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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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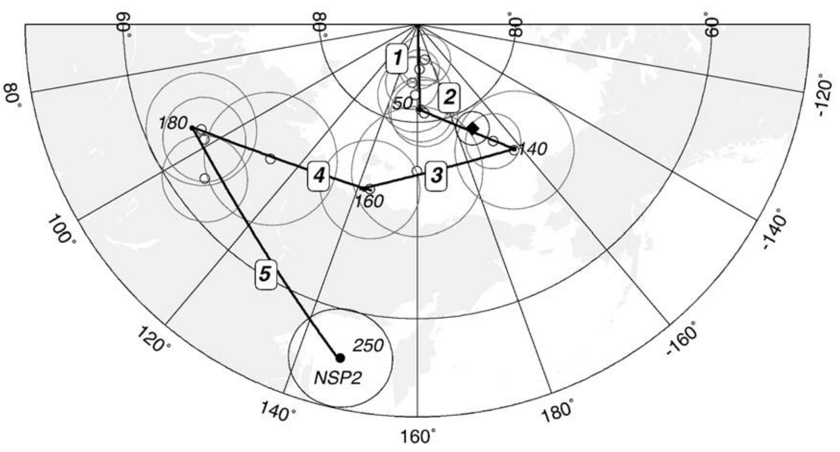

Fig. 1. Paleomagnetic poles used for PEP analysis (see text). Open circles show selected poles from the master apparent polar wander path (APWP) for Eurasia (Besse and Courtillot, 2002). Diamond shows the mean pole based on reliable Cretaceous paleomagnetic poles from North America rotated to the Eurasian 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

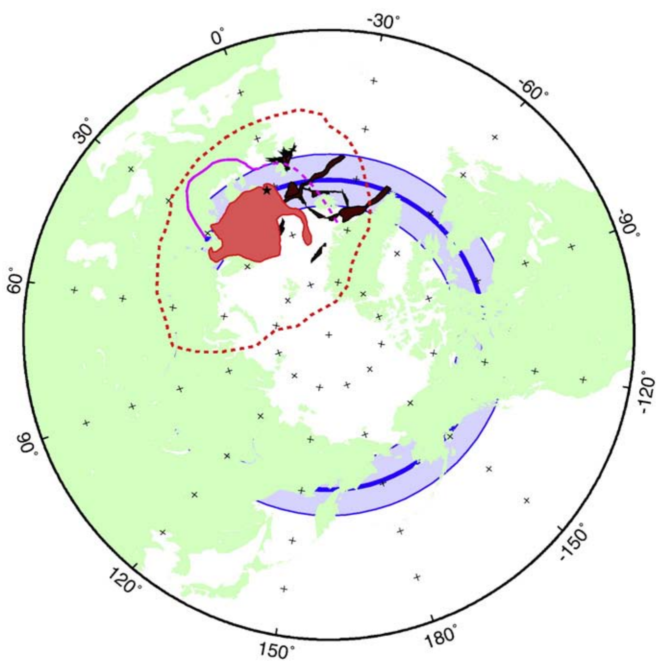

Fig. 2. Position of the Siberian Traps at 250 Ma (red shaded contour) and the 95% confidence area of the reconstruction (red dashed line). The star shows the position of the reference point (Norilsk) used for calculating the paleolatitude shown by solid blue line (light blue shaded band shows the α_{95} 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.

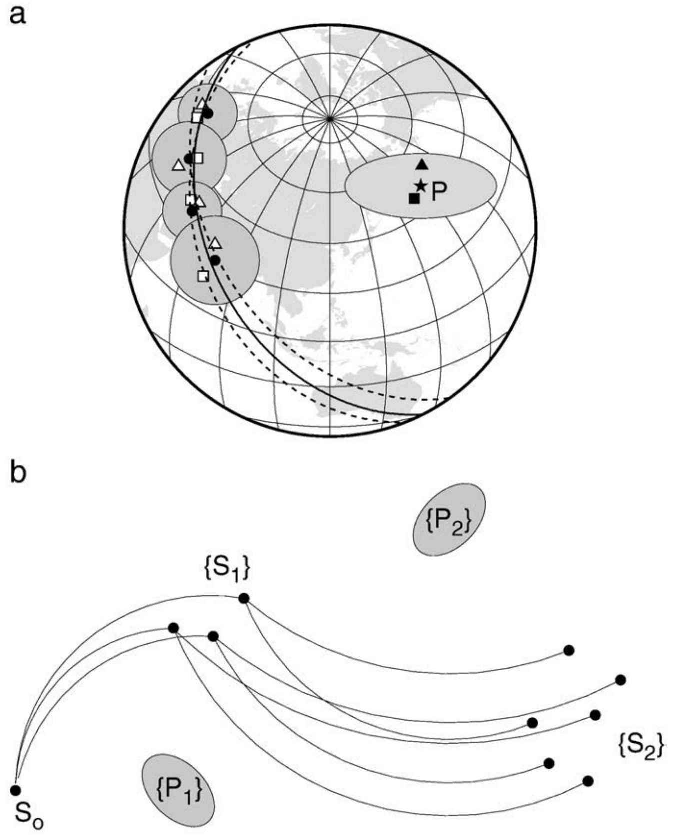

Fig. 3. (a) Calculation of the confidence area for a paleomagnetic Euler pole (P, solid star) corresponding to an APWP track (solid circles). Shaded circles show the A_{95} confidence areas for the APWP poles. Squares and triangles show two model APWP tracks (open symbols) and their corresponding model PEPs (solid symbols). Shaded ellipse represents the confidence area for P made by model PEPs (see text). (b) Calculation of the confidence area for the Trap reconstruction (see text).

contouring algorithm was applied to encircle the boundary of the final set ($\{S_5\}$) in order to represent the confidence area.

The 95% confidence area for the restored location (Fig. 2) has an irregular shape, that can be roughly approximated by an uncertainty ellipse with a semi-major axis of ~25°, and a semi-minor axis of ~18°. This relatively large uncertainty region is not surprising, considering the limited temporal distribution of poles available to model the apparent polar wander. An analysis using small circle fits to the APWP yields a similar, but more westerly position. The uncertainty region, however, is much larger (Supplementary Figure 3, Supplementary Table 1). We feel that the reconstructed position of the Traps and uncertainty region should be robust with respect to potential minor changes in APWP.

We have also estimated an additional uncertainty which could be associated with excluding some of the 60–110 Ma poles of Besse and Courtillot (2002) from our analysis. We assume that the poles represent a standstill due to a polar Euler pole and hence there could be a longitudinal motion of the continent missed by our PEP analysis. However, the movement of Eurasian plate in the late Cretaceous was mainly defined by the opening of Atlantic Ocean. The magnitude of this longitudinal motion can be gauged by estimating the amount of oceanic crust created during the time interval. We rotated a reference point (60 °N, 5 °E) back to 59 Ma and 118 Ma using the Eurasia–North America rotation poles from a global isochron chart (Royer et al., 1992). The angular distance between the reconstructed points is 6.3° (Supplementary Figure 4a). Assuming symmetrical spreading and entirely longitudinal motion, the amount of additional rotation of Eurasia around the polar Euler pole during the 60–120 Ma interval is estimated at ~3.2°, which has a negligible effect on the final reconstruction (Supplementary Figure 4b).

The 180–190 Ma poles from the master APWP show another potential standstill that is also observed from the individual continental datasets in Besse and Courtillot (2002). However, because during that time the Eurasian plate was still a constituent of Pangea, we believe that the standstill reflects slow motion of the supercontinent, rather than its rapid motion around a polar Euler pole.

We have also assumed here that polar wander, the rotation of the entire solid earth with respect to the spin axis, has been only a minor component of the APWP. There has been discussion of polar wander between 295 and 205 Ma (Marcano et al., 1999). Because all continents were gathered in one mass (Pangea), such polar wander is difficult to test. But the velocity of our reference site (Norilsk, 4.3 cm/yr) is well within typical plate velocities and plate tectonic scenarios to account for this motion are suggested by geological data (Supplementary Text 3 and Supplementary Figure 7). Moreover, polar wander since the Mesozoic has been very small (Tarduno and Smirnov, 2001; Tarduno, 2007), and it appears that mantle mass heterogeneities have not changed on time scales needed to drive large solid Earth rotations (see Supplementary Text 3).

We also note that the recent reconstruction based on a hybrid reference frame, in which a mantle flow model is used to correct hotspot drift and South Africa is assumed to be fixed relative to the mantle (Torsvik et al., 2008a,b), agrees well in latitude, but places the Traps ~40° eastward from our reconstructed location (Supplementary Table 2). The angular distance between the hybrid frame and PEP reconstructions are reasonably small (≤5.8°) for the last 160 Ma. We feel that the increasing distances at 180 Ma and 250 Ma may record longitudinal motion of South Africa with respect to the mantle.

4. Discussion and conclusion

The reconstructed position of the Traps using our preferred great circle fits is in the present-day North Atlantic region, close to Iceland and the eruptive sites of the ~61–58 Ma North Atlantic Igneous Province (NAIP) (e.g. Storey et al., 1998).The volume of the NAIP has been estimated to be ~$6.6 \cdot 10^6$ km^3 (Eldholm and Grue, 1994). Magmatism associated with emplacement of the Traps represents ~$3 \cdot 10^6$ km^3 (e.g., Reichow et al., 2009), but this must be considered a minimum estimate because it does not account for outlying volcanic areas, subsequent erosion, and some intrusive volumes.

A key component of non-plume models that seek to explain Trap magmatism, is the existence of a heterogeneous upper mantle (Anderson, 2004). After Trap formation, this upper mantle region would then be depleted; it could not be tapped again to form the NAIP. But, the presence of an enriched upper mantle is an essential part of non-plume models to explain the NAIP (Foulger, 2002). We note that, since the eruption of the Traps at ~250 Ma, the North Atlantic mantle region has not been the site of focused subduction that might otherwise replenish a hypothetical enriched upper mantle.

The Siberia Traps, NAIP and Iceland have also been linked to a Cretaceous large igneous province in the high Arctic (Tarduno et al., 1998; Maher, 2001) in some prior plate reconstruction models (e.g. Forsyth et al., 1986; Lawver and Müller, 1994; Lawver et al., 2002). The southern extent of Cretaceous flood basalt volcanism in the high Canadian Arctic occurred at ~71° N (Tarduno et al., 2002), some 6° north of Iceland. Because of the latitudinal mismatch, and the additional need to reconstruct Cretaceous eruptive sites on the North American plate relative to Eurasia, we do not consider further here the linkages with High Arctic volcanism. Instead, we emphasize the latitudinal and longitudinal matches between Iceland,the NAIP and the Siberia Traps evident from our PEP analysis of the Eurasian APWP.

The co-location of Trap and NAIP eruptive sites can be explained if there is communication between the upper and lower mantle. However, the pattern of volcanic production is quite different from standard ideas of mantle plume heads and tails (Campbell, 2007). Instead, significant temporal changes in plume flux are needed. Time dependent behavior of mantle plume in the form of solitary or periodic waves has been suggested in some experiments (Olson and Christensen, 1986). Lin and van Keken (2005) showed that multiple episodes of flood basalt activity may be a result of secondary instabilities in the mantle plume due to the entrainment of dense eclogite material at the mantle base.

The longevity of the mantle feature needed to explain our reconstructions is also of note; it is 1.5 to 2 times longer than estimates based on hotspots with extant tracks, but consistent with some other attempts at large scale reconstruction (Burke and Torsvik, 2004). Our analysis thus suggests that a long-lived (>250 million-year-long) lower mantle chemical and/or thermal anomaly beneath the current North Atlantic region has repeatedly resulted in large scale magmatism over a period longer than that typically associated with one plate tectonic cycle.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.epsl.2010.07.023.

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