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Ocean circulation and mantle melting controlled by radial flow of hot pulses in the Iceland plume

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Convection of the mantle influences elevation at the Earth's surface. For example, in the North Atlantic Ocean, V-shaped ridges of thickened oceanic crust that straddle the mid-ocean ridge are thought to arise from variations in the underlying mantle properties[1]. However, the detailed relationship between these V-shaped ridges and convective circulation is uncertain. Here we use measurements of residual water depth—a proxy for crustal thickness—and basaltic geochemistry to assess factors responsible for ridge formation. We find a correlation between basalt composition and crustal thickness that is best explained if V-shaped ridges are formed by the passage of unusually hot pulses of mantle away from Iceland. We also show that ocean circulation patterns over the past 7 million years, recorded by flow of the Northern Component Water[2–4] from the Norwegian Sea into the Atlantic Ocean and the accumulation of thick drifts of sediment[5], are controlled by variations in the elevation of sea floor between Greenland and Iceland. We suggest that pulses of hot mantle also drove periodic uplift of the sea floor, and moderated the export of water and sediment into the North Atlantic Ocean. Diverse observations can therefore be explained if blobs of mantle, 25 °C hotter than the background plume temperature, travelled up the conduit beneath Iceland and spread out radially at velocities of 40 cm yr^{-1}.

The pattern of convective circulation beneath lithospheric plates causes changes in elevation at the Earth's surface. As the Rayleigh number of the mantle is 10^6–10^8, convective flow is vigorous and varies on timescales of 1–100 Myr (ref. 6). Transient blobs of hot and cold fluid generated by instabilities of the lower boundary layer are expected. Emplacement of large igneous provinces is preceded by regional, kilometre-scale uplift which is caused by the impact of hot plumes at the base of the lithospheric plate[1]. Smaller temperature fluctuations also change surface elevation by tens to hundreds of metres[7].

We explore the link between elevation changes, basaltic geochemistry and convective circulation in the North Atlantic Ocean, where the Icelandic Plume has existed for ~60 Myr. We focus on this region for two reasons. First, the Icelandic Plume is located over a mid-ocean ridge (MOR) which acts as a linear sampler of transient behaviour within the underlying convecting layer[8,9]. Second, the plume controls the elevation of the Greenland–Scotland Ridge (GSR) which, in turn, moderates long-term export of North Atlantic Deep Water (NADW) from the Norwegian–Greenland Sea into the Atlantic Ocean[10]. Transient plume behaviour is manifest by a set of diachronous V-shaped ridges and troughs straddling the MOR near Iceland (Fig. 1). Since Vogt's insight[11], it is recognized that these ridges and troughs, which

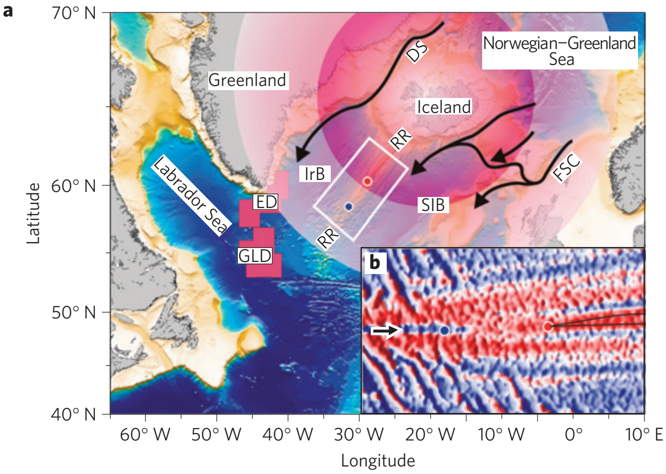

Figure 1 | Map of the Icelandic Plume. a, Map of North Atlantic Ocean showing idealized planform of the Icelandic Plume. Pale pink disc = extent of plume; dark pink disc = limit of youngest thermal anomaly; Red circle = intersection of youngest V-shaped ridge (VSR) with Reykjanes Ridge (RR); blue circle = position beyond youngest VSR. IrB = Irminger Basin; SIB = South Icelandic Basin; FSC = Faroe-Shetland Channel; DS = Denmark Straits; black lines = deep-water pathways; dark pink polygons (ED, GLD) = Eirik and Gloria drifts[19]; white box = inset map. **b**, Gravity anomalies delineating VSRs (red = positive anomalies with thicker crust; blue = negative anomalies with thinner crust)[9]; black lines = youngest VSR; black arrow = RR.

have bathymetric, gravitational and seismic expressions, record the temporal and spatial evolution of the plume[12–14]. Despite their significance, the formation of these V-shaped ridges is debated[14–16]. Are they generated by radial flow away from the plume centre or by channelized flow along the MOR? Do they represent compositional or temperature variations in the underlying asthenosphere?

Our starting point is a V-shaped ridge chronology which is used to track changes within the plume head[17]. First, we estimate how residual depth varies with time (Fig. 2a). Residual depth is the water-loaded depth to basement rock, which has been corrected for sediment loading, plate age and present-day dynamic support[17]. It varies by ±400 m and is controlled by changes in crustal thickness[14]. At the MOR, crustal thickness is used to estimate asthenospheric temperatures (Fig. 2a). Away from the MOR, this history of temperature fluctuations is used to constrain the history of elevation changes at specific distances from the plume centre[11]. At 600 km from its centre, plume models[8] suggest an ambient

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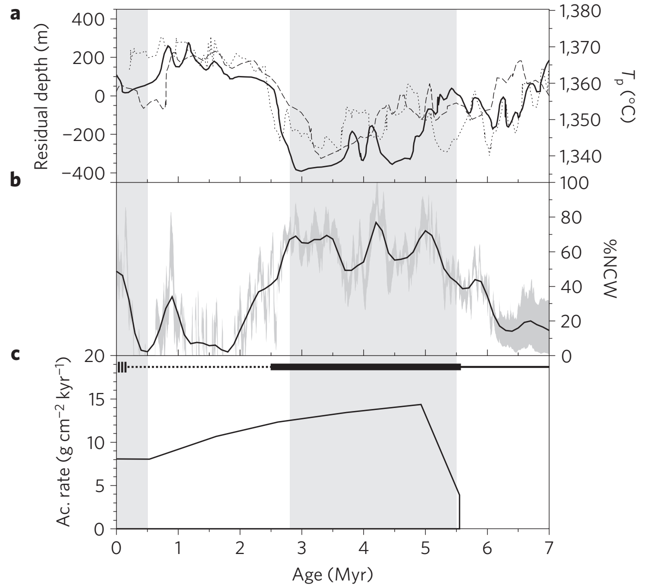

Figure 2 | Vertical motions, overflow and drifts. Residual depth, palaeoceanographic and sedimentary drift information plotted on an astronomical timescale[30]. Linear time correction for the radial distance to Denmark Straits was applied[17]. Grey bands = periods when the Icelandic plume was cooler. **a**, Residual depth calculated from three seismic profiles at the northeastern end of the white box in Fig. 1a; right-hand axis = inferred potential temperature[7]. **b**, Northern Component Water overflow (%NCW; ref. 3). **c**, Eirik drift accumulation rate (Fig. 1a; ref. 19); along top edge, thin horizontal line = weak bottom current; thick line = strong current; dotted line = weak current (that is restricted deep water, ice rafting); dashed lines = Holocene current increase[5].

potential temperature of 1,330 °C and a plume layer thickness of 100–200 km (ref. 18). At this distance, an additional increase of 25 °C generates 90–180 m of regional uplift[7]. Our residual depth analysis shows that two thermal anomalies were generated during the past 7 Myr (Fig. 2a). If these anomalies travel by radial flow away from the plume conduit, we can calculate their arrival time at distal locations[17]. For the Denmark Straits, we predict that surface elevation declined 7–5 Myr ago, and remained subdued until 2.75 Myr ago. A new thermal anomaly appeared 2.75 Myr ago and decayed ∼1 Myr ago.

The plume has created a shallow submarine sill between Greenland and Europe, which plays a key role in moderating the export of NADW and its precursor, Northern Component Water (NCW), into the Atlantic Ocean[2–4]. At present, 50% of NADW flows through the Denmark Straits[10]. Poore *et al.*[3] used a global inventory of δ^{13}C measurements from benthic foraminifera recovered in drill core to calculate NCW overflow during Neogene times (Fig. 2b). Overflow peaked 5.5–2.75 Myr ago and again 0.5 Myr ago. These results are corroborated by the record of sedimentary drifts located downstream of the Denmark Straits (Fig. 2c; refs 5, 19). Sedimentary flux measurements and bottom current strength estimates suggest that the Eirik Drift grew ∼7.5 Myr ago. Currents remained weak until 5.6 Myr ago, when sediment flux increased, accompanied by an increase in grain size. Stronger currents are inferred from bedform analysis for 5.6–2.5 Myr ago (ref. 5). The acme of Eirik Drift formation is 4.5 Myr ago, after which sediment flux slowly decreased. A sharp decrease in bottom current 2.5 Myr ago coincides with initiation of ice rafting.

The correlation between predicted uplift at the Denmark Straits, overflow of NCW, and deposition of the Eirik Drift suggests that temperature fluctuations, spreading radially away from the plume centre, control distal surface elevation. In the past 7 Myr, two hot blobs have travelled up the plume conduit as solitary waves[6,8]. The younger blob formed a radially spreading annulus ∼3 Myr ago. Shortly afterwards, the GSR was uplifted and overflow of NCW was significantly reduced[3]. This annulus has travelled 650 km away from the plume centre, leaving cooler asthenosphere in its wake and causing subsidence which increased NCW overflow 0.5 Myr ago. The surficial expression of this annulus occurs where the youngest V-shaped ridge intersects the Reykjanes Ridge at 61° N (ref. 9). Our hypothesis is predicated on a thermal origin for V-shaped ridge formation which can be tested by geochemical modelling of basaltic rocks dredged along the Reykjanes Ridge[20].

The chemical composition of these basaltic rocks varies along the ridge axis (Fig. 3; ref. 20). The trace element ratio, Nb/Y, is a convenient way of showing this variation because it is insensitive to crustal processes (for example fractional crystallization). Instead, Nb/Y reflects mantle melt composition which is controlled either by source composition or by depth and degree of melting. A southward decrease of Nb/Y between 63° N and 61° N correlates with deepening of the MOR, with a gradual decrease in crustal thickness, and with decreasing source enrichment estimated by isotopic indicators (for example ^{87}Sr/^{86}Sr; refs 20–22). Geochemical enrichment closer to Iceland results from melting of compositional heterogeneities within the plume conduit. Southward flow along the ridge axis progressively melts out these heterogeneities[22].

Figure 3c reveals a short wavelength chemical variation, which is visible in a suite of major and trace elements, and correlates with the pattern of V-shaped ridges. This variation continues down the ridge axis south of 57° N (ref. 23). At 60.3° N, the youngest V-shaped ridge intersects the ridge axis. Beneath this V-shaped ridge, crustal thickness measured in a wide-angle seismic experiment is 10.4 ± 0.5 km (ref. 13; red location, Figs 1 and 3). At 58.5° N, the trough has a projected crustal thickness of 8.6 ± 0.5 km (ref. 13; blue location). It is instructive to compare the geochemical signatures at both locations. At the red location, thicker oceanic crust correlates with lower Nb/Y, with lower values of other trace element ratios (for example La/Yb, Zr/Y), with lower concentrations of incompatible elements (for example La, Rb, Ba), and with ^{87}Sr/^{86}Sr ∼ 0.70270. At the blue location, thinner oceanic crust correlates with higher concentrations of incompatible elements, and with ^{87}Sr/^{86}Sr ∼ 0.70276. Crucially, the observed negative correlation between chemical enrichment and crustal thickness is inconsistent with a compositional origin for V-shaped ridges and troughs. Melting of enriched, fusible parcels of mantle beneath a spreading ridge would generate thicker, not thinner, crust. Instead, the negative correlation means that variation in melting must be primarily controlled by temperature anomalies[14] rather than by compositional anomalies[24]. Beneath the ridge axis, higher asthenospheric temperatures give rise to greater degrees of melting, which produce thicker crust, lower values of Nb/Y, and more depleted ^{87}Sr/^{86}Sr values.

To examine the importance of temperature variation alone, a two-dimensional melting model is used to predict chemical and crustal thickness observations along the MOR (Fig. 3a,b). In this model, solid material flows through the melting region by corner flow, which is controlled by plate spreading. Corner flow is a reasonable assumption south of 60.3° N because the narrow (∼100 km diameter) plume conduit is confined to Iceland[25,26]. To quantify the role of thermal anomalies, we assume that source composition beneath the MOR south of 60.3° N is invariant. We adapted the algorithm of White *et al.*[27], which models chemical composition and crustal thickness by varying melt fraction as a function of depth. Our modelling procedure is divided into a series of iterative steps. First, we matched a crustal thickness of 8.6 km at the blue location by varying the asthenosphere's potential temperature, T_p. The required value, T_p = 1,330 °C, constrains melt fraction as a function of depth, which allows us to quantify

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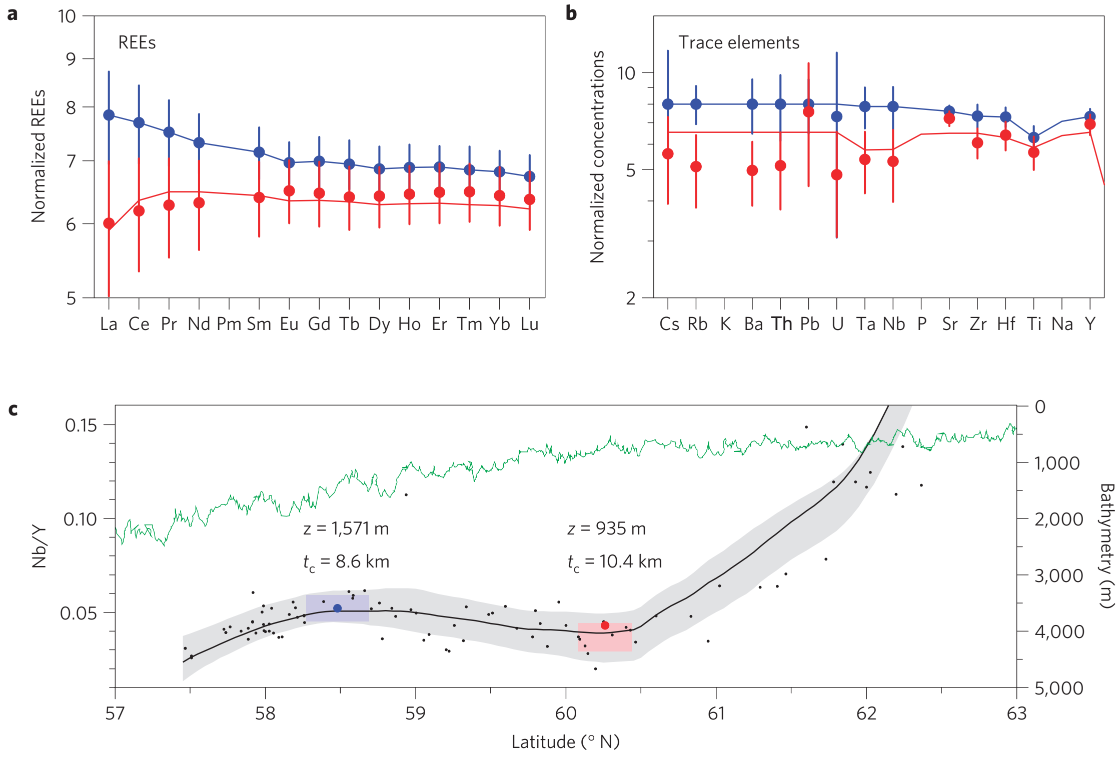

Figure 3 | Geochemical modelling. Observed and modelled geochemical variation along the MOR (Fig. 1a). Fractional crystallization corrected using Mg–Fe data[27]. **a**, Rare-earth element (REE) concentrations normalized to calculated local source. Red circles = averaged REE values $\pm 1\sigma$ at red locus; red line = best-fitting model for T_p = 1,354 °C (see text). Blue circles = REE values $\pm 1\sigma$ at blue locus; blue line = model for T_p = 1,330 °C. REEs averaged within red and blue boxes in **c**. **b**, Observed and modelled trace elements at red and blue loci. Sr discrepancy indicates crustal processes. **c**, Nb/Y along MOR. Black circles = measured Nb/Y; black/grey line = best-fitting line $\pm 1\sigma$ (ref. 11); red and blue circles = calculated Nb/Y for T_p = 1,354 and 1,330 °C respectively. Green line = bathymetry; bathymetry (z) and crustal thicknesses (t_c) at red and blue loci are shown.

the relationship between composition of the mantle source and composition of the generated melt. Thus, by simultaneously fitting crustal thickness and the chemistry of observed melt at the blue location, we constrain a local source composition. Finally, this local source is used to estimate melt fraction as a function of depth at the red location. Crustal thickness and basaltic composition are matched for T_p = 1,354 °C, if no melt is extracted from the bottom 3 to 5 km of the melting column (Fig. 3). This exclusion is justified given the geometry of the melting region (Fig. 4). We envisage a pulse of hot asthenosphere spreading radially away from the plume conduit beneath Iceland. Its cross-sectional geometry is parabolic and governed by Poiseuille flow[7]. Along the ridge axis, the upper half of this pulse traverses the melting region, generating chemically depleted melts. Colder asthenosphere rises in the wake of this pulse and suppresses the generation of enriched melts at the base of the melting region. Our simplified model demonstrates that temperature fluctuations produce a negative correlation between crustal thickness and geochemistry.

How do compositional variations within the source region affect our results? It is generally assumed that the source region beneath Iceland consists of enriched heterogeneities embedded within a depleted and refractory mantle[22,28,29]. Along the Reykjanes Ridge, this variation is less pronounced. $^{87}Sr/^{86}Sr$ does vary and lower values clearly correlate with increased crustal thickness. This negative correlation arises from progressive melting of a source within which heterogeneities occur on length scales that are short compared with the dimensions of the melting region. When T_p is higher, a greater proportion of melt is sourced from depleted portions of the source region, which results in more depleted isotopic compositions. Conversely, basalts generated from a source with a lower T_p are preferentially enriched by melting of heterogeneities[28,29].

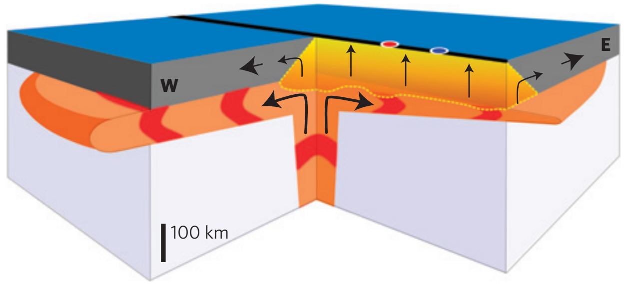

Figure 4 | Cutaway cartoon showing the geometry of the Iceland Plume. Orange body = Icelandic plume flowing beneath lithosphere; red patches = blobs of hotter than average plume material which expand radially outwards by Poiseuille flow at ~40 cm yr^{-1} (ref. 17); blue and grey block = lithosphere; black line = MOR ridge straddling the plume; red and blue loci as before; cut-away yellow prism = melting region below MOR beneath which hot annuli of plume material travel; black arrows indicate plate motion, plume flow, and corner flow within the melting region.

In summary, the particular location of the Icelandic Plume enables us to investigate its transient convective behaviour. Diverse observations, ranging from estimates of ancient overflow of NADW to the chemical variation of dredged basalts, suggest that plume changes have had unexpected and far-reaching consequences. Plume-controlled vertical motions moderate deep-water overflow through the Denmark Straits and influence sedimentary drift accumulation. Horizontal advection of hot blobs beneath the MOR owing to pulsing of the plume controls the melt geochemistry of MOR basalts. A melting model which matches crustal thicknesses and compositions shows that T_p varies

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by ∼25 °C. Thus, a suite of geochemical observations are consistent with the estimate of White *et al.*[14] for T_p fluctuations obtained from crustal thickness measurements alone. Transient convective behaviour is undoubtedly common, and a global examination of geochemical, palaeoceanographic and stratigraphic observations will yield rich dividends.

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References

1. White, R. S. & McKenzie, D. Magmatism at rift zones: The generation of volcanic continental margins and flood basalts. *J. Geophys. Res.* **94,** 7685–7729 (1989).
2. Wright, J. D. & Miller, K. G. Control of North Atlantic Deep Water Circulation by the Greenland–Scotland Ridge. *Paleoceanography* **11,** 157–170 (1996).
3. Poore, H. R., Samworth, R., White, N. J., Jones, S. M. & McCave, I. N. Neogene overflow of northern component water at the Greenland–Scotland ridge. *Geochem. Geophys. Geosyst.* **7,** 67–82 (2006).
4. Abelson, M., Agnon, A. & Almogi-Labin, A. Indications for control of the Iceland plume on the Eocene–Oligocene 'greenhouse–icehouse' climate transition. *Earth Planet. Sci. Lett.* **265,** 33–48 (2008).
5. Hunter, S. E. *et al.* The Eirik Drift: A long-term barometer of North Atlantic deepwater flux south of Cape Farewell, Greenland. *Geol. Soc. Spec. Publ.* **276,** 245–263 (2007).
6. Schubert, G., Turcotte, D. L. & Olson, P. *Mantle Convection in the Earth and Planets* 940 (Cambridge Univ. Press, 2001).
7. Rudge, J. F., Shaw Champion, M. E., White, N., McKenzie, D. & Lovell, B. A plume model of transient diachronous uplift at the Earth's surface. *Earth Planet. Sci. Lett.* **267,** 146–160 (2008).
8. Ito, G. Reykjanes V-shaped ridges originating from a pulsing and dehydrating mantle plume. *Nature* **411,** 681–684 (2001).
9. Searle, R. *et al.* The Reykjanes Ridge: Structure and tectonics of a hot-spot-influenced, slow spreading ridge, from multi-beam bathymetry, gravity and magnetic investigations. *Earth Planet. Sci. Lett.* **160,** 463–478 (1998).
10. Vogt, P. R. The Faroe–Iceland–Greenland aseismic ridge and the western boundary undercurrent. *Nature* **239,** 79–81 (1972).
11. Vogt, P. Asthenosphere motion recorded by the ocean floor south of Iceland. *Earth Planet. Sci. Lett.* **13,** 153–160 (1971).
12. Jones, S. M., White, N. & Maclennan, J. V-shaped ridges around Iceland: Implications for spatial and temporal patterns of mantle convection. *Geochem. Geophys. Geosyst.* **3,** 67–82 (2002).
13. Smallwood, J. R., White, R. S. & Minshull, T. A. Sea-floor spreading in the presence of the Iceland plume: The structure of the Reykjanes Ridge at 61° 40′ N. *J. Geol. Soc.* **152,** 1023–1029 (1995).
14. White, R. S., Bown, J. W. & Smallwood, J. R. The temperature of the Iceland plume and origin of outward-propagating V-shaped ridges. *J. Geol. Soc.* **152,** 1039–1045 (1995).
15. Hey, R., Martinez, F., Höskuldsson, Á. & Benediktsdóttir, Á. Propagating rift model for the V-shaped ridges south of Iceland. *Geochem. Geophys. Geosyst.* **11,** Q03011 (2010).
16. White, N. & Lovell, B. Measuring the pulse of a plume with the sedimentary record. *Nature* **387,** 888–891 (1997).
17. Poore, H. R., White, N. & Jones, S. A Neogene chronology of Iceland plume activity from V-shaped ridges. *Earth Planet. Sci. Lett.* **283,** 1–13 (2009).
18. Delorey, A. A., Dunn, R. A. & Gaherty, J. B. Surface wave tomography of the upper mantle beneath the Reykjanes Ridge with implications for ridge-hot spot interaction. *J. Geophys. Res.* **112,** B08313 (2007).
19. Wold, C. N. Cenozoic sediment accumulation on drifts in the northern North Atlantic. *Paleoceanography* **9,** 917–941 (1994).
20. Murton, B. J., Taylor, R. N. & Thirlwall, M. F. Plume-Ridge interaction: A geochemical perspective from the Reykjanes Ridge. *J. Petrol.* **43,** 1987–2012 (2002).
21. Schilling, J. Iceland mantle plume: Geochemical study of Reykjanes Ridge. *Nature* **242,** 565–571 (1973).
22. Shorttle, O., Maclennan, J. & Jones, S. M. Control of the symmetry of plume-ridge interaction by spreading ridge geometry. *Geochem. Geophys. Geosyst.* **13,** Q0AC05 (2010).
23. Jones, S. M., Murton, B. J., Fitton, J. G. & White, N. J. New joint geochemical-geophysical record of time-dependent mantle convection south of Iceland. Abstract U44A-07 presented at 2010 Fall Meeting, AGU, San Francisco, California, 13–17 Dec. (2010).
24. Kitagawa, H., Kobayashi, K., Makishima, A. & Nakamura, E. Multiple pulses of the mantle plume: Evidence from Tertiary Icelandic lavas. *J. Petrol.* **49,** 1365–1396 (2008).
25. Maclennan, J., McKenzie, D. & Grönvold, K. Plume-driven upwelling under central Iceland. *Earth Planet. Sci. Lett.* **194,** 67–82 (2001).
26. Allen, R. M. Imaging the mantle beneath Iceland using integrated seismological techniques. *J. Geophys. Res.* **107,** 67–82 (2002).
27. White, R. S., McKenzie, D. & O'Nions, R. K. Oceanic crustal thickness from seismic measurements and Rare Earth element inversions. *J. Geophys. Res.* **97,** 19,683–19,715 (1992).
28. Fitton, J. G., Saunders, A. D., Kempton, P. D. & Hardarson, B. S. Does depleted mantle form an intrinsic part of the Iceland plume? *Geochem. Geophys. Geosyst.* **4,** 67–82 (2003).
29. Maclennan, J. Lead isotope variability in olivine-hosted melt inclusions from Iceland. *Geochim. Cosmochim. Acta* **72,** 4159–4176 (2008).
30. Lourens, L., Hilgen, F., Shackleton, N. J., Laskar, J. & Wilson, D. *A Geologic Time Scale* 409–440 (Cambridge Univ. Press, 2004).

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Author contributions

This project was planned by N.W. Data compilation, analysis, and modelling was carried out by H.P. with guidance from N.W. and J.M. The paper was written by N.W. and J.M. and the figures were drafted by H.P. and J.M.

Additional information

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