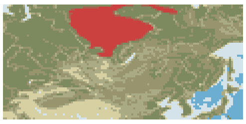
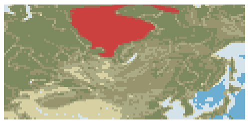


The Demise of the Siberian Plume



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Introduction

The Siberian flood-volcanic province represents the largest subaerial volcanic event known, although the original volume of more ancient events is difficult to determine because of erosion. Considering the coeval, mafic volcanic and intrusive formations known on the Siberian Platform, the Taymyr Peninsula, and the Western Siberian Lowlands, Masaitis (1983) estimated their volume to be ~ 4 x 10^6 km^3, originally extending over ~7 million km^2 (see Figure 1). *Reichow et al.* (2002) recently confirmed that the extensive, buried basalts in the Western Siberian Lowlands are coeval with the basalts on the platform. Taking into consideration their studies of the Noril'sk and Maymecha-Kotuy areas, where the lava/tuff sequences approach 3500 m and 3000 m, respectively, with much of the sequence in the Maymecha-Kotuy area considered to be younger than most of the sequence at Noril'sk, *Fedorenko & Czamanske* (1997) estimated a combined maximal thickness of ~ 6500 meters.

Figure 1

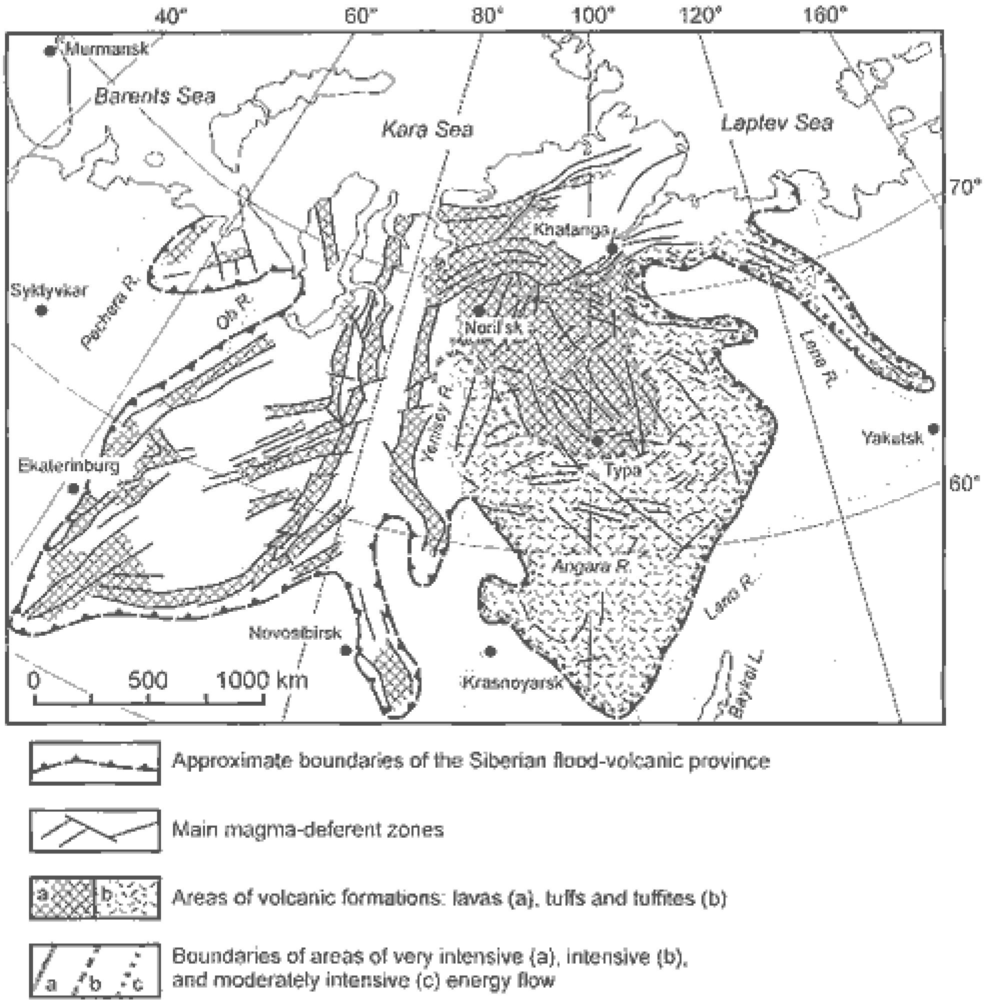

Chart of reconstruction of the Siberian flood-volcanic province
(simplified after Masaitis, 1983)

The Geologic Record of the Sedimentary Sequence

Siberian flood-volcanic rocks are underlain almost everywhere by terrigenous, coal-bearing sedimentary rocks of the Tungusskaya Series, which is Middle Carboniferous to Upper Permian in age and commonly ranges in thickness from 100 - 150 m to 1400 m. As reviewed in *Czamanske et al.* (1998), systematic studies of paleogeographic and paleotectonic conditions during Tungusskaya Series accumulation indicate that its deposition was accompanied by well-balanced subsidence throughout the area occupied by well-developed, flood-volcanic sequences. The surrounding territories, which experienced denudation and fed this accumulation, subsequently experienced little or no flood-volcanic activity. The Permian rocks of the Tungusskaya Series include many of shallow-water, lagoonal character, including abundant coal beds. Indeed, these abundant coal beds (more than 24 of economic import, and as much as 36 m thick) have led to the suggestion that the sedimentary sequence immediately underlying the flood-volcanic sequence constitutes the greatest coal basin in the world. Pronounced inheritance from the mid-Cretaceous onward is observed in the evolution of the areas of accumulation and denudation, with no reorganization in the Late Permian that can be ascribed to the influence of a mantle plume (see Figures 2 - 6 in *Czamanske et al.*, 1998).

Because the Siberian flood-basalt sequence is thickest (3500 - 4000 m) and most complex in the Noril'sk and Maymecha-Kotuy areas, along the northern margin of the Siberian platform (e.g., *Fedorenko et al.*, 1996; *Fedorenko & Czamanske*, 1997), it is particularly appropriate to look for evidence of a plume head in these areas. However, the first of these areas experienced even more subsidence in the Late Permian than in the Middle to Late Carboniferous or Early Permian, whereas the second area was subsiding continually over the entire time (see Figures 2 - 4 in *Czamanske et al.*, 1998).

The Geologic Record of the Sedimentary/Volcanic Interface

The coal-bearing sequence is closely tied to the overlying volcanic sequence, as evidenced by the common presence of volcanic material in the uppermost units of the Tungusskaya Series and the lateral replacement of some sedimentary strata by the Ivakinsky volcanic suite. On the other hand, the volcanic sequence may overlie different Upper Paleozoic strata, down to the Carboniferous. The depth of the erosional break varies, but may reach a few hundred meters. This break was not an exceptional event. On a lesser scale (as much as 50 m) erosion occurred more than once during accumulation of the Tungusskaya Series. In the best-studied, Noril'sk area, the Tungusskaya Series is subdivided into six suites, each of which is separated by erosional breaks of irregular distribution. However, the broader scale paleogeographic maps (Figures 2 - 6 in *Czamanske et al*., 1998) show that those breaks did not disturb the general regime of sedimentation during Tungusskaya time.

Uneven mapping does not allow systematic description of the sedimentary/volcanic interface throughout the entire Siberian platform. The two best studied regions are the Noril'sk area and the northwest side of the Anabar-Olenyok anteclise. Detailed study of sections along the northwest side of the Anabar-Olenyok anteclise suggests that variations in depth of erosion are related to flat-platform (synorogenic) folding of the coal-bearing sediments at the boundary of the Paleozoic and Mesozoic (*Gurevitch et al.*, 1984). This led to stratigraphic unconformity and sometimes (in the Kayak coal deposit on the Kotuy River) to a shallow-angle disconformity between the coal-bearing and volcanic sequence (Figure 7 in *Czamanske et al.*, 1998). The width of the folds is 30 - 80 km, their amplitude as much as 300 m, and their axes close to E-W, judging from boreholes south of the Kheta River, where the entire, Upper Paleozoic sequence consists only of C_{2-3} sedimentary rocks, 100 - 130 m thick. The total amplitude of this uplift is estimated as 300 - 500 m over at most several hundred square kilometers, an amplitude comparable to that of local folds within it.

Similar folding probably occurred northwest of the Tunguska basin, in the Noril'sk area. The most complete stratigraphic section of the Tungusskaya Series (as much as 400 m) is known there in the Kayerkan coal deposit. There the uppermost Ambarninsky Suite, belonging to the Degalinsky horizon of the Upper Permian has a thickness of ~ 70 m and is composed of interlayers (0.1 to 10 - 15 cm thick) of fine-grained, tuff-sandstones and sideritized tuffs. A few kilometers to the west, the Ambarninsky Suite disappears from the sequence, and several tens of kilometers to west, the entire Tungusskaya Series is only 20 m thick. Judging from lithology, this 20-m-thick section represents the lowermost units of the series. Approximately 50 km west of the Kayerkan deposit, the entire Upper Paleozoic sequence and the 2 - 3 lower-most suites of the volcanic sequence disappear from the stratigraphic section. The erosion break and uplift was not less than 400 - 500 m there, but it can be more readily connected to Late Hercynian folding and regional uplift in the Ural - West Siberian province (e.g., *Fotiadi*, 1967) than to evolution of the Siberian platform with its coal-bearing and flood-volcanic sequences.

The Geologic Record of the Volcanic Sequence

Uneven exposure and detail of mapping preclude reconstruction of tectonic and paleogeographic conditions during accumulation of the volcanic sequence for the entire Siberian platform (Figure 1). However, the volcanic sequence (as thick as 3500 m) which covers more than half of the ~ 50,000 km^2 Noril'sk area is exceptionally well documented (e.g., *Wooden et al.*, 1993; *Fedorenko et al.*, 1996). These volcanic rocks have been carefully mapped everywhere by several generations of geologists since the 1940s and 1950s, and hundreds of holes drilled for metal exploration passed through the volcanic sequence and into the underlying Tungusskaya Series. *Fedorenko* (1979, 1991) summarized the results of this intensive study, considering tectonic and paleogeographic implications with respect to the volcanic activity. Additional data were presented by *Fedorenko et al.* (1996).

The volcanic sequence can be conveniently mapped as lava packets composed of simple flows of relatively uniform lithologic and chemical composition, tens to a few hundreds of meters thick, interlayered with ~ 30 layers of tuff and volcanic agglomerate. The tuff layers range from tens of centimeters to 100 m in thickness and compose ~ 10% of the overall, volcanic pile. Many of the lava packets and tuff layers can be traced through almost the entire area, with little variation in thickness and composition (e.g., *Fedorenko et al.*, 1996, Figure 5 in their paper). One tuff layer, located ~ 400 m above base of the sequence is 15 – 25 m thick over ~ 30,000 km^2. Interestingly, the volcanic sequence shows less stratigraphic variability than many of the sedimentary sequences, including the Tungusskaya Series.

In the entire Noril'sk area, only one small erosional break of only few meters has been recognized, ~ 1400 m above the base of the sequence. In addition, only a single example of small-scale weathering has been seen, ~ 50 m below this erosional break. Thus, the entire area experienced balanced subsidence over the entire period during which the volcanic sequence accumulated. The distribution of the lava and tuff units shows that they accumulated on a relatively flat plain. The presence of aquatic fauna in tuffs of the lower 1100 m of the volcanic sequence shows that these tuffs accumulated in shallow-water lakes or lagoons, in paleogeographic conditions similar to those which prevailed during deposition of the Tungusskaya Series. Subaerial conditions prevailed during deposition of the upper part of the volcanic sequence, as shown by the fact that aquatic fauna disappeared. A terrestrial dinosaur skeleton was found ~ 1900 m above the base of the sequence (*Distler & Kunilov*, 1994; *Fedorenko et al.*, 1996). This paleontological evidence of the change from aquatic to subaerial conditions is supported by geochemical data relating to the oxidation state of the tuffs. The ratio $Fe_2O_3/(FeO+Fe_2O_3)$ in the tuffs changes from 0.16 at the base of the sequence, to 0.39 - 0.43 at 400 - 500 m, 0.51 - 0.64 at 700 - 1800 m, and 0.88 - 0.87 in the upper part of the sequence, some 2000 - 3200 m from its base (*Fedorenko*, 1991).

Isopach maps were prepared by *Fedorenko* (1979) for the main lava packets in the lower 1800 m of the volcanic sequence of the Noril'sk area (e.g., *Naldrett et al.*, 1992, their Figure 5; *Wooden et al.*, 1993, their Figure 3). They show that recent positive structures in the Noril'sk area are post-volcanic in age and were not present during accumulation of the volcanic sequence. In fact, it was concluded that no positive tectonic structures were present in the area during the entire duration of volcanic activity. Successive groups of volcanic suites can be related to a series of depressions that migrated across the area with time (*Fedorenko*, 1979). *Fedorenko et al.* (1996) reasoned that these volcanic depressions were a surficial response to the draining of intermediate-level, crustal magma chambers.

The lower part of the volcanic sequence, ~ 1800 m thick and composed mainly of lava flows at Noril'sk, grades laterally to the east (in the Maymecha-Kotuy area, see Figure 1) into a suite ~ 350 m thick in which tuffs predominate (*Fedorenko & Czamanske*, 1997). However, the overall, paleogeographic evolution revealed in the tuffaceous suite is the same as that for the correlative volcanic pile at Noril'sk. Aquatic fauna are found in the lower part of the tuff suite, but not in the upper part (*Shikhorina*, 1970). Likely, the decrease in thickness and the replacment of lavas by tuffs, with progression from the Noril'sk area to the Maymecha-Kotuy area, is not evidence for relative uplift but has a petrogenetic/tectonic basis. It would appear that during this early part of the volcanic history, extensive, intermediate magma chambers evolved and drained beneath the Noril'sk area, but not to the northeast (*Fedorenko & Czamanske*, 1997).

The extremely high rate of the balanced subsidence that accompanied Siberian volcanism (estimated as locally more than 3500 m in 1 m.y.; *Lind et al.*, 1994; *Kamo et al.*, 2000, 2003) may represent subsidence maintained by draining mafic magma from intermediate chambers in the crust.

The Case for Convective Partial Melting

Because surficial uplift in response to thermal expansion is a necessary consequence of the arrival of anomalously hot, plume-related material in the upper mantle, the geologic record shows conclusively that Siberian flood-volcanic volcanism was not plume related. Rather, we consider this extensive kimberlitic and flood-volcanic magmatism to represent convective, partial melting released by lithospheric shear and related, local extension.

Many workers feel that only a mantle plume can explain the huge volumes and high rates of eruption that characterize flood-volcanic provinces, and have embraced the mantle-plume model to explain their geochemical evolution. Earlier, we considered the model of *Griffiths & Campbell* (1991) attractive for providing large volumes of magma in a brief interval of time (e.g., *Wooden et al.*, 1993; *Arndt et al.*, 1993). This mantle-plume model has now been admitted by its proponents to require significant modification to explain the rates and volumes of flood-volcanic eruption (*Cordery et al.*, 1997). *Cordery et al.* (1997) do not discuss convective partial melting (*Mutter et al.*, 1988; *King & Anderson*, 1995) as a mechanism for the genesis of flood basalts or the explanation of *Arndt et al.* (1993) for the geochemical characteristics of continental flood-basalt (CFB) sequences. In fact, the plume-head model is, however, increasingly unable to account for the observations (e.g., *Anderson*, 1999).

The geologic record in north-central Siberia is clearly at variance with any mantle-plume model, as the thermal anomaly associated with the existence of anomously hot, plume-related material in the upper mantle requires regional uplift (for reviews of such models see, for example, *Anderson et al.*, 1992a or *Coffin & Eldholm*, 1994). The numerical modeling of *Farnetani & Richards* (1994) predicts precusory uplifts of 2 - 4 km sustained over tens of millions of years, for a plume head of 400-km radius with a initial excess temperature of 350°C. A cooler plume head would cause less uplift. Lack of surface uplift also has been documented for the voluminous volcanic activity in East Greenlend (*Larsen & Marcussen*, 1992). The latter situation, with its extensive development of basaltic sills and flood-volcanic rocks seems particularly comparable to Siberia except for the fact that extension in this area continued to the present day about the mid-Atlantic ridge. As a result, the Iceland large igenous province is still continuing to form.

King & Anderson (1995):

- argue that "... it is not an accident that CFB provinces occur next to Archons, the thickest lithosphere on Earth",
- note that "...asymmetric lithosphere provides a natural method for bringing up deeper and hotter material and provides the space for melting", and
- "... attribute the variety of basalt types, degree of evolution, and the time of

> sequence of eruption, to the various depths swept out by the upwellings at the lithospheric, asymmetry boundary ..."

These and other authors suggest the existence of convecting, hot cells and have noted that normal mantle geothermal and melting curves are such that partial melting is the normal state for much of the upper mantle.

Increasingly, authors are concluding that geologic fact is often at variance with all but the most fanciful modifications of mantle-plume theory. *Bailey* (1992), in discussion of episodic, alkaline igneous activity across Africa, concluded that the well-established periodicity and repetitive occurrence of alkaline magmatism at many locales across the entire African continent must rule out random, sub-lithospheric plumes as the generative mechanism. Rather, he concluded that lithospheric anisotropy controls this anorogenic activity, which is often contemporaneous and plate-wide,. The lithosphere acts as a template for the periodic release of mass and heat in response to external events which affected the whole plate. *McHone* (1996) concluded that one or even several, deep-mantle plumes do not provide a satisfactory mechanism for producing the Cretaceous alkaline rocks of northeastern North America and the adjacent western Atlantic (the "CAMP" province). Rather, the geologic evidence calls for widespread, heterogeneous source areas in the mantle, which produced magmas in concert with tectonic re-activation of lithospheric structures. *Smith* (1992) discussed the Columbia River Basalts in terms of a back-arc-convection model, and numerous other authors have proposed models for various "hotspots" and large igneous provinces that do not involve mantle plumes. Several of these (e.g., *Sykes*, 1978; *Holbrook & Keleman*, 1993; *Zehnder et al.*, 1990; *Giret & Lameyre*, 1995) have focused on the long duration (i.e., re-occurrence) of magmatism in many provinces and on the clear relation of within-plate magmatism to zones of lithospheric weakness.

Siberian kimberlites and alkaline-ultramafic rocks have a close relation to the Anabar-Olenyok anteclise and the Anabar shield. The Siberian kimberlites of this region range in age from 485 to 150 Ma (*Davis et al.*, 1980; *Komarov & Ilupin*, 1990). Alkaline-ultramafic rocks of the Maymecha-Kotuy area of the Siberian flood-volcanic province are of exactly the same age as the flood-volcanic rocks of the Noril'sk area (*Kamo et al.*, 2000, 2003). Among Siberian magmatic rocks, the alkaline-ultramafic magmas, especially the meymechites, show the greatest geochemical resemblance to kimberlites; both originated at great depth and extreme temperatures (e.g., *Sobolev et al.*, 1972; *Arndt et al.*, 1995), consistent with derivation from beneath the craton.

On the basis of tomography, *Zhang & Tanimoto* (1993) show that the Siberian craton is charaterized by an unusually thick, high-velocity anomaly and a root depth approaching 350 km. *Anderson et al.* (1992a, b) note that although the Siberian flood-volcanic province is relatively old, shear velocities determined from tomography reveal no evidence for the thermo-mechanical trauma expected from the arrival of a plume head at ~ 251 Ma. *Zorin & Vladimirov* (1989) interpret super-deep seismic data to indicate that the lithosphere is presently 180 - 200 km thick beneath the Tunguska basin and conclude that it was of comparable thickness in the Late Permian. In their calculations, they point out that the mean heat flow on the craton (38 - 40 mW m^{-2}) is similar to values for other ancient cratons and close to the minimum heat flow of continents. Such values argue that anomalously hot material was not emplaced by a mantle plume ~ 250 Ma.

Sengor et al. (1993) presented a detailed picture of continuous, orogenic interaction between the Angara (Siberian) and Eastern European (Baltica) cratons between the Vendian (latest Pre-Cambrian) and the Permian. In contrast to classic collisional orogens, they propose that the belt separating Baltica and Siberia (the Altaids) consists of subduction-accretion complexes which they judged to have added ~ 5.3 million km^2 of material to Asia, possibly half of which was of juvenile origin. From the Late Carboniferous to the Early Permian the dominant movement was right-lateral shear. Considering the ongoing disruption and strike-slip faulting involved in the evolution of the Altaids, the episodic kimberlitic activity which so clearly relates to the Anabar shield can be readily understood as representing small melt fractions released from deep beneath the craton through minor, lithospheric, stress fractures. *Sengor et al.* (1993) suggested that the onset of voluminous, Siberian flood volcanism may have been related to the reversal from right-lateral shear to left-lateral shear between Baltica and Siberia. This, the last act of Altaid evolution during the Paleozoic, was associated with numerous extensions peripheral to the Siberian craton. Boreholes in the Western Siberian lowlands (west of the Yenisey River) indicate that basalts of Siberian flood-basalt age (e.g., *Gurevitch et al.* 1995; *Reichow et al.*, 2002), and as much as 1150 m thick, occur under younger cover over an area of ~ 0.75 million km^2 (*Zhuralev*, 1986).

Following those such as *Mutter et al.* (1988), *Bailey* (1992), *Smith* (1993), *King & Anderson* (1995) and *Anderson* (1989, 1996) we favor models involving "top-down" lithospheric control for the genesis of large igneous provinces. Arguments for re-evaluation of the classic, deep-mantle plume model (e.g., *Griffiths & Campbell*, 1991; *Cordery et al.*, 1997) are presented by *Anderson* (1998), *Courtillet et al.* (1999) and *Tanton & Hager* (2000). If the upper mantle is partially molten and enriched (*Anderson*, 1989, 1996), then only slight extension in the lithosphere is needed to allow intrusion and extrusion, and magma ascent will be focused at lithospheric discontinuities (*King & Anderson*, 1995). This can explain the correlation between CFBs and cratons. The presence of pre-existing shear, associated with inevitable local extension, and the absence of uplift or heat-flow evidence for a thermal anomaly strongly favor a convective, partial-melting explanation (*Mutter et al.*, 1988; *King & Anderson*, 1995) over a plume explanation for Siberian flood volcanism. The necessary extensional stresses probably relate to plate reorganization and changes in boundary conditions (*Bailey*, 1992; *Anderson*, 1994). Other geophysical arguments against the plume-head hypothesis are summarized in *Anderson et al.* (1992a, b).

Clearly the remarks of *Renne et al.* (1995) regarding "... the large-scale dynamics of the starting plume head that *caused* (emphasis ours) the Siberian flood volcanism" and the ensuing discussion (with reference to *Farnetani & Richards*, 1994) concerning aspects of the supposed kilometer-scale uplift associated with the presumed plume, take no cognizance of the geologic reality outlined herein and known in less detail for decades (e.g., *Krasnov et al.*, 1966; *Malich*, 1975). A far less extreme example is that provided by the paper of *Duncan et al.* (1997). Their Figure 6, in combination with their discussion, would imply a significant plume contribution to magmas erupted contemporaneously across 45° of latitude! In passing, they themselves note, with discussion, that "Indeed, compositional aspects of the province are often more compatible with a subduction rather than a plume source." Finally, in their discussion of the interaction of plume heads with Earth's surface, *Griffiths & Campbell* (1991, their Figure 13) show the cell-like structures evident in the Siberian flood-volcanic province and suggest them to be a possible example of plume-head instability, rather than recognizing that the region had been one of steady subsidence.

Although it is beyond the scope of this webpage to present all the details, the data appear to be in hand to develop an in-depth, non-plume, geophysical and geochemical model for Siberian flood volcanism (e.g., *Tanton & Hager*, 2000). The geochemical nature of the volcanism is as well documented as that for any continental flood-volcanic province (see references cited herein by *Fedorenko & Czamanske* and their references) and the temporal framework is established as < 1 m.y for the bulk of Siberian flood volcanism and mafic intrusive activity, based on U-Pb geochronology (*Kamo et al.*, 1996, 2000, 2003).

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