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Co-location of eruption sites of the Siberian Traps and North Atlantic Igneous Province: Implications for the nature of hotspots and mantle plumes

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ABSTRACT

One of the striking exceptions to the mantle plume head–tail hypothesis that seeks to explain magmatism of large igneous provinces (LIPs) and hotspot tracks is the ~250 million-year-old Siberian Traps. The lack of a clear hotspot track linked to this LIP has been one motivation to explore non-plume alternative mechanisms. Here, we use a paleomagnetic Euler pole analysis to constrain the location of the Siberian Traps at the time of their eruption. The reconstructed position coincides with the mantle region that also saw eruption of the ~61–58 million year-old North Atlantic Igneous Province (NAIP). Together with LIP volume estimates, this reconstruction poses a dilemma for some non-plume models: the partial-melts needed to account for the Siberian Traps should have depleted the enriched upper mantle source that is in turn crucial for the later formation of the NAIP. The observations instead suggest the existence of a long-lived (>250 million-year-long) lower mantle chemical and/or thermal anomaly, and significant temporal changes in mantle plume flux.

1. Introduction

Petrological and geochemical data have been interpreted (Campbell, 2007) as support for a deep mantle plume origin of the ~250 million-year-old Siberian Traps (Sharma, 1997; Reichow et al., 2005; Saunders et al., 2005; Reichow et al., 2009), but some challenge this view. Non-plume models for the Siberian Traps call for fertile spots in the upper mantle (Meibom and Anderson, 2004) that may be relicts of past focused subduction (e.g., Foulger, 2002). All models, however, must explain the apparent lack of a post-250 Ma track of magmatism that would otherwise reflect plate motion over the mantle source that gave rise to the Siberian Traps. The paleoposition of the Siberian Traps (hereafter, the Traps) is our starting point for addressing this issue.

The rotation of a point on a plate about an axis, or Euler pole, will trace a small circle. For example, oceanic fracture zone segments tend to fall along small circle paths, reflecting constant plate motion about fixed Euler poles (e.g., Morgan, 1968). Francheteau and Sclater (1969) noted that some paleomagnetic apparent polar wander data seemed to trace small circle segments and that such data could be used to constrain poles of rotation. Irving and Park (1972) interpreted the North American apparent polar wander path (APWP) in terms of smooth long segments (tracks), corresponding to periods of steady plate motion, separated by cusps, representing times of rapid plate motion change. They further suggested that this might be a general feature of apparent polar wandering and plate motion. This motivated the analyses of APWP in terms of small circle segments and Euler pole rotations; the derived poles have been called paleomagnetic Euler poles (PEP) (Cox and Hart, 1986). The accuracy of the PEP determination depends on the angle subtended by the APWP segment, the angular distance to the paleomagnetic poles and the errors in paleomagnetic database.

Taken alone, paleomagnetic data constrain only past latitudes. Because rotations about Euler poles can completely define plate motion, PEP analysis also constrains paleolongitude. With a careful accounting of uncertanties, addressing the factors above, the approach is useful for reconstructing the Traps to their place of eruption.

2. Paleomagnetic data

As a starting point for our paleomagnetic database, we used the master APWP for Eurasia, averaged over 20 million-year-long windows for the last 200 million of years, compiled by Besse and Courtillot (2002). However, because of problematic reliability of this APWP for the Paleocene–Mid-Cretaceous time, we opted to replace the 60–120 Ma mean poles of Besse and Courtillot (2002) with several high-quality paleomagnetic poles from the North American craton rotated to the Eurasian reference frame (Fig. 1; see Doubrovine and Tarduno, 2008, and Supplementary Text 1 for detailed discussion).

For the Siberian traps we utilize the recent NSP2 pole of Pavlov et al. (2007) (55.1 °N, 147.0 °E, A95 = 5.0°; Fig. 1). This pole differs from coeval poles from Europe, but this is not unexpected because Siberia could have been not fully attached to Pangea at that time (e.g. Torsvik et al., 2008a). The Triassic paleomagnetic database for Eurasia contains only a few poles, mostly derived from sediments and,

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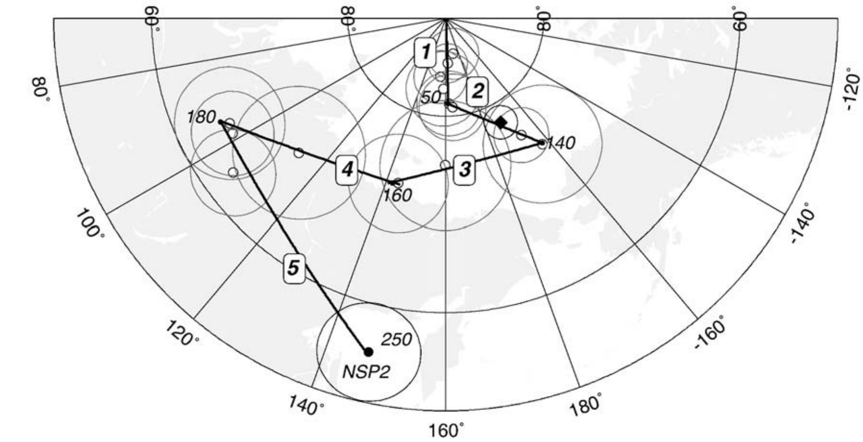

Fig. 1. Paleomagnetic poles used for PEP analysis (see text). Open circles show selected poles from the master apparent polar wander path (APWP) for Eurasia (Besse and Courtillot, 2002). Diamond shows the mean pole based on reliable Cretaceous paleomagnetic poles from North America rotated to the Eurasian reference frame (see text). NSP2 is the new Siberian Pole 2 (Pavlov et al., 2007). Lines show five APWP tracks (0–50, 50–140, 140–160, 160–180 and 180–250 Ma) represented by great circle segments. Numbers in rectangles show a track number.

hence, may be affected by sedimentary inclination shallowing (e.g., Pavlov et al., 2007). For these reasons, we do not use post-200 Ma European poles in our analyses (see Supplementary Text 1).

From the final paleomagnetic dataset we identify five tracks (Fig. 1). Track 1 extends to 50 Ma, when it forms a cusp with Paleocene to mid-Cretaceous Track 2 (50–140 Ma). The distinct change in the direction and velocity of plate motion seen after 140 Ma may reflect the beginning of separation between North America, Europe, and Africa.

Early-Cretaceous and Jurassic poles of the APWP suggest relatively fast plate motion between 180 and 140 Ma. We represent this APWP interval by two tracks, Tracks 3 and 4 at 140–160 Ma and 160–180 Ma, respectively, although we note that the existence of the cusp in the Middle Jurassic (~160 Ma) remains controversial (Van der Voo, 1993; Kent and Olsen, 2008). Track 5 extends from 180 Ma to 250 Ma, the age of the Traps.

A cursory examination of the resulting master Eurasian APWP (Fig. 1) suggests that the paths tend to fall along great circles. Modeling the trajectories as great circles moves us one step from the simple application of Euler's theorem and its apparent manifestation on the Earth's surface in the form of oceanic fracture zones. But the small circle approach to PEP analysis (Gordon et al., 1984) has been criticized (e.g. Van der Voo, 1993), because the intervals over which a constant rotation can be assumed (10–20 million-year-long) are shorter than the typical resolution of APWPs. Thus, the great circle parametrization can be thought of as a more conservative modeling approach. By analogy to a straight line on a plane, the great circle is the first order approximation of motion on a sphere when data are limited.

3. Reconstruction

PEPs and corresponding finite rotation angles calculated for the Eurasian APWP (Supplementary Table 1 and Text 2) using great circles suggest that the Traps have been at relatively high latitudes since their formation (Supplementary Figure 2). The location of the Traps at their time of eruption resulting from these PEP analyses (Fig. 2) is consistent with a paleolatitude 60.6 ± 5.0 °N calculated for a site in Norilsk area based on the NSP2 pole of Pavlov et al. (2007). We note that this reconstruction is robust with respect to alternative paleomagnetic data selection (see Supplementary Text 1).

We performed an exhaustive uncertainty analysis of our reconstruction using a bootstrap approach. The analysis consisted of two steps. First, we estimated the confidence area for PEPs. For this, we replaced each paleomagnetic pole in the original APWP track with a discrete Fisherian distribution (Fisher et al., 1987) with the concentration parameter equivalent to that of the original pole. Next, we constructed 200 model APWP tracks by random selection of one point from each of the Fisherian distributions and calculated a great circle pole (a model PEP) for each model track (Fig. 3a). The 200 model PEPs constituted an uncertainty cloud for the PEP calculated from the original APWP track.

During the second step we calculated a confidence area for the final reconstruction of the Traps. We started with a set of points $\{S_0\}$ outlining the present position of the Traps. Points $\{S_0\}$ were first rotated around each of the model PEP poles $\{P_1\}$ representing the PEP uncertainty cloud for the first APWP track, into a new set of points $\{S_1\}$. Next, each point from $\{S_1\}$ was rotated around each of the PEP uncertainty poles $\{P_2\}$, resulting in a set $\{S_2\}$ (Fig. 3b). This procedure was repeated for all five PEP poles. After the final rotation was done, a

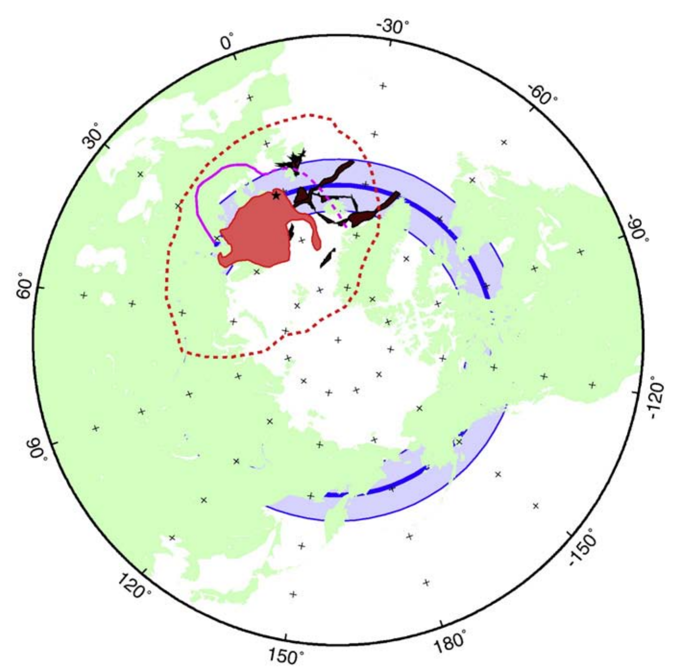

Fig. 2. Position of the Siberian Traps at 250 Ma (red shaded contour) and the 95% confidence area of the reconstruction (red dashed line). The star shows the position of the reference point (Norilsk) used for calculating the paleolatitude shown by solid blue line (light blue shaded band shows the α_{95} confidence interval for paleolatitude). Solid magenta line shows the extent of the Traps into the West Siberian Basin, and dashed magenta line shows potential norhtward extension of the Trap basalts into the Kara and Laptev Seas (Reichow et al., 2009, and references therein). Dark brown areas indicate the North Atlantic Igneous Province.