to explain, particular observations. However, some evidence can be fatal for some models. For example, the enormous size and volume of the Siberian Traps cannot be explained in the framework of impact and edge-driven convection models and are problematic for lithospheric delamination models. Plume models face problems in explaining the uplift and subsidence pattern and the absence of mixing curves between expected high-Ti primary plume melts and contaminated low-Ti melts. Therefore, a model that relates Siberian Trap magmatism and subduction is suggested. In this model, subducting slabs brought significant amounts of water into the mantle transition zone. Consequent release of water from the transition zone lowered the solidus of the upper mantle, leading to voluminous melting. Major supporting observations for this model include (1) the tectonic position of the Siberian Traps in a back-arc setting of Permian subduction systems, (2) island arc basaltic-like trace-element patterns for the majority of the erupted basalts, (3) primary mica found in volcanic rocks, and (4) experimental data on the high water capacity of the mantle transition zone and its recharging via the subduction process.

Keywords: Siberian Traps, subduction, plume, delamination, convection, impact

INTRODUCTION

A number of completely different models have been discussed in the scientific literature to explain the origin of the Siberian Traps. These include the extraterrestrial bolide impact model (Jones et al., 2002) and terrestrial models, which consider the Siberian Traps to result from a large mantle plume from the core-mantle boundary (Campbell and Griffiths, 1990), lithospheric delamination involving a weaker plume (Elkins-Tanton, 2005), redistribution of heat in the upper mantle without a plume (King and Anderson, 1998; Puffer, 2001), or saturation of the upper mantle with water following prolonged subduction beneath Siberia (Ivanov and Balyshev, 2005). The plume model is the most popular, and thus it is considered the conventional model. Other models are viewed as alternatives. Each model employs its own line of arguments. Useful evidence includes magma volumes, timing of magmatism, uplift history, geophysical data, and trace-element and isotope geochemistry. This chapter evaluates the conventional and alternative models from the viewpoint of the evidence.

TERMINOLOGY

Large Igneous Province and Flood Basalt Province

The Siberian Traps contain mafic, ultramafic, and silicic rocks, both intrusive and effusive. In this sense the Siberian Traps is a large igneous province (LIP) because it is large and igneous (for discussion of the definition and classification of LIPs, see http://www.mantleplumes.org/LIPI html#Discussion). The Siberian Traps were built from one or more volcanic events involving the outpouring of large volumes of mainly basaltic magma. The large volumes distinguish the Siberian Traps, which are, in this sense, a flood basalt province (FBP). Therefore, in this chapter I use two terms: (1) the Siberian Traps LIP, meaning the spatially and temporally related rocks of different composition and probably variable origin, and (2) the Siberian Traps FBP, meaning the large volume of mainly basaltic volcanic units. The majority of the Siberian Traps FBP units have distinct subduction-like major- and trace-element features such as low concentrations of high field-strength elements (HFSE) relative to large-ion lithophile elements (LILE) (Fedorenko et al., 1996; Puffer, 2001; Ivanov and Balyshev, 2005).

Plumes and Plate Tectonic Processes

Morgan (1971) suggested that plumes are localized upwelling convective currents originating in the lower mantle, probably at the core-mantle boundary. He suggested that plumes are the driving force for plate tectonics. As noted by Korenaga (2005), in the fluid dynamic literature a plume is any self-buoyancy-driven flow. In this sense, all subducting slabs, sinking delaminated lower crust, and Morganian lower-mantle upwellings are plumes. Such usage of the term however, is unacceptable to Earth scientists, who distinguish between subduction-related volcanism occurring at plate boundaries and intraplate volcanism occurring far from plate boundaries. Many different, sometimes contradictory, definitions of plumes can be found in the literature. A complete survey of plume definitions is beyond the scope of this chapter, but the following quote from Campbell (2005, p. 265) expresses a commonly held view of what a “mantle plume” is:

“High-pressure experimental studies of the melting point of iron-nickel alloys show that the core is several hundred degrees hotter than the overlying mantle. A temperature difference of this magnitude is expected to produce an unstable boundary layer above the core which, in turn, should produce plumes of hot, solid material that rise through the mantle, driven by their thermal buoyancy. Therefore, from theoretical considerations, mantle plumes are the inevitable consequence of a hot core.”

Such plumes, referred to as Morganian by Courtillot et al. (2003), are often viewed as phenomena unrelated to plate tectonics. Plates can be driven by cooling from above without internal heating (Anderson, 2001), whereas Morganian plumes are driven by heating from the core (Courtillot et al., 2003; Campbell, 2005). According to the conventional view, Morganian plumes are necessary to form LIPs. They may or may not lead to breakup of a continent (e.g., the Central Atlantic magmatic province and the Siberian Traps, respectively). Therefore, in evaluating plume models in this chapter, I use the term plume only for first-order upwelling currents, which are either unrelated to plate tectonics or play a role as its driving force. Any upper-mantle processes (e.g., shallow recycling of subducted material, upper-mantle convection) are considered nonplume plate tectonic processes. Lithospheric delamination may be related either to plume or to plate tectonic processes depending on the original causes of the delamination.

EVIDENCE

Size and Volume

The Siberian Traps LIP is one of the largest in size and volume on Earth, though estimates vary significantly. For example, Fedorenko et al. (1996) referred to the work of Milanovskiy (1976), whose estimates of its size and volume were $4 \times 10^6$ km$^2$ and $>2 \times 10^6$ km$^3$. Fedorenko et al. (1996) wrote, “We believe that even this volume may be underestimated.” Reichow et al. (2002) estimated separately the sizes of the Siberian Traps LIP located on the Siberian craton and in the West Siberian basin, as $2.6 \times 10^6$ km$^2$ ($1 \times 10^6$ km$^3$) and $1.3 \times 10^6$ km$^2$ ($1.3 \times 10^6$ km$^3$), respectively. The distribution of igneous rocks that can be attributed to the Siberian Traps LIP is shown in Figure 1, from Masaitis (1983). According to this author, the area of the Siberian Traps LIP is $\sim 7 \times 10^6$ km$^2$, and the volume could be as much as $4 \times 10^6$ km$^3$. This volume is not the largest reported in the literature. Dobretsov (2003) estimated that it is over $16 \times 10^6$ km$^3$, including the Kara and Barents undersea areas.
The various estimates of the size of the Siberian Traps LIP reported in the literature are summarized in Table 1. Most of these, however, are rough guesses from the size and average thickness of volcanogenic deposits. Precise calculation of the volume has been performed only by Vasil’ev et al. (2000). These authors focused on the cratonic part and calculated separately the present-day preserved volume of lava and volcanoclastic and intrusive rocks using geological survey data. Note that the size of the Siberian Traps erupted on the platform after Vasil’ev et al. (2000) is on the same order as the size assumed by Milanovskiy (1976) and Reichow et al. (2002) for the whole LIP. This is partly because a large part of the Siberian Platform experienced only intrusive magmatism with extensive but relatively low-volume sills that are hardly exposed on the surface and known mostly from drilling. The volume estimated by Vasil’ev et al. (2000) is $1.75 \times 10^6 \text{ km}^3$, over half of which is located in the Tunguska syncline. Tuffs are abundant within the syncline (Fig. 1).

The estimates discussed earlier form three general groups:

1. A size of $\sim 4 \times 10^6 \text{ km}^2$ and a volume of $\sim 2 \times 10^6 \text{ km}^3$...
TABLE 1. ESTIMATES OF THE SIZE AND VOLUME OF THE SIBERIAN TRAPS LARGE IGNEOUS PROVINCE

<table>
<thead>
<tr>
<th>Papers (in chronological order)</th>
<th>Size (10⁶ km²)</th>
<th>Volume (10⁶ km³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Milanovskiy (1976)</td>
<td>4</td>
<td>≥2</td>
</tr>
<tr>
<td>Masaitis (1983)</td>
<td>~7 × 10⁶</td>
<td>≤4</td>
</tr>
<tr>
<td>Fedorenko et al. (1996)</td>
<td>n.r.</td>
<td>&gt;2</td>
</tr>
<tr>
<td>Vasil’ev et al. (2000)³</td>
<td>4.31 ± 2 – 8.6</td>
<td>1.751 ± 9 × 2 – 3.5</td>
</tr>
<tr>
<td>Reichow et al. (2002)</td>
<td>3.9</td>
<td>2.3</td>
</tr>
<tr>
<td>Dobretsov (2003) n.r.</td>
<td></td>
<td>≥16</td>
</tr>
</tbody>
</table>

Notes: n.r.—not reported.

³The calculations of Vasil’ev et al. (2000) were only for the Siberian craton, so those authors multiplied by 2 to estimate the total.

The Siberian Traps FBP has been widely considered to have formed during 1 m.y. or less despite the fact that older and younger ages have been published (e.g., Dalrymple et al., 1995; Reichow et al., 2002). For example, Walderhaug et al. (2005) obtained Middle–Late Triassic ⁴⁰Ar/³⁹Ar ages and paleomagnetic poles for dolerite sills emplaced within Taimyr peninsula and concluded that these rocks are unrelated to the Siberian Traps FBP because of the assumption that the Siberian Traps FBP was a Permo-Triassic boundary event. However, to be correct, it is unknown when there were major (by volume) events within the Siberian Traps. Figure 2 summarizes dated localities within approximately one-fourth of the Siberian Traps LIP. It clearly shows that most Permo-Triassic ages come from a narrow strip from the Noril’sk-Kharaelakh to the Mainmecha-Kotui subprovince. Huge regions have not been studied by precise radioisotopic dating.

Timing

Comments on the Use of Different Isotopic Systems. The question of timing is discussed here on the basis of U-Pb and ⁴⁰Ar/³⁹Ar dating. Both radioisotopic systems may yield erroneous ages due to loss of radiogenic lead and argon (giving younger apparent ages) and inherited lead and extraneous argon (giving older apparent ages). In general, particular criteria such as concordance in the U-Pb system and plateau in the ⁴⁰Ar/³⁹Ar system have been developed to separate the true crystallization ages from apparent ages. However, when dealing with a short time duration, an error of a few million years may bias the conclusions (e.g., see Renne, 1995, for ⁴⁰Ar/³⁹Ar reconsideration of the Noril’sk-I intrusion and Mundil et al., 2004, for debate on the U-Pb age of the Permo-Triassic boundary). Zircon and baddeleyite U-Pb ages are usually considered more reliable than ⁴⁰Ar/³⁹Ar ages. However, zircon and baddeleyite are rare minerals in basaltic melts, and thus there are few published U-Pb ages for the Siberian Traps FBP. ⁴⁰Ar/³⁹Ar ages are more abundant. They are reported (recalculated) here relative to the same age of 98.79 Ma for the GA1550 standard (Renne et al., 1998) unless otherwise stated. The choice of this age merely reflects the fact that it was used in the two most recent reviews of the Siberian Traps (Reichow et al., 2002; Ivanov et al., 2005). Accepting this age for the GA1550 standard makes the ⁴⁰Ar/³⁹Ar ages 0.7% younger than the U-Pb ages. The reason for the difference is most likely due to biased ⁴⁰K decay constants (e.g., Min et al., 2000; Ivanov, 2006) using a more recent value of 98.5 Ma (Spell and McDougall, 2003) for the GA1550 standard makes the ⁴⁰Ar/³⁹Ar ages 0.9% younger than the U-Pb ages (Ivanov, 2006). The errors in the ⁴⁰Ar/³⁹Ar ages shown here are at the 2σ level and include reported analytical errors on the J-factor, but not errors that would result from inhomogeneities of the standards (because this information is rarely reported in original publications) and errors due to intercalibration of the standards.

Duration of Siberian Traps FBP Magmatism. A short duration for Siberian Traps FBP magmatism was suggested on the basis of two ⁴⁰Ar/³⁹Ar ages (Renne and Basu, 1991), for the stratigraphically oldest and youngest lava units in the northern part of the FBP (for locations of dated samples, see Fig. 2). Later it was shown that these ages are statistically indistinguishable from the ⁴⁰Ar/³⁹Ar age for the Permo-Triassic boundary dated from the Meishan section in China (Renne et al., 1995). Since then, the Siberian Traps FBP has been widely considered to have formed during 1 m.y. or less despite the fact that older and younger ages have been published (e.g., Dalrymple et al., 1995; Reichow et al., 2002). For example, Walderhaug et al. (2005) obtained Middle–Late Triassic ⁴⁰Ar/³⁹Ar ages and paleomagnetic poles for dolerite sills emplaced within Taimyr peninsula and concluded that these rocks are unrelated to the Siberian Traps FBP because of the assumption that the Siberian Traps FBP was a Permo-Triassic boundary event. However, to be correct, it is unknown when there were major (by volume) events within the Siberian Traps. Figure 2 summarizes dated localities within approximately one-fourth of the Siberian Traps LIP. It clearly shows that most Permo-Triassic ages come from a narrow strip from the Noril’sk-Kharaelakh to the Mainmecha-Kotui subprovince. Huge regions have not been studied by precise radioisotopic age dating!

A basis for suggesting that the Siberian Traps FBP formed over a prolonged interval of time up to the Middle–Late Triassic, and probably in multiple volcanic events, is the following: (1) Tunguska subprovince, with the most voluminous volcanic deposits (see the earlier estimations of the volume) is characterized by Middle Triassic and Middle–Late Triassic ⁴⁰Ar/³⁹Ar ages (240.7 ± 2.8 Ma for Korvuchana tuffs and 232.1 ± 4.6 Ma for an uppermost lava unit; Baks and Farrar, 1991); (2) Usol’skii sill, emplaced within Angara-Taseevskaya syncline (Fig. 1), yielded an Early Triassic ⁴⁰Ar/³⁹Ar age (243.9 ± 1.4 Ma; Ivanov et al., 2005); (3) combined paleomagnetic and ⁴⁰Ar/³⁹Ar studies show that doleritic sills from Taimyr peninsula were emplaced in the Middle–Late Triassic (230.2 ± 14, 230.7 ± 2.5, and 232.5 ± 8 Ma; Walderhaug et al., 2005); (4) Daldykan dolerite sill emplaced within the Noril’sk-Kharaelakh subprovince and Avamsky dike within the Kamensk subprovince yielded Middle and Middle–Late Triassic ⁴⁰Ar/³⁹Ar ages, respectively (299.9 ± 2.6
and 226.4 ± 1.6 Ma; Dalrymple et al., 1995); (5) lamproite dikes in the southern mountains framing the Kuznetsk basin yielded Early and Middle Triassic 40Ar/39Ar ages (the original 40Ar/39Ar values relative to the MCA-11 standard with no reported age were 244.0 ± 0.8, 244.4 ± 0.8, 245.7 ± 0.7, and 236.5 ± 3.8 Ma; Vrublevskii et al., 2004); (6) the Nadezhinsky and Honama-Makitsky Suites within the Central Putorana subprovince yielded 40Ar/39Ar ages of 246.6 ± 2.4 and 241.0 ± 2.5 Ma, respectively (the absolute values may be slightly biased by the J-factor, but the age difference of 5.6 ± 3.5 Ma will remain unchanged for these two suites, as discussed by Ivanov et al. (2006); (g) combined paleomagnetic and biostratigraphic study of the SG-6 superdeep drillhole revealed that volcanic rocks in the deep rift structures of the West Siberian basin were formed up to the Early–Middle Triassic (Olenekian–Anisian) (Kazanskii et al., 2000).

Many of the volcanic and intrusive rocks mentioned earlier have traditionally been considered part of the Siberian Traps FBP. In the section on geochemistry I shall show that Usol’skii sill dolerites are practically indistinguishable on the basis of trace elements from geochemically uniform upper lava units in the Noril’sk-Kharaelakh subprovince. Therefore, magmas of similar composition were erupted in different regions at different times. A detailed 40Ar/39Ar study of the Ethiopian Traps FBP revealed the same feature: chemically similar magmas erupted during different pulses of volcanism (Kieffer et al., 2004).

It is worth repeating that thick lavas in the north Siberian Traps were formed briefly at the Permo-Triassic boundary, but
in other regions voluminous eruptions occurred during other, probably also brief, periods of time (Fig. 3).

**Timing of Initial Eruptions within the Siberian Traps FBP**

Basu et al. (1995) reported a Late Permian $^{40}\text{Ar}^{39}\text{Ar}$ age of 253.3 ± 2.6 Ma for phlogopite from olivine nephelinite in the Arydjansky Suite, which represents the initial phase of mafism in the northern part of the Maimecha-Kotui subprovince. This age is significantly older than the Permo-Triassic age of the initial lava suites of the Khantaisk-Rybninsk subprovince dated in the same laboratory (Renne and Basu, 1991). However, for the Arydjansky Suite, Kamo et al. (2003) reported the U-Pb perovskite age of 251.7 ± 0.4 Ma, which is statistically indistinguishable from the Permo-Triassic U-Pb zircon and baddeleyite age 251.2 ± 0.3 Ma for the Noril’sk-I ore-bearing intrusion of the Noril’sk-Kharaelakh subprovince (Kamo et al., 1996).

Ivanov (2006) compared $^{40}\text{Ar}^{39}\text{Ar}$ and U-Pb ages obtained for the same intrusions and lava units from the Siberian Traps LIP, among other regions, and showed that the $^{40}\text{Ar}^{39}\text{Ar}$ ages are systematically younger than the U-Pb ages. The exception is the $^{40}\text{Ar}^{39}\text{Ar}$–U-Pb pair age for the Arydjansky Suite. This inconsistency may be explained either by excess argon in the phlogopite, which leads to an older apparent $^{40}\text{Ar}^{39}\text{Ar}$ age, or by an incorrect correction for the initial Pb composition in the perovskite, which would lead to a younger U-Pb age.

Reichow et al. (2002) obtained Late Permian $^{40}\text{Ar}^{39}\text{Ar}$ ages for biotites from olivine gabbros of the Van Eganskaya borehole within the West Siberian basin (253.4 ± 0.8 and 252.5 ± 1.5 Ma). These ages and a $^{40}\text{Ar}^{39}\text{Ar}$ age for the Arydjansky Suite are statistically indistinguishable. To verify this finding, Ivanov et al. (2006) performed a Monte Carlo test as follows. First, it was assumed that all Permo-Triassic $^{40}\text{Ar}^{39}\text{Ar}$ ages are true crystallization ages. Second, a data set of ages in the range 260–220 Ma with errors similar to true analytical errors was stochastically created. Third, the Permo-Triassic and stochastic ages were plotted as a probability distribution. The second and third steps were repeated about one hundred times. The highest stochastic peak heights are lower than that of the late Permian $^{40}\text{Ar}^{39}\text{Ar}$ peak, showing that the coincidence between West Siberian Basin gabbro and Arydjansky Suite ages is not due to stochastic errors (Fig. 3).

In the Kuznets basin there are mafic rocks of both Late Permian and Early Triassic age (e.g., Dobretsov et al., 2005). The reported $^{40}\text{Ar}^{39}\text{Ar}$ ages (Dobretsov et al., 2005) are, however, not supported by analytical details, whereas all age spectra shown by Fedoseev et al. (2005) revealed disturbed K-Ar isotope systems in the samples studied (though the authors, unaware of this disturbance, interpreted the spectra as true crystallization ages). Paleomagnetic study of the SG-6 superdeep drillhole has shown that the initial volcanic rocks are as old as latest Late Permian (upper Late Tatatrian) (Kazanskii et al., 2000).

In summarizing the data presented in this section I should mention that the question of timing of the initial eruptions within the Siberian Traps FBP requires further geochronological investigation. At present, it is obvious that in the West Siberian basin the oldest mafic magmas erupted at the end of the Permian. Probably simultaneous eruptions of mafic magmas took place in the Kuznets basin and in the northern part of the Siberian craton (in the Maimecha-Kotui subprovince).

**Timing of the Siberian Traps LIP**

As mentioned earlier, the Siberian Traps LIP is a broad term that includes, in addition to mafic rocks, intrusive rocks of acidic composition. So-called anorogenic granitoids (mainly granodiorites and granosyenites) are abundant in the Kuznets basin and its mountain borders and on the Taimyr peninsula (e.g., Vernikovsky et al., 2003; Dobretsov et al., 2005). The Bolgokhtokh granodiorite intrusion is known in the Noril’sk-Kharaelakh subprovince (e.g., Kamo et al., 2003). An important feature of these anorogenic granitoids is that the oldest are characterized by zircon U-Pb ages that are statistically indistinguishable from those of the Permo-Triassic boundary (256 ± 8, 253 ± 4, and 245 ± 7 Ma for different massifs of the late Kolba Complex within the mountain border of the Kuznets basin (Vladimirov et al., 2001) and 249.0 ± 5.2 Ma for the Taimyr (Vernikovsky et al., 2003); it is debated whether the U-Pb age of the Permo-Triassic boundary is 251.4 ± 0.3 Ma (Bowring et al., 1998) or 252.6 ± 0.3 Ma (Mundil et al., 2004). The youngest anorogenic granitoids yielded Middle–Late Triassic ages (231 ± 11 and 225 ± 4 Ma for different massifs of the Monastyrskii Complex within the mountains bordering the Kuznets Basin (Vladimirov et al., 2001) and 229.0 ± 0.4 Ma for the Bolgokhtokh granodiorite intrusion (Kamo et al., 2003). Therefore, the mafic and acidic magmatism of the Siberian Traps was, in general, coeval.
Uplift History

There is debate about the subsidence-uplift history in the region of the Siberian Traps LIP. Czamanske et al. (1998) noted that volcanic rocks on the Siberian craton erupted within a subsided Tunguska syncline and that these rocks were not preceded by any uplift, as would be expected from a plume model (e.g., Campbell and Griffiths, 1990; Campbell, 2005). Saunders et al. (2005) claimed that there was plume-related uplift in the area of the West Siberian basin and that this uplift is now hidden beneath Mesozoic sedimentary cover.

In Figure 4 a paleogeographic map of Siberia is shown for the Early Permian (Vinogradov, 1968). The subsidence-uplift pattern shown in Figure 4 remained virtually unchanged until the Permo-Triassic boundary, as reflected by paleogeographic maps reconstructed through different stratigraphic ages (Vinogradov, 1968). Deep rifts in the West Siberian basin (the long, linear south-north structures in Fig. 1) developed mainly in the Triassic along a preexisting long north-south linear uplift. Uplift commenced at least 25–30 m.y. before initiation of Siberian Traps magmatism. Tectonic development of this region may be interpreted in the context of collision between Euro-American (the left part of Fig. 4), Kazakh (bottom left part of Fig. 4), and Siberian (central part of the Fig. 4) paleocontinents (Podurushin, 2002). Saunders et al. (2005), however, argued for a relationship between the uplift and a plume. The question as to whether the subsidence-uplift history recorded for Siberia is associated with a plume is considered in more detail below.

Tectonic Setting

In the Permian and the Permo-Triassic, Siberia was part of Pangea. It was surrounded by convergent plate boundaries with subduction of oceanic plates beneath the continent (Fig. 5) (Nikishin et al., 2002). In present-day coordinates, the southern remnant of the convergent plate boundary is represented by the Mongolia-Okhotsk suture zone (e.g., Zonenshain et al., 1990; Zorin, 1999). It is ~800 km south of the southeastern end of the Siberian Traps LIP (Fig. 1). Noril’sk is ~2500 km from the Mongolia-Okhotsk suture zone. According to paleotectonic reconstructions in the east and southwest (in present-day coordinates) there should be other Permian subduction systems (Fig. 5).

The Transbaikalian volcano-plutonic belt was located between the Mongolia-Okhotsk suture zone and the Siberian Traps LIP (Fig. 1). This belt developed in the Permian and the Triassic and is composed of granitic and syenitic batholites, basaltic and rhyolitic volcanic deposits, and dikes (e.g., Yarmolyuk et al., 2001). The origin of the belt is debated. Some authors attribute it to the Siberian Traps LIP (Dobretsov, 2003, 2005), but others consider it an independent intraplate rift phenomenon (Yarmolyuk et al., 2001) or a continental margin Andean-type orogen (Zorin et al., 1998; Zorin, 1999; Nikishin et al., 2002).

Geophysics

Lithospheric Structure. The upper mantle structure beneath Siberia has been investigated in a number of studies using nuclear explosion data (Thybo and Perchuc, 1997; Morozov et al., 1999; Egorkin, 2001; 2004; Pavlenkova et al., 2002; Pavlenkova, 2006; Pavlenkova and Pavlenkova, 2006). Notable features are alternating low- and high-velocity zones in the upper mantle, despite some mismatch between published results on their depths. It is not clear from the seismic data at what depth the lithosphere-asthenosphere boundary lies. Most likely the base of the lithosphere is at the so-called L-boundary (Pavlenkova et al., 2002; Pavlenkova, 2006; Pavlenkova and Pavlenkova, 2006).
Lithospheric low-velocity zones have been interpreted as thin fluid-rich or partial melt–bearing layers (e.g., Thybo and Perchuc, 1997; Pavlenkova and Pavlenkova, 2006; Pontevivo and Thybo, 2006). A 3-D model of the L-boundary is shown in Figure 1 (from Pavlenkova and Pavlenkova, 2006). The thinnest rounded part corresponds to the position of the Tunguska syncline, and the thickest part underlies the West Siberian basin. The seismic structure disagrees with a thermal model that places the hottest, thinnest parts and the coldest, thickest parts of the lithosphere beneath the West Siberian basin and the Siberian craton, respectively (Artemieva, 2006).

**Heatflow.** The Siberian craton is characterized by a low mean heatflow of ~40 mW/m², which is typical for cratons (Lysak, 1984). According to thermal modeling (Zorin and Vladimirov, 1989; Hyndman et al., 2005) such a low heatflow implies a very long (billions of years) history of stability of the lithosphere. In other words, if the lithosphere was significantly thinned at ca. 250 Ma, elevated heatflow would be expected. But this is not observed. However, the calculated thermal thicknesses of the lithosphere vary widely, from 180 to 350 km (Artemieva, 2006). The thermal thickness of the lithosphere beneath the West Siberian basin is ~100 km, similar to that of many mobile belts (Artemieva, 2006). As noted earlier, these results disagree with seismic data (Fig. 1).

**Geochemistry**

**Noril’sk-Kharaelakh Chemostratigraphic Subdivisions.** The Noril’sk-Kharaelakh subprovince is characterized by the presence of economically important Cu-Ni-Pt deposits (e.g., Naldrett et al. 1992). Due to this, more than 3 km thickness of lava was drilled out, and samples recovered horizon-by-horizon were analyzed in great detail (e.g., Lightfoot et al., 1993; Wooden et al., 1993).

Lava strata in the Noril’sk-Kharaelakh subprovince were subdivided into several suites and subsuites (formations and subformations; Fedorenko, 1981; Zolotukhin et al., 1984, 1986) (Fig. 6). These suites and subsuites were grouped into early, middle, and late assemblages, which in practice correspond to three major chemical units: high-Ti, low-Ti–2, and low-Ti–1 (Fedorenko, 1981; Fedorenko et al., 1996). High- and low-Ti series were distinguished by Lightfoot et al. (1993) on the basis of a TiO₂-Mg# diagram. Ivanov and Balyshev (2005) suggested using a discrimination line calculated as TiO₂ = 3.45 – 0.0317 × Mg#, where Mg# is Mg/(Mg + 0.85Fe total) (elements are presented in atomic units, and Fe total is calculated from FeO total). High-Ti rocks are characterized by higher ratios of light and middle rare earth elements (REE) compared to the low-Ti rocks. For example, Fedorenko et al. (1996) separated rocks of the high- and low-Ti series by a divider of Gd/Yb = 2. These authors used the Th/U ratio to distinguish two subseries of the low-Ti rocks; a lower Th/U, generally below 3.5, characterized the low-Ti–1 subseries, and a higher Th/U, above 3.2, characterized the low-Ti–2 subseries. In the ∆8/4–Th/U diagram, basalts of the Noril’sk-Kharaelakh subprovince are separated into two groups (Fig. 7); a group of DUPAL basalts with ∆8/4 > ~50, Th/U > ~2.5, and with systematically more radiogenic Sr and Nd isotopes and a group of non-DUPAL basalts with ∆8/4 < ~70, Th/U < ~3.0, and nonradiogenic Sr and Nd isotopes (∆8/4 is calculated as 100 × ([208Pb/204Pb] Pb/204Pb) / (1.209 × 206Pb/204Pb)) (Hart, 1984), reflecting a shift in the 208Pb/204Pb–206Pb/204Pb diagram from a linear regression line through north Atlantic MORBs. DUPAL is an acronym for the names of Dupré and Allègre (1985). It appears that DUPAL and non-DUPAL basalts alternate in the continuous lava pile (Fig. 6). Changes between different chemostratigraphic subdivisions are very sharp, without any mixing trends on isotopic and trace-element diagrams (Fig. 7).

DUPAL basalts are systematically depleted in Pt and Pd (usually at the detection limit of neutron activation, with the exception of part of the Tuklonsky Suite; Wooden et al., 1993). Non-DUPAL basalts yield higher concentrations of Pt and Pd distributed in a Gaussian fashion (Fig. 8). DUPAL rocks are generally more enriched in the radiogenic isotopes Sr and Nd,
though there is a large overlap. Initial values at 250 Ma are as follows: $^{87}\text{Sr}/^{86}\text{Sr}$ from 0.7053 to 0.7088 and $\varepsilon_{\text{Nd}}$ from 2 to –11 for DUPAL and $^{87}\text{Sr}/^{86}\text{Sr}$ from 0.7041 to 0.7072 and $\varepsilon_{\text{Nd}}$ from 4.2 to –2.5 for non-DUPAL rocks, where $\varepsilon_{\text{Nd}} = ([^{143}\text{Nd}/^{144}\text{Nd}]_{\text{sample}}/[^{143}\text{Nd}/^{144}\text{Nd}]_{\text{chondrite}} – 1) \times 10,000$ at 250 Ma. Limited data for osmium isotopes show that Tuklonsky DUPAL rocks and Gudchikhinsky non-DUPAL rocks have similar positive $\gamma_{\text{Os}}$ values of 3.4–6.5 and 5.3–6.1, respectively, where $\gamma_{\text{Os}} = ([^{187}\text{Os}/^{188}\text{Os}]_{\text{sample}}/[^{187}\text{Os}/^{188}\text{Os}]_{\text{chondrite}} – 1) \times 100$ at 250 Ma; Horan et al., 1995).

Such distribution of Pt and Pd together with radiogenic isotopes and trace-element data can be interpreted as evidence for an eclogitic source of the DUPAL basalts of the Noril’sk-Kharaelakh subprovince. It is worth mentioning that DUPAL basalts are interpreted as derivates of an eclogitic (recycled crustal) source everywhere in the world (see the discussion in Ivanov and Balyshev, 2005), including the classical DUPAL of the Indian Ocean (e.g., Escrig et al., 2004; Meyzen et al., 2005).

Figure 9 gives an overview of trace-element patterns in different chemostratigraphic units of the Noril’sk-Kharaelakh subprovince. It may be seen that there are two major types, with trace-element concentrations (1) at a level of ocean island basalts (OIB) and (2) at a level of enriched mid-ocean ridge basalts (E-MORB). The Nadezhdinsky Suite is enriched in the most incompatible elements (Rb to K), like OIB, but depleted in more compatible elements (Sr to Yb), like E-MORB. Despite the similar levels of concentration, the trace-element patterns exhibit more irregular patterns than do OIB and E-MORB. A general feature of most suites is depletion of Ta relative to La and K. The Gudchikhinsky Suite is an exception. However, it differs from E-MORB in depletion of K and Ba and absence of depletion in Pb relative to Ce and Pr. The Ivakinsky Subsuite is similar to OIB, but differs from it in depletion of Sr and enrichment of Ba, Th, U, and P relative to neighboring elements.

Heavy REE are compatible (e.g., Green, 1994) in garnet,
and therefore melting of garnet-bearing mantle will produce particular REE patterns in the derivative melts with high ratios of light to heavy REE at low concentrations of heavy REE. In spinel, heavy REE are incompatible, producing low ratios of light to heavy REE with highly variable concentrations of the heavy REE (compare Models 1 and 2 in Fig. 10). This reasoning would lead to estimation that the source mineralogy of Siberian Traps basalts lies within the shallow (less than 50–60 km depth) spinel stability field of the mantle. The lithosphere is at least 180 km thick beneath the Tunguska syncline and more than 240 km thick beneath Noril’sk. The lithosphere could not be thinned to 60 km and restored to the normal cratonic value in only 250 m.y. (Zorin and Vladimirov, 1989; Hyndman et al., 2005). Therefore, either voluminous melting appeared solely within cold cratonic lithosphere, which is unlikely from the thermal point of view, or geochemical data require another explanation. From Mg# variations, only a few stratigraphic units at Noril’sk can be regarded as containing primary mantle-derived melts. These are the non-DUPAL Gudchikhinsky Subsuite and the DUPAL Tuklonsky Suite (Figs. 6 and 10). Their compositions can be modeled as ∼18% and ∼45–70% partial melting from garnet lherzolite and eclogite, respectively (Fig. 10). All other stratigraphic units contain variably differentiated melts. Due to the differentiation, these melts are characterized by higher Yb content. It should be noted that the modeling presented in Figure 10 shows in principle the possibility of derivation of the Siberian Traps basalts from garnet-bearing sources with consequent differentiation rather than finding the best-fitting solution for each suite.

The Maimecha-Kotui Subprovince. In the Maimecha-Kotui subprovince, a lava stratum ∼4 km thick formed. Initial eruptions of the Aryzhansky Suite high-Ti lava took place probably as early as the Late Permian, as shown by 40Ar/39Ar dating (Basu et al., 1995), but this was questioned by a Permo-Triassic U-Pb perovskite age (Kamo et al., 2003; see the earlier section on dating). A large part of the stratum consists of low-Ti basalts similar to the Noril’sk-Kharaelakh low-Ti basalts. The uppermost Maymechinsky Suite was preceded by the high-Ti Delkansky Suite (Fedorenko and Czamanske, 1997). High-Ti lavas including unusual picritic lavas, meimechites, comprise ∼50% by volume. The Maymechinsky Suite makes up no more than one-third of the total lava sequence. This suite is intruded by carbonatites with a U-Pb baddeleyite age of 250.2 ± 0.3 Ma (Kamo et al., 2003).

Meimechites are of particular interest. These are unusual high-Mg (MgO > 18 wt%), high-Ti (TiO2 > 1 wt%) mafic and ultramafic rocks (SiO2 < 52 wt%) (Le Bas and Streckeisen, 1991). They are characterized by porphyritic texture, with olivine and serpentine phenocrysts in a dark feldspar-free groundmass. Primary biotite also occurs occasionally (e.g., Fedorenko and Czamanske, 1997). These rocks exhibit enriched OIB-type trace-element patterns without Ta-Nb depletion and depleted Sr and Nd isotopes (87Sr/86Sr from 0.7030 to 0.7034 and δNd from 2.8
to 5.9; Arndt et al., 1995). Arndt et al. (1995) concluded that it is not evident from what source (lithospheric or sublithospheric) the meimechites originated. Kogarko and Ryabchikov (1995) suggested they formed from interaction of sublithospheric melts with lithospheric refractory harzburgites. In both cases a low degree of melting for the primary meimechite melts was accepted (Arndt et al., 1995; Kogarko and Ryabchikov, 1995).

A high Mg content is usually considered evidence of high temperature. On the basis of analysis of melt inclusions in the meimechites and numerical calculations, Sobolev et al. (1991) suggested that meimechites were derived from a depth of 230–300 km at a temperature of 1800–1900 °C due to mantle upwelling of a plume from greater depths (~700 km). Elkins-Tanton et al. (2007) performed an experimental study of the meimechites and concluded that their primary melts were derived from a source with as much as 1 wt% of H₂O at ~180 km depth and a temperature of 1700 °C. They noted that incorporation of additional H₂O and CO₂ would lower the temperature to 1550 °C.

The West Siberian Basin and Angara-Taseevskaya Syncline. Medvedev et al. (2003) and Reichow et al. (2005) provided analytical data on almost the same samples recovered from a number of drillholes in the West Siberian basin. The volcanic rock compositions vary from mafic to acidic. If only mafic rocks are considered, according to these authors’ data and the classification scheme of Fedorenko et al. (1996), all but one sample belongs to the low-Ti basalts (tholeiites and shoshonites).
Shoshonites and tholeiites exhibit similar island arc basalt (IAB)–like trace-element patterns, with Ba, U, Pb, and Sr relative enrichment and Nb relative depletion, though shoshonites are characterized by higher concentrations of most trace elements (Fig. 11). The dolerite sills of the Angara-Taseevskaya syncline are characterized by lower concentrations of the trace element at the level of E-MORB. But the IAB-like trace-element pattern is also typical of the dolerite sills. Usol’skii and Tolstomysovkii sill dolerites are geochemical analogues of the low-Ti–1 subseries and the low-Ti–2 subseries (Tuklonsky Suite) of the Noril’sk-Kharaelakh subprovince, respectively. This is reflected in their almost identical trace-element patterns and Sr isotopes (Ivanov et al., 2003).

Petrographic examination of the dolerite sills revealed that some samples contain primary magmatic mica, probably biotite (Fig. 12).

**DISCUSSION: EVIDENCE AND MODELS**

**Impact Model**

Interest in the impact model for the origin of the Siberian Traps FBP is mainly due to the idea that collisions of large extraterrestrial bodies with the Earth cause biotic mass extinctions, an idea that was originally suggested for the Cretaceous-Tertiary boundary (Alvarez et al., 1980) and also debated over years for the Permo-Triassic boundary (see Erwin et al., 2002, for a review). Two varieties of the impact model can be discussed in relation to the Siberian Traps FBP: one proposes that the impact site was somewhere within the Siberian Traps and impactor material. The latter model has related Cu-Ni-Pt mineralization in the Siberian Traps and impactor material. The latter model could explain the absence of a Permo-Triassic impact crater because of its disappearance due to subduction of the Pantalassa oceanic flow (see Fig. 5). In any case, the sizes of the impactor and the impact crater must be...
on the order of the Cretaceous-Tertiary meteorite and the Chicxulub Crater or even larger (≥10–15 km for the impactor and 200–300 km for the crater). However, each of these two impact models meets irresolvable problems in explaining the volume of the outpoured basaltic magma and the size of the Siberian Traps LIP (Fig. 1; Table 1). Various calculations suggest that an impact of such a size might have initiated magma generation on the order of \(10^5 \text{ km}^3\) (Glikson, 1999; Ivanov and Melosh, 2003). If an initial hot geotherm and thin oceanic lithosphere is considered, an increase in magma volume of up to \(2.5 \times 10^6 \text{ km}^3\) would be expected due to the additional effect of decompression (Jones et al., 2005). As Jones et al. (2005) noted, the largest impact would have generated a footprint up to 1000 km in diameter if it occurred on oceanic lithosphere, but much smaller if it occurred on continental lithosphere. Therefore, the extent of the Siberian Traps LIP (Fig. 1) is too large even for the most favored conditions of the impact model.

Besides the previously mentioned problems, a large impact would have left geochemical fingerprints in Permo-Triassic boundary sedimentary records. All earlier findings of such fingerprints have either been disproved or at least engendered doubts (see the critiques by Erwin et al., 2002, and by Koeberl et al., 2002, for reviews). The apparently prolonged volcanism of the Siberian Traps FBP, starting in the Late Permian and continuing until the end of the Middle Triassic, is also against the impact model.

**Plume Model**

To explain the large size of LIPs, Campbell and Griffiths (1990) suggested a starting plume head model in which a plume has a particular flattened head and a thin tail structure. The head is responsible for the voluminous eruptions. As Campbell (2005) recently pointed out, this model makes testable predictions: (1) new plumes consist of a large head and a thin tail; (2) flattened plume heads should be 2000–2500 km in diameter; (3) plumes must originate from a hot boundary layer, probably the core-mantle boundary; (4) both head and tail should erupt high-temperature picrites; (5) the temperature excess of a plume head is highest at the center of the head and decreases toward the margin; (6) picrites should erupt early during flood volcanism and be most abundant near the center of the plume head and less abundant toward the margin; and (7) flood basalt should be preceded by domal uplift of 500–1000 m at the center of the dome. Not all of the listed predictions can be tested for an ancient event such as that which produced the Siberian Traps FBP without additional assumptions. The following assumptions are numbered to correspond to the related predictions.

1. For example, we do not know whether a Siberian plume, if one existed, had a head-and-tail structure. According to the formulated plume model, the head and tail should yield a LIP (FBP) and a continuous chain of volcanoes, respectively (Campbell, 2005). A continuous volcanic chain from the Siberian Traps LIP to any active or more recent hotspot is unknown, though some authors speculate that there is a link between Iceland and the Siberian Traps and that the volcanic track between them is hidden beneath the polar ocean (e.g., Burke and Torsvik, 2004; Chernysheva et al., 2005).

2. The Siberian Traps LIP is larger than the expected 2000–2500 km circular flattened head (Fig. 1). Actually, the Siberian Traps do not exhibit a rounded structure, but rather their volcanic rocks filled preexisting elongated depressions (compare Figs. 1 and 4).

3. The depth of origin of the supposed plume cannot be inferred by any means, though Sobolev et al. (1991) interpreted their data on meimechites to suggest that these melts came from as deep as 700 km. On the basis of these extrapolations, the depth of origin and how to find it are both unclear.

4. Picrites are known from many parts of the Siberian Traps LIP. However, at least some are cumulates (for example, picrites within sills of the Angara-Taseevskaya syncline). Detailed petrographic studies are required from all over the Siberian Traps FBP to test a primary versus cumulative origin of the picrites.

5. The temperature profile of the mantle at 250 Ma is not known. However, we may expect the greatest erosion of the lithosphere where the plume is hottest, i.e., at its center. The geographical center of the Siberian Traps LIP is the western part of the Tunguska syncline (Fig. 1). The lithosphere there is significantly thinned (Fig. 1). This is in agreement with the prediction. However, because of the absence of uplift in the Tunguska syncline (Fig. 4), Saunders et al. (2005) placed the plume center beneath the West Siberian basin. The lithospheric thickness is great there (Fig. 1).

6. In the Noril’sk-Kharaulakh subprovince, picrites are recorded within the Gudchikhinsky and Tuklonsky Suites (see Fig. 6 for the stratigraphic locations of the suites). These are not the earliest suites. In the Maimecha-Kotui subprovince, the most magnesium, and expectedly the highest-temperature melts were erupted at the very end of the Permo-Triassic volcanism pulse, once more the opposite of what is predicted. If we locate the plume center in the geographical center of the Siberian Traps LIP, the meimechites appear to be at the margin of the supposed plume head. If instead we assume that the meimechites mark the position of the plume center, the plume would have been highly asymmetric even if the FPB extended into the Kara and Laptev undersea areas (Fig. 1).

7. There was no domal uplift at the center of the suggested plume head. Both the Tunguska and the Maimecha-Kotui subprovinces are located in subsided areas (Fig. 4). Burov and Guillou-Frottier (2005) calculated that a plume beneath a continent may result in a complex pattern of uplifts and sedimentary basins. They even showed that a subsidence may overlie the center of the plume head. One may then question the testability of the domal uplift prediction, when...
the presence of uplift prior to emplacement of the Emeishan Traps (He et al., 2003) is taken as classical evidence of a plume (Campbell, 2005), but the presence of subsidence prior to the eruption of the Siberian Traps is also taken as evidence of a plume. However, even incorporation of a “realistic lithosphere model” cannot explain the observed subsidence-uplift pattern (Fig. 4) in the context of the plume model. According to the calculations of Burov and Guillou-Frottier (2005), while a plume is entering the upper mantle (crossing the 660 km discontinuity) a small to moderate uplift occurs above the plume center. After a few m.y. the uplift may be converted to deep subsidence. The subsidences in the Tunguska and Maimecha-Kotui subprovinces originated long before the initiation of the volcanism (at least 25–30 m.y. before), and these subsidences remained virtually unchanged until the Perm–Triassic volcanism (Vinnogradov, 1968).

There are a number of possible explanations as to why the evidence expected on the basis of the plume model is not observed in the Siberian Traps (for example, picrite melts could have ponded in crustal magmatic chambers and not reached the surface). However, a successful theory cannot be built on non-observed evidence. In my view, much available evidence contradicts the expectations of the plume model, while data on paleogeography argue strongly against the plume model. The only supporting evidence is the high temperatures calculated for the meimechite melts (Sobolev et al., 1991; ), which are hard to explain in terms of conventional thinking regarding a “dry” peridotitic source of melt. The addition of volatiles lowers the melting temperature required to produce meimechites (Elkins-Tanton et al., 2007). The effect of volatile addition thus requires further thorough investigation.

Wooden et al. (1993) considered geochemical aspects of the plume model for the Noril’sk-Kharaelakh subprovince. These authors suggested a model in which a deep crustal reservoir is periodically replenished with sublithospheric magma (the Ivakinsky, Subsuite type of magma), and tapped. Fractionation and assimilation of wallrocks leads to subduction-like magmas (e.g., the Tuklonsky and Nadezhdinsky Suite types of magma; see Fig. 9 and 11). Such a model would explain the alternating non-DUPAL and DUPAL lavas (Fig. 6), which would represent sublithospheric melts and crustal contaminated melts, respectively. However, this model is unlikely to pertain for several reasons. First, there are no mixing trends between “uncontaminated” (Iv1) and “contaminated” (e.g., Tuklonsky and Nadezhdinsky Suite) magmas, as would be expected (Fig. 7). Second, it does not explain why the non-DUPAL lavas of the late assemblage bear subduction-like signatures that make them remarkably different in trace-element geochemistry from the Ivakinsky, lavas (Fig. 9). Involvement of lithospheric mantle instead of lower crust to explain the subduction-like trace-element patterns would also require mixing trends between uncontaminated and contaminated melts that are not observed (Fig. 7).

The subductionlike trace-element pattern of the low-Ti basalts has usually been considered a fingerprint of lithospheric contamination (e.g., Lightfoot et al., 1993; Reichow et al., 2005, for the Siberian Traps). Recently, Kieffer et al. (2004) studied the question of lithospheric sources for Oligocene Ethiopian traps, which also contain typical high- and low-Ti basalt series, and concluded that “the lithospheric mantle did not contribute significantly to the formation of any of the Oligocene lavas from northern Ethiopia.” This shows that the interpretation of subductionlike trace-element patterns in continental basalts as lithospheric melts is at least not unique. Reviewing lithospheric mantle melting literature, Kieffer et al. (2004) posed the question “Is the label ‘lithosphere’ just given to the source of any magma whose composition is thought to be inconsistent with that of an asthenosphere or plume source?”

The timing of volcanism (Fig. 3) can be explained by a starting plume model if dense eclogite patches (e.g., pieces of subducted oceanic crust) were incorporated into the plume (Lin and van Keken, 2005). However, the plume model is not a unique explanation for the pulsing volcanism (see later discussion).

Edge-Driven Convection Model

The edge-driven convection model was suggested by King and Anderson (1998) as an alternative to the plume model. Its basic idea is that at a boundary separating thick cratonic lithosphere and thinner lithosphere, upper-mantle convective flow may be controlled by the lithospheric structure. Puffer (2001) combined this model with evidence of IAB-like trace-element features in Siberian Traps basalts. According to Puffer (2001), lithospheric mantle of the Siberian craton attained subduction-like features (trace elements characteristic of the upper mantle wedge) long before the Perm–Triassic magmatism as a result of paleosubductions. This source, which contained a fusible water-rich mineral assemblage, melted, producing voluminous but brief volcanism as a result of redistribution of heat in the upper mantle due to craton-induced convection. However, this model cannot explain the size of the Siberian Traps LIP (Fig. 1) and the subductionlike features in the volcanic rocks both on and off the craton (Fig. 11). Nor can it explain the alternating pattern of DUPAL and non-DUPAL basalts in the Noril’sk-Kharaelakh subprovince unless the model is coupled with a lithospheric delamination model (see later discussion). It does not resolve the problem of the high temperatures of the meimechite melts.

Lithospheric Delamination Model

Elkins-Tanton (2005) suggested a model in which a weak plume caused a low degree of partial melting. Melt crystallized within the lithosphere in the form of dense eclogites and the lithospheric root, subsequently delaminated via a Rayleigh-Taylor instability. After the delamination, deeper sublithospheric material upwelled into the place of the delaminated lithospheric root and melted to a high degree. Combining this model and the
observation of alternating DUPAL and non-DUPAL rocks (Fig. 6), I suggest the following scenario. The sublithospheric melts are represented by Ivakinsky Subsuite lavas. The delaminated lithospheric root is represented by an eclogite layer, which would be stable at ~185 km depth (Anderson, 2006). After delamination the eclogitic material crossed the solidus and almost completely melted. These melts are represented by the Ivakinsky \( \times \) and Ivakinsky \( \times \) Subsuites. Sublithospheric material rose and produced non-DUPAL Gudchikhinsky melts. Another portion of the lithospheric eclogite delaminated and, after crossing the eclogite solidus, melted again, producing the Tuklonsky and Nadezhdinsky Suite DUPAL basaltas. Next, a portion of the sublithospheric material rose to a shallow level, where it melted to a high degree, producing monotonous non-DUPAL lavas of the late assemblage.

Lithospheric thinning occurred beneath the Tunguska syncline (Fig. 1), which is filled by the most voluminous volcanics (Vasil’ev et al., 2000), in agreement with the delamination model. The number of volcanic pulses (Fig. 3) could be explained as the number of delamination events that occurred in different parts of the Siberian Traps FBP.

However, geochemically similar low-Ti basalts were erupted in different parts of the Siberian Traps FBP (see the section headed “Geochemistry”). Their similar trace-element compositions require similar mechanisms of origin. Therefore, a single weak mantle plume could not have produced the whole FBP via the process of delamination. If several plumes were involved, this model would inherit all the problems of the classical mantle plume model discussed earlier. In other words, the delamination model requires a cause for the delamination on the scale of the whole Siberian Traps FBP. In addition, it offers no solution for coeval basaltic effusive and acidic intrusive volcanism.

### Subduction-Related Model

Low-Ti volcanic rock is the dominant rock type among the mafic rocks of the Siberian Traps FBP. In the Noril’sk-Kharaelakh subprovince it comprises up to 80% of the basalts by volume, and in the West Siberian basin and the Angara-Taseevskaya syncline practically all the rocks belong to this type. In the Maimecha-Kotui subprovince low-Ti rocks are the lowest percentage, but they still make up to half of the lava sequence. The important feature of the low-Ti rocks is their IAB-like trace-element pattern (Figs. 9 and 11). Interestingly, the percentage of low-Ti rocks seems to be higher in the southern part of the Siberian Traps FBP and lower in the northern part. If this feature is not an artifact of incomplete sampling, it must correspond to the position of the erupted rocks relative to the paleosubduction systems (Fig. 5); the closer to the subduction system, the more prominent the IAB-like fingerprint would be expected to be. This geochemical evidence, coupled with location of the Siberian Traps FBP in the back-arc tectonic setting (Fig. 5), led to the suggestion that subduction beneath the Siberian part of Pangea and voluminous eruptions of the Siberian Traps FBP are two related phenomena (Ivanov et al., 2004; Ivanov and Balyshnev, 2005). A similar conclusion was reached by Zhu et al. (2005) for the Emeishan Traps FBP, which formed in the Late Permian in a similar tectonic setting (Fig. 5). These authors suggested interaction between a lower-mantle plume, depleted upper mantle, and a recycled subduction component. The question, however, is this: “Is the lower-mantle plume necessary?” In the case of the Siberian Traps FBP, the lower-mantle plume is necessary only to explain the meicchite petrology, which requires too high a temperature for a likely origin in upper-mantle plate tectonic processes. However, the meicchite source could be wet (>1 wt% of water), and if so, a high-temperature model is not necessary. This question is thus of particular interest for future investigation.

Ivanov and Balyshnev (2005) suggested that the mantle transition zone beneath the Siberian part of Pangea was saturated by water from subduction during the Permian. Dewatering of the transition zone during the latest Permian created a wet upper-mantle source that melted to a high degree. Silver et al. (2006) argued that rapid eruption of voluminous basalts within cratons could be related to tectonic events that were preceded by relatively long-term (>1 m.y.) supersolidus conditions. They discussed several possible causes of the supersolidus conditions maintained beneath the cratons, one of which is subduction-related increase in volatile components.

This model can explain the large volume of eruptions. For example, in Kamchatka the two most productive volcanoes, neighboring Klyuchevskoi and Tolbachik volcanoes, lie above the edge of a modern subducting slab in an area where lateral flow of normal asthenospheric mantle may influence the hydrated mantle-wedge source (Portnyagin et al., 2005). These volcanoes are characterized by averaged Holocene eruption rates of ~0.02 and 0.01 km\(^3\) per year of essentially basaltic magma (Fedotov, 1984). In 1975–1976, the large Tolbachik fissure erupted 2.2 km\(^3\) of lava and pyroclastics, which is comparable to the volume of the largest fissure eruptions in Iceland and Hawaii. The total volume of Holocene volcanic rocks in the vicinity of Tolbachik volcano is ~10\(^2\) km\(^3\) (Fedotov, 1984). The, so-called zone of the Klyuchevskoi group of volcanoes is ~110 km long and up to 70 km wide (Fedotov, 1984). That is not much smaller than the size of the northern subprovinces of the Siberian Traps (e.g., Noril’sk-Kharaelakh, ~330 × 110 km; Khantaisk-Rybninsk, ~250 × 110 km; Kamensk, ~390 × 110 km; Kheta, ~390 × 130 km; Kureika-Letninsk, ~330 × 150 km; Fig. 2). Extrapolating these values to the size of the whole Siberian Traps FBP easily makes the total volume on the order of 4 × 10\(^6\) km\(^3\) (Table 1). A direct comparison of island arc and Siberian Trap volcanism is not necessary because of the differences in lithospheric thinning, depth of melting, water recycling style, and so on.

This model may explain the geochemistry of the Siberian Traps FBP and was inspired by the IAB-like geochemistry. Alternating DUPAL and non-DUPAL rocks in the Noril’sk-Kharaelakh subprovince can be explained by recycling of the oceanic crust (eclogites). Patches of eclogite material could have
been brought to sublithospheric depths by composite diapirs such as those modeled by Yasuda and Fujii (1998). Eclogite has a much lower solidus than lherzolite and will melt at high (50–70%) degrees of partial melting, while lherzolitic ambient rocks remain solid (Anderson, 2005). This could explain the practical absence of mixing between DUPAL and non-DUPAL melts (Fig. 7).

This model probably can explain the eruptions in a several short pulses during the 20–25 m.y. overall duration of the magmatism and the temporal and spatial coincidence of basaltic and acidic magmatism (granitic batholites are usual in subduction setting). The model does not require uplift, as the plume model does. Because the essence of the model is chemical modification of the upper mantle with lowering of its solidus, it does not require thinning of the lithosphere, though preexisting thinning beneath the Tunguska syncline would have increased melt productivity. The primary mica in typical dolerite samples of the Angara-Taseevskaya syncline (Fig. 12) and the meimechites of the Maimecha-Kotui subprovince (Fedorenko and Czamanske, 1997), as well as the shoshonites in the West Siberian Basin (Medvedev et al., 2003), can be regarded as evidence for water in the source of melting.

Saturation of the transition zone with water is a popular model (Bercovici and Karato, 2003; Ohtani, 2005). The transition zone has a high water capacity due to the high water capacity of its major minerals, wadsleyite and ringwoodite (Ohtani, 2005). Superhydrous phases can survive under fast subduction conditions in a subducting slab (Litasov and Ohtani, 2003) (Fig. 13). In the anhydrous mineral stability field at depths of 200–250 km, the water could be transported by nominally anhydrous minerals such as omphacite, garnet, and rutile (Katayama et al., 2006). Due to the metastable mineral assemblage, the subducting slab tends to deflect horizontally while crossing the 410 and 660 km discontinuities (Bina et al., 2001). Figure 13 shows that subducting slabs should have recharged the transition zone with water throughout geological history. Increasing the amount of water may lead to partial melting within the transition zone (Huang et al., 2005). The mantle transition zone is denser than silicate melt, but in the bottom part of the upper mantle, silicate melt is, conversely, denser than ambient peridotitic mantle (Matsukage et al., 2005; Sakamaki et al., 2006). However, increasing the amount of water leads to a decrease in melt density. Current experimental studies, which have large uncertainties, suggest that the melt will rise from the bottom of the upper mantle due to its own buoyancy at ~6 wt% of saturation without any additional source of heating. Dense hydrous magnesian silicate E, which is stable at these depths (Fig. 13), contains 11.4 wt% H2O (Ohtani, 2005). With conductive heating, the phase E will decompose, releasing H2O into the silicate melt. Therefore, the creation of high water concentrations in silicate melts in the bottom part of the upper mantle is not impossible in principle. The process of saturation of the transition zone with water will be inevitably reflected on the Earth’s surface as volcanism. Here I suggest that Siberian Traps vol-

Figure 13. Saturation of the transition zone with water via subduction. The left panel shows that a fast subducting slab attains positive buoyancy while crossing the 410 km discontinuity. Both fast and slow subducting slabs attain positive buoyancy while crossing the 660 km discontinuity (after Bina et al., 2001). The right panel shows the stability fields (shadowed) of deep water-bearing minerals in the CaO-MgO-Al2O3-SiO2-H2O system (after Litasov and Ohtani, 2003). Water-bearing minerals: Wd—wadsleyite; Rw—ringwoodite; E—dense hydrous magnesian silicate; B and G/D/F—superhydrous phases. The straight lines show boundaries between different mineral assemblages (not included for simplicity).
canism and other similar trap volcanism is likely to have been formed by this process.

**Subduction-Related Model and Other Traps**

Almost thirty years ago, Cox (1978) noted that the Paraná, Karoo, and Beacon (Ferrar and Kirkpatrick) Traps erupted within the southern part of Gondwana in back-arc tectonic settings, and because of this coincidence he speculated that their origin was linked to subduction. Other traps, not investigated but mentioned in conjunction with the subduction-related model, were the Deccan Traps, the Siberian Traps, the North Atlantic igneous province, and the Columbia River plateau. The detailed investigation of the Siberian Traps presented here shows that the subduction-related model is viable. The origin of the Columbia River plateau as a back-arc phenomenon was considered by Smith (1992). In addition to these examples, the Emeishan Traps were considered in relation to subduction by Zhu et al. (2005). All these examples have abundant or dominant low-Ti basalts. The Oligocene Ethiopian province is one of the few examples that cannot be directly related to subduction. Low-Ti basalts are also abundant there (Kieffer et al., 2004). If all low-Ti basalts originated as a result of hydration of the sublithospheric mantle, as suggested here, this implies that dehydration of transition zones may appear not only in areas of nearly coeval subduction but also in regions of paleo subductions. A relationship between Cenozoic African volcanism and ancient paleo subducted slab was suggested by Balyshhev and Ivanov (2001).

**CONCLUSIONS**

If the correct origin of the Siberian Traps is to be known, a number of important pieces of evidence must be explained:

1. The Siberian flood basalts erupted in a number of brief volcanic events from the Late Permian until the end of the Middle Triassic. Acidic intrusive magmatism was almost coeval with the basaltic volcanism.
2. The Siberian Traps erupted within the Pangean supercontinent in a back-arc tectonic setting.
3. The size and volume of the Siberian Traps flood basalts were \(7 \times 10^6 \text{ km}^2\) and \(4 \times 10^6 \text{ km}^3\). Most of the erupted rocks are within the Tunguska syncline. The abundant tuff units correspond to the syncline.
4. The Tunguska syncline experienced long-term subsidence prior to the initiation of the volcanism. The present-day lithosphere is thinned beneath the same region.
5. Low-Ti volcanic rocks with prominent subductionlike trace elements are the dominant rock type within the Siberian Traps. High-Ti rocks are subordinate. In the Noril’sk area, DUPAL and non-DUPAL types of basalts alternate. There is no evidence for mixing between the different rock types.
6. Petrographic examination of volcanic rocks reveals primary magmatic mica in some samples (though the number of samples with primary water-bearing minerals is not known).
7. The inferred temperature of meimechite melts in dry (or semidry) conditions is too high for the upper mantle, and the volatile contents of the source is unknown.

Various models for the origin of the Siberian Traps discussed in the literature were tested against the stated evidence. The models that fit the observations most poorly seem to be the impact and edge-driven convection models. The plume model can explain the evidence if some expected evidence has not yet been (or cannot in principle be) observed. The high inferred temperature of the meimechites is the only real supporting evidence. However, the addition of volatiles lowers the temperature of the meimechite primary melts.

The lithospheric delamination model is viable, though it has problems with explaining the size of the Siberian Traps and the causes of delamination on the scale of the Siberian Traps FBP. It offers no solution for coeval effusive basaltic and intrusive acidic magmatism. It explains the meimechite origin as a volatile-rich source of melting.

A subduction-related model is proposed in this chapter. This model can explain the enormous volume and size of the Siberian Traps, their tectonic setting, the coeval basaltic and acidic magmatism, the geochemistry of the dominant low-Ti basalt type, and the presence of water-bearing minerals in rocks. This model can explain meimechite origin without a thermal (plume) anomaly by the addition of large quantities of volatiles. The various pieces of evidence, coupled with assessment of existing models, enable us to draw the conclusion that the Siberian Traps phenomenon was related to an upper-mantle plate tectonics process and not a lower-mantle plume.

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**REFERENCES CITED**


Evaluation of different models for the origin of the Siberian Traps


Malitch, N.S., editor-in-chief., 1999, Geological map of Siberian platform and adjoining areas: St. Petersburg, Vserissuusjuu Geologicheskii Institute, scale 1:1,500,000.


**DISCUSSION**

**15 January 2007, Ajoy K. Baksi**

Ivanov’s assessment of aspects of Siberian Trap volcanism serves as a useful adjunct to our knowledge about flood basalt volcanism. However, numerous ages used therein do not qualify as proper estimates of the crystallization ages; that is, $^{40}\text{Ar}/^{39}\text{Ar}$ ages need to be evaluated for both statistical validity and freshness of samples dated (Baksi, this volume, chapters 15 and 16).

First, the ages reported in Baksi and Farrar (1991a) are known to be incorrect on the basis of both mass spectrometric problems and ages of standards used (Baksi, 2005; Baksi and Farrar, 1991b). These analyses are now evaluated for freshness (Baksi, 2007a). The plateau steps for ST-154 ($K = 0.60\%$) and ST-524 ($K = 0.13\%$) give alteration index (A.I.) values in the range 0.044–0.0030 and 0.020–0.0015, respectively. The cutoff for freshness is <0.0006; both rocks are altered and cannot give proper estimates of the time of crystallization. ST-563 is a dike, and its A.I. cannot be unequivocally used for a freshness test (see discussion of Baksi, this volume, chapter 16). The ages of Walderhaug et al. (2005) must all be discounted because they fail statistical tests for proper plateaus and/or are altered as based on the A.I. test. Earlier efforts (Renne and Basu, 1991; Dalrymple et al., 1995; Venkatesan et al., 1997; Reichow et al., 2002) must all be critically evaluated, in particular by the A.I. technique. This is not always possible because some of the data sets are currently not available for examination. Some of the analyses fail the freshness test; the major portions of mafic rocks appear to have been extruded in ca. 1 Ma around 250 Ma. The best ($\text{U–Pb}$) ages are those of Kamo et al. (2003) at 252–251 Ma, and the screened $^{40}\text{Ar}/^{39}\text{Ar}$ ages are in general agreement with these.

The total duration of volcanism remains unknown. All relevant $^{40}\text{Ar}/^{39}\text{Ar}$ ages must be critically examined by the techniques set out earlier (see Baksi, 2007). I strongly urge scientists to carry out such critical examination for themselves before advancing hypotheses related to the (temporal) formation of this immense province and its possible environmental effects.

**19 January 2007, Alexei Ivanov**

Baksi (15 January) raises two important questions about (1) duration of the Siberian Traps and (2) reliability of published $^{40}\text{Ar}/^{39}\text{Ar}$ ages.

The U–Pb ages of Kamo et al. (2003) were obtained on samples from a localized area compared to the whole Siberian Traps, and assigning these ages to other remote regions is questionable. A paleomagnetic study in the Noril’sk area shows that volcanism started there at the end of a reversed-polarity chron (Latest Permian) and continued during a normal-polarity chron (earliest Lower Triassic) (e.g., Heunemann et al., 2004). A paleomagnetic study of volcanic rocks recovered from the superdeep drill hole No. 6 (SG-6) within the West Siberian Basin revealed five normal- and four reversed-polarity chronos (e.g., Heunemann et al., 2004). These ages are complementary by a paleomagnetic study that revealed paleomagnetic poles in agreement with sill emplacement in the Middle Triassic. U–Pb and $^{40}\text{Ar}/^{39}\text{Ar}$ ages obtained on the same lava units and intrusions appeared to be in good agreement, taking into account a slight systematic difference of <1% (Ivanov, 2006). Among these, the Bolgokhtokh granodiorite intrusion is dated as old as 228.9 ± 0.3 Ma and 226.8 ± 0.8 Ma by U–Pb and $^{40}\text{Ar}/^{39}\text{Ar}$, respectively. (The original $^{40}\text{Ar}/^{39}\text{Ar}$ age [Dalrymple et al., 1995] is recalculated relative 98.5 Ma for GA1515 standard.) Similar
types of intrusions are found elsewhere within Siberian Traps and dated by U–Pb from ca. 250 to ca. 225 Ma (see references in Ivanov, this volume). Thus, long-lived magmatism of the Siberian Traps is expected, even if no \(^{40}\text{Ar}/^{39}\text{Ar}\) ages had been published.

As mentioned by Baksi (15 January), most published \(^{40}\text{Ar}/^{39}\text{Ar}\) ages for the Siberian Traps are presented without full analytical details. So, A.I., suggested as a measure of \(^{40}\text{Ar}/^{39}\text{Ar}\) age reliability by Baksi (this volume, chapters 15 and 16) can be calculated only by the authors of those papers. Plateau steps from \(^{40}\text{Ar}/^{39}\text{Ar}\) stepwise-heating dating of plagioclases from Ivanov et al. (2005) yielded negative A.I. values. The negative A.I. values are caused by \(J\) factors of about 0.08, which is sufficiently low to fit the range of optimal production of \(^{39}\text{Ar}\) and \(^{37}\text{Ar}\) (e.g., Fig. 3-7 in McDougall and Harrison, 1999), but too high for the A.I. equation in Baksi (this volume, chapter 15). Should these plateau ages with negative A.I. be accepted? Probably yes, because \(^{36}\text{Ar}/^{37}\text{Ar}\) for plateau steps is low (0.00003–0.00017). The low-temperature steps with too low apparent ages (Fig. 2 in Ivanov et al., 2005) are characterized by high A.I. up to 0.5, showing alteration of plagioclases at crystal edges and within cracks. The weighted mean of the two plateau ages is 243.9 ± 1.4 Ma (relative to 129.4 Ma for LP6) or 243.9 ± 5.8 Ma if possible subsampling inhomogeneity of LP6 is accounted for (Ivanov et al., 2005).

Baksi (15 January) reports that the A.I. for his samples (Baksi and Farrar, 1991a) varies between 0.0015 and 0.04, and he rejects these ages as altered on the basis of the cutoff value of 0.0006. Ivanov et al. (2006) dated three samples using the \(^{40}\text{Ar}/^{39}\text{Ar}\) stepwise-heating technique. The samples yielded concordant plateau and isochron ages. Application of the method of Baksi (this volume, chapters 15 and 16) shows that for plateaus of these samples, A.I. is between 0.002 and 0.05. According to Baksi (this volume, chapters 15 and 16), these ages should be rejected. However, there are some arguments to keep these ages as true crystallization ages. First of all, the age for the Nadezhdinsky suite agrees within analytical uncertainty with those published by Venkatesan et al. (1997), whose ages are in agreement with the U-Pb ages of Kamo et al. (2003). Second, there is a difference between the ages obtained for samples from the Nadezhdinsky and Hona-Makitsky suites, whereas there is no difference in their A.I. indices. Third, Baksi (this volume, chapters 15 and 16) acknowledges that the A.I. will be higher than the cutoff value in fresh samples of volcanic rocks if they were derived from a subduction-derived water-bearing mantle source. I argue that the Siberian Traps (Ivanov, this volume) and probably other flood basalt provinces (see Ivanov, 17 January comment to discussion of Hooper et al., this volume) were derived from such mantle sources. Therefore, an A.I. cutoff value of 0.0006 may be not applicable for the Siberian Traps.

As to the rest, I fully agree with Baksi (15 January) that careful evaluation of \(^{40}\text{Ar}/^{39}\text{Ar}\) data is essential for correct interpretation of geological models.

REFERENCES


Baksi, A.K., and Farrar, E., 1991b, \(^{40}\text{Ar}/^{39}\text{Ar}\) ages of whole-rock basalts (Siberian Traps) in the Tunguska and Noril’sk regions, USSR: Eos (Transactions, American Geophysical Union), v. 72, p. 570.


Ivanov, A.V., 2006, Systematic difference between U–Pb and \(^{40}\text{Ar}/^{39}\text{Ar}\) dates: Reasons and evaluation techniques: Geochemistry International, v. 44, p. 1041–1047.


Ivanov, A.V., Ryabov, V.V., Shevko, A.Y., and He, H., 2006, Single short episode or multiple non-coeval episodes of voluminous basaltic volcanism of the Siberian Traps? Data of \(^{40}\text{Ar}/^{39}\text{Ar}\) dating, in Proceedings of III Russian conference on isotopic geochronology, Moscow, IGEM RAS, p. 278–282 (in Russian).


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