LETTERS

Seismic evidence for convection-driven motion of the North American plate

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Since the discovery of plate tectonics, the relative importance of driving forces of plate motion has been debated[1,2]. Resolution of this issue has been hindered by uncertainties in estimates of basal traction, which controls the coupling between lithospheric plates and underlying mantle convection[2–4]. Hotspot tracks preserve records of past plate motion[5] and provide markers with which the relative motion between a plate's surface and underlying mantle regions may be examined. Here we show that the 115–140-Myr surface expression of the Great Meteor hotspot track in eastern North America is misaligned with respect to its location at 200 km depth, as inferred from plate-reconstruction models and seismic tomographic studies[6]. The misalignment increases with age and is consistent with westward displacement of the base of the plate relative to its surface, at an average rate of $3.8 \pm 1.8\,\mathrm{mm\,yr^{-1}}$. Here age-constrained 'piercing points' have enabled direct estimation of relative motion between the surface and underside of a plate. The relative displacement of the base is approximately parallel to seismic fast axes and calculated mantle flow[7], suggesting that asthenospheric flow may be deforming the lithospheric keel and exerting a driving force on this part of the North American plate.

Theoretical studies indicate that plate motion is primarily controlled (~90%) by convective flow driven by density heterogeneities in the mantle, particularly those associated with sinking oceanic slabs[1,7–9]. The nature and strength of viscous coupling of tectonic plates to mantle convection remains unclear, however. In western North America where lithosphere is thin (<100 km), indirect evidence from seismic anisotropy suggests weak coupling of plate motion to the underlying flow, resulting in a small drag force[10]. On the other hand, tectonically quiescent continental regions (cratons) are generally underlain by refractory lithospheric keels that may extend 200 km or more into the mantle[11]. Although it is recognized that these keels could increase basal traction[1–4], quantifying this force is hindered by a lack of direct observations[10].

Bokelmann[2,12] proposed that analysis of deformation fabrics of lithospheric keels inferred from seismic anisotropy may provide clues about whether basal traction constitutes a net drive or drag force in these regions (Fig. 1). We chose to study the North American plate because it is among the fastest-moving plates that possess a thick lithospheric keel[3]. Seismic P-wave anisotropy beneath the craton indicates a consistently southwest-dipping deformation fabric, roughly parallel to plate motion, suggesting that North American plate motion is driven (rather than impeded) by interaction of mantle flow with the keel[2,12].

Here we apply similar deformation analysis to an ancient hotspot track. Hotspots represent localized sublithospheric sources of magmatism that exhibit far less motion with respect to a whole-mantle reference frame than most plates[5]. Although hotspots are traditionally interpreted as thermal plumes that originate in the lower mantle[5], alternative models for hotspots include secondary plumes, convective instabilities and fertility variations in the upper mantle[13]. Regardless of source, hotspot-related magmatism enables the determination of relative motion between a plate surface and the underlying mantle.

The Great Meteor hotspot track in the Atlantic and North America has been studied extensively[14–16]. Various crustal features are interpreted to mark the continental segment, delineating an arcuate track (Fig. 2). Igneous crystallization ages increase monotonically along the track (Fig. 2), generally consistent with the hotspot model[17]. Surface features attributed to the hotspot include small-volume kimberlite eruptions that penetrate through thick cratonic lithosphere[17], intermediate-volume alkaline magmas near the edge of the craton[16], and an intervening region of unusually deep crustal seismicity[18]. These changes in near-surface expression may reflect hotspot interaction with progressively thinner lithosphere, owing to motion of the overriding plate (Fig. 1a).

Surface-wave tomographic studies of North America[6] reveal an elongate low-velocity anomaly beneath the Great Lakes. This feature is strongly expressed at 200 km depth (Fig. 2), placing it at (or near) the base of the lithosphere[19]. The anomaly has been interpreted as an indentation, or 'divot', in the high-velocity mantle keel[20]. Curiously, the axis of the divot is better aligned with the oceanic hotspot track (New England seamount chain) than are surface features inferred to mark the continental segment. Here, we explore whether the divot may have formed as a result of the passage of North America over the hotspot.

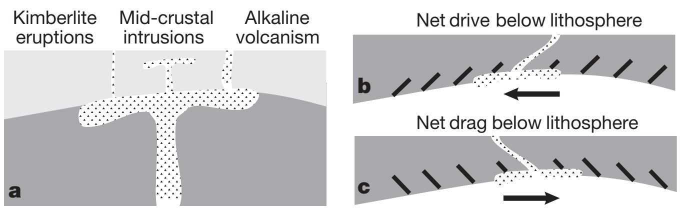

Figure 1 | Schematic diagram showing near-surface manifestations of a hotspot and shear sense from different polarities of basal traction. **a**, Depending on the thickness of the plate, the near-surface expressions of a hotspot may include small-volume kimberlite eruptions that penetrate the lithosphere, intermediate-volume alkaline volcanism and intervening regions where no surface volcanic rocks are evident, but where mid-crustal seismicity is observed. In the latter case, the absence of surface volcanism suggests that intrusions do not penetrate beyond the mid-crust. **b**, If sublithospheric mantle flow exerts a net drive on plate motion, the base of a hotspot track will tend to be displaced in the direction of plate motion, relative to the surface. Deformation fabric and corresponding seismic fast axes are shown schematically by dipping lines[2,12]. **c**, If basal traction exerts a net drag, the opposite sense of shear is produced. In both **b** and **c**, plate-edge forces such as collision resistance contribute to overall torque balance[1]. Creep processes in the mantle may accommodate the postulated deformation of the lithosphere[3].

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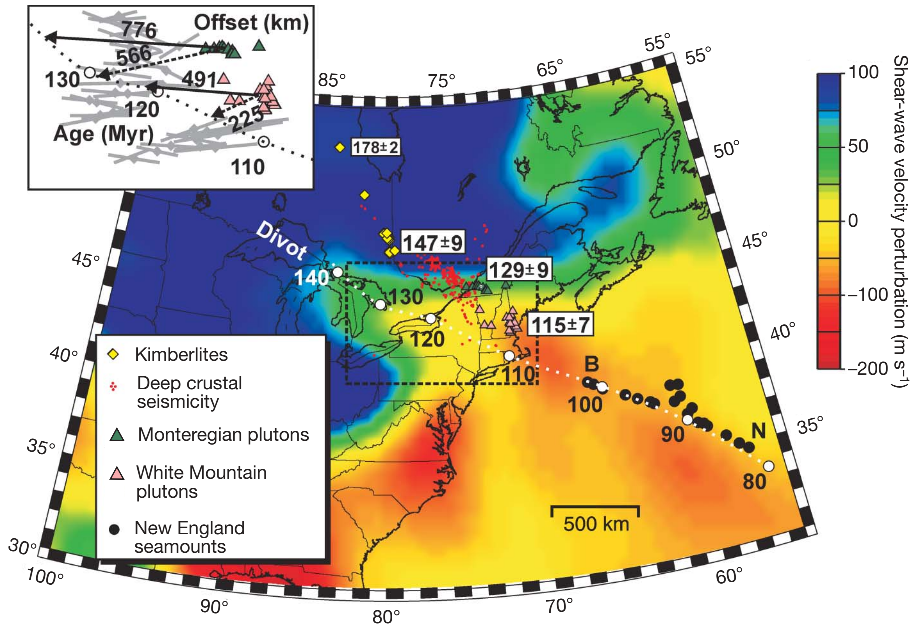

Figure 2 | Inferred track of the Great Meteor hotspot. Track is superimposed on shear-wave velocity perturbation at a depth of 200 km from model NA04 (ref. 6). Blue colours in the map indicate high-velocity regions associated with the mantle keel beneath North America. Numbers inside white rectangles are ages in Myr (mean ± standard deviations) of surface features along the track[17,27,30]. The dashed white line shows the projected position of the Great Meteor hotspot (present location 27° E, 26° N) based on a recent plate-reconstruction model[24]. The projected track has been rotated by 27.2° about a pole at 138.8° E, 13.4° S to minimize the least-squares misfit to the Bear (B) and Nashville (N) seamounts (103 and 82 Myr, respectively). It agrees well with the position of an elongate low-velocity anomaly in the Great Lakes region ('divot'), but is misaligned with the surface expression of the track. The upper inset shows the offset of the centroid location of the Monteregian and White Mountain igneous provinces, relative to coeval points on the projected track (dotted line with circles). Black arrows show displacement for maximum (solid) and mean (dashed) emplacement ages; grey bars show seismic fast-axis directions[29]. The inset region is indicated by the dashed rectangle in the main figure.

Seismic velocity anomalies in the continental upper mantle can be classified as thermal or compositional in origin, or a combination of both[21]. To test whether a thermal anomaly could persist since passage over the hotspot (120 Myr before), we have conducted a two-dimensional numerical experiment. The initial thermal anomaly is represented by a 300 km × 50 km rectangular region (underplate) in the lowermost 50 km of the lithosphere (150–200 km), fed by a 40-km-wide vertical conduit. This region is initially perturbed from a cratonic geotherm by resetting the temperature to adiabatic conditions. For a relative plate velocity of 3 cm yr^{-1} and buoyancy flux of 2,000 kg s^{-1} (ref. 16), 10% of the volume of this zone is replenished continuously by the hotspot. The track is generated much faster than it decays by thermal diffusion, so our two-dimensional treatment is justified. We obtained a finite-difference solution to the diffusion equation using thermal conductivity parameters for this region[22]. After 120 Myr, the residual thermal anomaly is about 80 °C and is most intense at ~200 km depth (Fig. 3). The thermal anomaly is similar in size and shape to the observed seismic anomaly

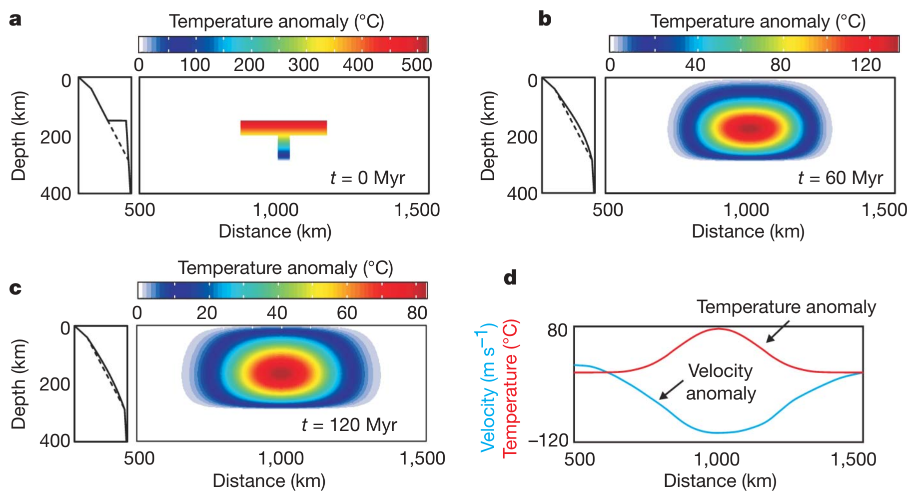

Figure 3 | Modelled evolution of the thermal anomaly from a hotspot. **a**, Passage of a plume at $t = 0$, 'resets' the geotherm by increasing the temperature to the adiabat within a 40-km-wide plume and a 300 km × 50 km underplate region. The graphs on the left show the initial geotherm (dashed) and temperature field (solid) in the centre of the thermal anomaly. The temperature range is 0 °C to 1,500 °C. In **b** and **c**, the subsequent temperatures evolve by diffusion in two dimensions, thus effectively treating the anomaly as infinite and out of the plane. Panel **d** compares the modelled temperature anomaly ($t = 120$ Myr) with the shear-wave velocity anomaly at 200 km depth from model NA04 (ref 6). The shear-wave velocity profile extends from 39.69° N, 83.36° W to 48.09° N, 76.62° W.

in the divot. We note, however, that if the seismic anomaly is entirely thermal in origin, then a thermal sensitivity of $1.1\,\mathrm{m\,s^{-1}\,{}^{\circ}C^{-1}}$ is required, at the upper limit of laboratory-derived values for mantle rocks under subsolidus conditions[21].

It is likely that a mantle anomaly produced by a plume would also have a compositional signature owing to enrichment of the lithospheric keel by plume material[23]. Such chemical enrichment tends to reduce seismic velocity, while increasing density. For mantle rocks an excess temperature of $\sim$80 °C predicted by our model would result in a density decrease of about 0.25% (ref. 23). Isostatic compensation for this mass deficiency would require an increase of 4% in the FeO/(FeO + MgO) ratio, well within the natural range of values for continental lherzolites[23].

We computed the track of the Great Meteor hotspot in North America based on a recent plate reconstruction model[24], constrained to fit the New England seamount trend (Fig. 2). The projected track agrees well with the mantle divot at 200 km depth, but is misaligned with near-surface continental features. Such a discrepancy could arise from deflection of a plume tail by cross-currents in the mantle[5] (the 'mantle wind'). Alternatively, a plume may be deflected by the cratonic keel, in which case its surface expression may follow the path of least mechanical resistance through the lithosphere[25]. Finally, a hotspot may not be stationary with respect to the overall mantle reference frame[26], in which case a projection of the track based on an independently derived plate-reconstruction model may be in error.

If the mantle divot were produced by the Great Meteor hotspot, none of these explanations is consistent with the observed misalignment. Plume deflection by mantle wind is unlikely, because the hotspot track extends sufficiently far into the continent for thick lithosphere west of the track to have shielded it from cross-currents above 200 km. Furthermore, deflection by a dipping zone of weakness does not satisfactorily explain the observed increase in offset with age along the track (see below). Similarly, although a departure from hotspot fixity may explain discrepancies between computed and observed tracks, it does not explain a systematic misalignment between deep and shallow segments.

We propose that the near-surface track of the hotspot was originally emplaced on top of the mantle seismic anomaly, but has since become offset. By connecting coeval points along the inferred shallow and deep trends, we can estimate the net displacement. There is evidence for extended magma residence time in the shallow lithosphere[27], so we assume, for a particular igneous suite, that passage of the hotspot occurred within one standard deviation above the mean age. Using the centroid location (average location of dated intrusions), we estimate a net offset of 556–776 km for the Monteregian intrusions (129 ± 9 Myr) and 225–491 km for the White Mountain intrusions (115 ± 7 Myr) (Fig. 2, inset). Assuming that displacement between the surface and 200 km depth occurred as a continuous process, these estimates indicate an average offset rate of $3.8 \pm 1.8\,\mathrm{mm\,yr^{-1}}$, implying a depth-averaged lithospheric strain rate of $6.0 \pm 2.9 \times 10^{-16}\,\mathrm{s^{-1}}$.

Instantaneous flow calculations[7] predict subhorizontal westward mantle flow of $\sim 2\,\mathrm{cm\,yr^{-1}}$ beneath this part of North America, driven by excess density in the lower mantle from the remnant Farallon slab. Our inferred displacement rate is intermediate between zero (rigid plate) and the calculated asthenospheric flow velocity. We interpret the observed displacement to arise from lithospheric deformation. This interpretation is supported by recent seismic tomographic data, which reveal a southwest-dipping low-velocity anomaly extending upward from 200 km (within the divot) towards the surface near the Monteregian intrusions[28].

The deformation implied by our model represents horizontal simple shear in the lithospheric mantle keel arising from viscous coupling with underlying asthenospheric flow, for which strain compatibility can be maintained in the mantle independently of crust and surface deformation[3]. The sense of shear supports Bokelmann's hypothesis[2,12] that mantle flow is deforming the cratonic keel and thus in part driving the motion of North America (Fig. 1b). Assuming a simple newtonian rheology, for an effective viscosity of $\sim 5 \times 10^{21}$ Pa s (ref. 3) our estimated strain rate of $\sim 6.0 \times 10^{-16}\,\mathrm{s^{-1}}$ implies a basal shear stress of $\sim$3 MPa. This stress magnitude is of the same order as recent estimates of basal traction beneath thick lithospheric roots, on the basis of laboratory data[3] and mantle-flow modelling[4].

Seismic anisotropy induced by basal traction should lead to shear-wave fast-polarization directions that are parallel, to within 180° uncertainty, to the lithosphere–asthenosphere velocity difference[10]. In many continental regions, such a relationship is obscured by multiple layers of anisotropy (for example, ref. 3), but in the region of the mantle divot only a single anisotropic layer is observed[29]. Both asthenospheric flow[7] and absolute plate motion[29] are approximately westward in this area, so flow-induced anisotropy from basal traction should result in a simple pattern of east–west fast-splitting directions. Shear-wave splitting results (Fig. 2, inset) confirm this orientation, providing further support for our model.

Thus our study documents a conspicuous misalignment between an elongate seismic velocity anomaly at 200 km depth (the so-called Great Lakes mantle divot) and the surface track of the Great Meteor hotspot. The mantle divot is compatible with the projected track of the hotspot and may be caused by the combined effects of residual thermal perturbation and compositional changes. We propose that the base of the track is displaced westward from the surface as a result of viscous coupling of the North American cratonic keel with mantle flow. Our observations represent the first instance, to our knowledge, in which age-constrained piercing points are available to estimate net displacement between the top and base of a continental plate. The inferred sense of shear implies that basal traction may in part drive plate motion.

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1. Forsyth, D. & Uyeda, S. On the relative importance of the driving forces of plate motion. *Geophys. J. R. Astron. Soc.* **43**, 163–200 (1975).
2. Bokelmann, G. H. R. Which forces drive North America? *Geology* **30**, 1027–1030 (2002).
3. Bokelmann, G. H. R. & Silver, P. Shear stress at the base of shield lithosphere. *Geophys. Res. Lett.* **29**, doi:10.1029/2002GL015925 (2002).
4. Conrad, C. P. & Lithgow-Bertelloni, C. Influence of continental roots and asthenosphere on plate-mantle coupling. *Geophys. Res. Lett.* **33**, doi:10.1029/2005GL025621 (2006).
5. Duncan, R. A. & Richards, M. A. Hotspots, mantle plumes, flood basalts, and true polar wander. *Rev. Geophys.* **29**, 31–50 (1991).
6. Van der Lee, S. & Frederiksen, A. in *Seismic Data Analysis and Imaging With Global and Local Arrays* (eds Nolet, G. & Levander, A.) 67–80 (AGU Geophysical Monograph 157, Washington DC, 2005).
7. Conrad, C. P. & Lithgow-Bertelloni, C. Iceland, the Farallon slab, and dynamic topography of the North Atlantic. *Geology* **32**, 177–180 (2004).
8. Lithgow-Bertelloni, C. L. & Richards, M. A. The dynamics of Cenozoic and Mesozoic plate motions. *Rev. Geophys.* **36**, 27–78 (1998).
9. Conrad, C. P. & Lithgow-Bertelloni, C. How mantle slabs drive plate tectonics. *Science* **298**, 207–209 (2002).
10. Silver, P. G. & Holt, W. E. The mantle flow field beneath western North America. *Science* **295**, 1054–1057 (2002).
11. Jordan, T. H. The continental tectosphere. *Rev. Geophys.* **13**, 1–12 (1975).
12. Bokelmann, G. H. R. Convection-driven motion of the North American craton: Evidence from P-wave anisotropy. *Geophys. J. Int.* **148**, 278–287 (2002).
13. Courtillot, V., Davaille, A., Besse, J. & Stock, J. Three distinct types of hotspots in the Earth's mantle. *Earth Planet. Sci. Lett.* **205**, 295–308 (2003).
14. Crough, S. T. Mesozoic hotspot epeirogeny in eastern North America. *Geology* **9**, 2–6 (1981).
15. Morgan, W. J. Hotspot tracks and the early rifting of the Atlantic. *Tectonophysics* **94**, 123–139 (1983).
16. Sleep, N. H. Monteregian hotspot track: A long-lived mantle plume. *J. Geophys. Res.* **95**, 21983–21990 (1990).
17. Heaman, L. M. & Kjarsgaard, B. A. Timing of eastern North American kimberlite magmatism: continental extension of the Great Meteor hotspot track? *Earth Planet. Sci. Lett.* **178**, 253–268 (2000).
18. Adams, J. & Basham, P. in *Neotectonics of North America* (eds Slemmons, D. B., Engdahl, E. R., Zoback, M. D. & Blackwell, D. D.) 261–276 (Geological Society of America, Boulder, Colorado, 1991).
19. Darbyshire, F. A., Eaton, D. W., Frederiksen, A. W. & Ertolahti, L. New insights into the lithosphere of the Superior Province from Rayleigh wave dispersion and receiver function analysis. *Geophys. J. Int.* (in the press).

20. Fouch, M. J., Fischer, K. M., Parmentier, E. M., Wysession, M. E. & Clarke, T. J. Shear wave splitting, continental keels, and patterns of mantle flow. *J. Geophys. Res.* **105,** 6255–6275 (2000).
21. Artemieva, I. M., Magali, B., Leveque, J.-J. & Mooney, W. D. Shear wave velocity, seismic attenuation, and thermal structure of the continental upper mantle. *Geophys. J. Int.* **157,** 607–628 (2004).
22. Mareschal, J.-C. *et al.* Heat flow and deep thermal structure near the southeastern edge of the Canadian Shield. *Can. J. Earth Sci.* **37,** 399–414 (2000).
23. VanDecar, J. C., James, D. E. & Assumpção, M. Seismic evidence for a fossil mantle plume beneath South America and implications for plate driving forces. *Nature* **378,** 25–31 (1995).
24. Schettino, A. & Scotese, C. R. Apparent polar wander paths for the major continents (200 Ma to the present day): A palaeomagnetic reference frame for global plate tectonic reconstructions. *Geophys. J. Int.* **163,** 727–759 (2005).
25. Sleep, N. H., Ebinger, C. J. & Kendall, J.-M. in *The Early Earth: Physical, Chemical and Biological Development* (eds Fowler, C. M. R., Ebinger, C. J. & Hawkesworth, C. J.) 135–150 (GSL Special Publication 199, Geological Society of London, London, 2002).
26. Tarduno, J. A. & Gee, J. Large-scale motion between Pacific and Atlantic hotspots. *Nature* **378,** 477–480 (1995).
27. Eby, G. N. Geochronology of the Monteregian Hills alkaline igneous province, Quebec. *Geology* **12,** 468–470 (1984).
28. Aktas, K. & Eaton, D. W. Upper-mantle velocity structure of the lower Great Lakes region. *Tectonophysics* **420,** 267–281 (2006).
29. Eaton, D. W., Frederiksen, A. & Miong, S.-Y. Shear-wave splitting observations in the lower Great Lakes region: Evidence for regional anisotropic domains and keel-modified asthenospheric flow. *Geophys. Res. Lett.* **31,** L07610, doi:10.1029/2004GL019438 (2004).
30. Zartman, R. E. Geochronology of some alkaline rock provinces in eastern and central United States. *Annu. Rev. Earth Planet. Sci.* **5,** 257–286 (1977).

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