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A continuous 55-million-year record of transient mantle plume activity beneath Iceland

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In the North Atlantic Ocean, a mid-ocean ridge bisects the Icelandic mantle plume, and provides a window into its temporal evolution[1–3]. V-shaped ridges of thick oceanic crust observed south of Iceland are thought to record pulses of upwelling within the plume[4–7]. Specifically, excess crust is thought to form during the quasi-periodic generation of hot solitary waves triggered by thermal instabilities in the mantle[8]. Here we use seismic reflection data to show that V-shaped ridges have formed over the past 55 million years—providing the longest record of plume periodicity of its kind. We find evidence for minor, but systematic, asymmetric formation of crust, due to migration of the mid-ocean ridge with respect to the underlying plume. We also find changes in periodicity: from 55 to 35 million years ago, the V-shaped ridges form every 3 million years or so and reflect small fluctuations in plume temperature of about 5–10 °C. From 35 million years ago, the periodicity changes to about 8 million years and reflects changes in mantle temperature of 25–30 °C. We suggest that this change in periodicity is probably caused by perturbations in the thermal state at the plume source, either at the mantle-transition zone or core–mantle boundary.

Spatial and temporal patterns of convective circulation beneath lithospheric plates cause regional elevation changes at the Earth's surface that have important—but poorly understood—implications for the development of dynamic topography on geologic timescales. As the Rayleigh number of convecting mantle is 10^6–10^8, this circulation is expected to be transient, varying on timescales of 1–100 Myr and on length scales of hundreds to thousands of kilometres[3,9]. A global network of mid-ocean ridges provides a useful means of estimating the temperature of underlying asthenospheric mantle[10,11]. At spreading mid-ocean ridges, accretion of oceanic crust is sensitive to small temperature fluctuations that change the thickness of newly formed crust by kilometres[2].

In the North Atlantic Ocean, the Reykjanes Ridge crosses the Icelandic plume, a hot convective upwelling with a radius of at least 1,200 km (ref. 12). Within the region influenced by this plume, average thickness of oceanic crust increases from 7 to 14 km and the seabed is anomalously shallow by up to 2 km. Both observations are consistent with an average temperature anomaly of 150 °C (ref. 2). Several different timescales of transient behaviour are sampled by the mid-ocean ridge's interaction with this plume. On the shortest timescale, the most obvious and best-known features are diachronous V-shaped ridges (VSRs) that are visible on either side of the ridge axis where sedimentary cover is minimal (Fig. 1). These VSRs probably reflect minor changes in the thickness and composition of oceanic crust and are generated when hotter than average parcels of plume material travel radially away from the plume's conduit[13,14]. On a much longer timescale, there is a transition from smooth crust without fracture zones, accreted over hotter asthenosphere, to rough crust with fracture zones, accreted over colder asthenosphere (Fig. 1). This observation suggests that the plume's planform has changed through time. Today, the plume's thermal (as opposed to chemical) influence extends to the intersection between the mid-ocean ridge and the Bight Fracture Zone at 57° N and 33° W (refs 2,5,15). Despite their importance in providing otherwise inaccessible insights into convective processes, the structure and extent of these VSRs are poorly known and their origin is still debated[16,17]. It is especially unclear how many VSRs exist and how far back in time their history can be traced.

To address these general issues, we acquired two regional (>1,200 km) seismic reflection profiles that traverse the oceanic basin south of Iceland (Fig. 1). Crucially, these profiles provide conjugate images of the Iceland and Irminger basins, because each one of them is oriented parallel to plate-spreading flowlines[18]. Acquisition and processing details are provided in the Methods. We have two significant findings. First, we have mapped the sediment–basement interface, which demonstrates that VSR activity can be continuously traced back to 55 Myr ago (Ma). Second, this activity has been used to build a detailed chronology of asthenospheric potential temperature, T_p. This continuous record provides a reference frame for analysing relationships between plume activity and other geologic observations.

Profile 2 resolves the detailed structure of the Iceland and Irminger basins (Fig. 2a). Away from a prominent mid-ocean ridge, the top of oceanic crust is clearly imaged beneath layered sediments, which thicken in either direction. A sediment–basement interface can easily be traced, despite being cut by minor faults (Fig. 2b). The sedimentary pile is dominated by contourite drift deposits that record the history of deep-water overflow across the Greenland–Scotland Ridge. For example, Eirik Drift records 7 Myr of overflow through the Denmark Strait and is visible at the northwestern end of the profile[14]. This overflow caused incision of older contourite deposits northwest of the mid-ocean ridge. The sediment–basement interface is deformed into a series of prominent ridges and troughs that are imaged out to ~500 km on either side of the mid-ocean ridge. These ridges and troughs are 20–40 km wide with amplitudes of up to 1 km and they correlate with small free-air gravity anomalies (Fig. 2c,d). Detailed interpretation shows that these ridges and

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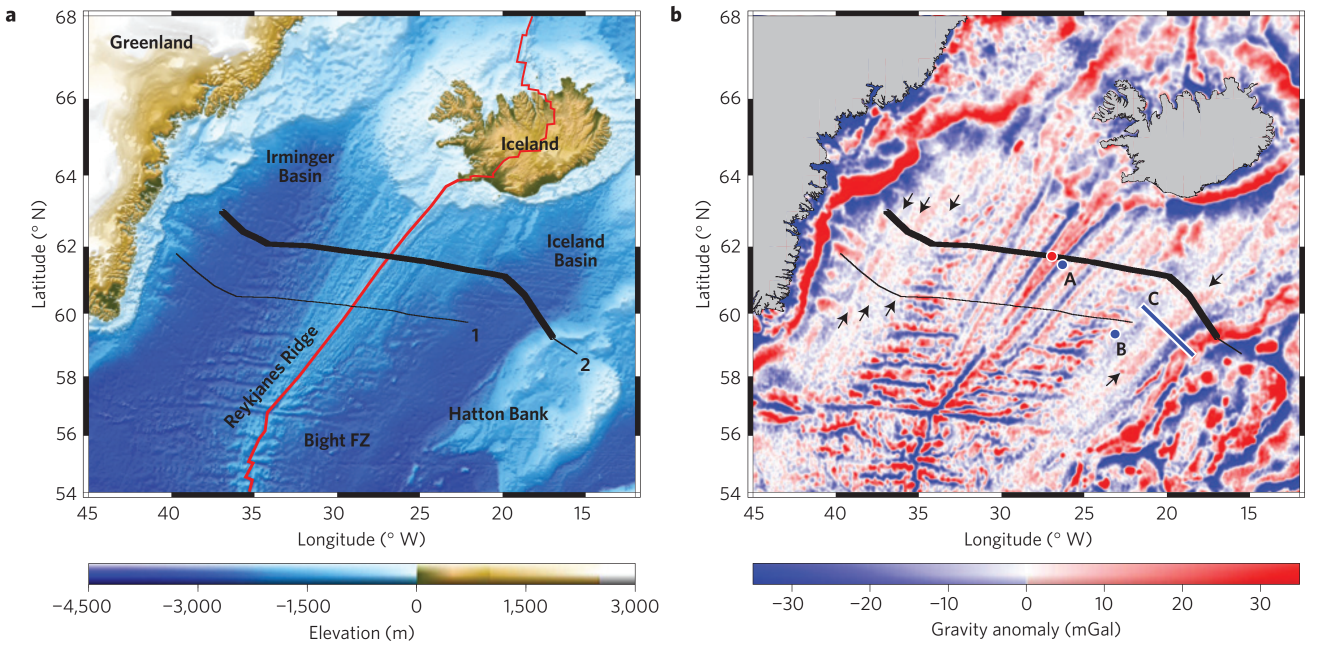

Figure 1 | Location of seismic experiment. a, Bathymetric map showing the location of the seismic reflection profiles. Emboldened portion of profile 2 is shown in Fig. 2. Red line, plate-spreading axis along Reykjanes Ridge. **b**, Map of short (<250 km)-wavelength free-air gravity anomalies[29]. Red/blue circles at A, ridge/trough crustal thicknesses[18]; blue circle at B, crustal thickness[21]; blue line at C, crustal thickness profile[20]; arrows, weak linear anomalies.

troughs are broken up, but not controlled, by normal faulting (Fig. 2e,f).

Average crustal thickness along the Reykjanes Ridge is primarily controlled by asthenospheric temperature within the plume head[13]. V-shaped ridges and troughs are maintained by minor changes in oceanic crustal thickness, which in turn are generated by temperature fluctuations within the plume[18]. Changes in the composition of basaltic rocks and in the geometry of active faults along the Reykjanes Ridge suggest that these temperature fluctuations are $\pm 25\,^{\circ}$C (refs 13,14,19). Here, we exploit residual depth anomalies as a proxy for tracking crustal thickness and asthenospheric temperature fluctuations (Fig. 3a). Residual depth is the water-loaded depth to oceanic crust that has been corrected for sediment loading, plate age and present-day dynamic support[6]. South of Iceland, residual depth varies by ±400 m and is controlled by changes in crustal thickness. If crust is generated at the mid-ocean ridge by isentropic decompression of anhydrous mantle[11,13], T_p can be estimated from residual depth measurements using

$$T_p \approx 16\left[t_c + \left(\frac{\rho_a - \rho_w}{\rho_a - \rho_c}\right) d_r\right] + 1{,}200$$

where $t_c = 8.4$ km is a reference crustal thickness[18], d_r is residual depth, $\rho_a = 3.2\,\mathrm{Mg\,m^{-3}}$ is density of asthenospheric mantle, $\rho_c = 2.8\,\mathrm{Mg\,m^{-3}}$ is density of oceanic crust, and $\rho_w = 1\,\mathrm{Mg\,m^{-3}}$ is the density of sea water. We have projected our T_p estimates into age–distance space and combined them with satellite gravity observations (Fig. 3b). There is excellent agreement between these estimates and free-air gravity anomalies on young, smooth oceanic crust (<20 Ma). On the oldest crust, VSRs are also visible and correlate with weak linear gravity anomalies whose significance was not previously recognized owing to variable thicknesses of sedimentary cover (Fig. 1). Some of the oldest VSRs are manifested by resolvable crustal thickness changes of ±1 km (ref. 20). At radial distances of >500 km from the plume centre, symmetric lobes of rough crust are intersected by profile 1 between 20 and 35 Ma (Fig. 3b). Within these highly fractured lobes, coherent VSRs are not clearly observed and legacy seismic refraction data suggest that the crust is only 6.1 km thick[5,21]. This observation suggests that the rough–smooth boundary represents the lateral extent of the plume.

VSRs are not exactly symmetric about the Reykjanes Ridge. For example, an old and prominent VSR occurs at a distance of 350 km from the ridge axis on the eastern side of profile 2 (Fig. 2b). On the western side of the same profile, this VSR occurs at 370 km, which corresponds to a cumulative offset of 20 km. Over the past 30 Myr, a systematic pattern of increasing offset is consistent with a history of asymmetric crustal accretion documented using magnetic anomaly profiles located closer to Iceland[16,17]. At distances of <250 km from the ridge axis, estimates of asymmetry made from magnetic anomalies and VSRs agree within error (Fig. 3c). Increasing asymmetry corresponds to a series of well-known eastward ridge jumps on Iceland that reflect the fact that the mid-ocean ridge gradually drifts westward with respect to the plume centre, periodically relocating itself at the centre of the plume[22]. VSR asymmetry between 300 and 500 km corresponds to a much older westward switching in seafloor spreading from the now-extinct Aegir Ridge to the active Kolbeinsey Ridge located north of Iceland[15,23].

Growth and decay of asymmetry enables us to synchronize VSR chronology on either side of the Reykjanes Ridge (Fig. 3a,d). The optimal result is obtained by adjusting a subset of poorly constrained magnetic anomaly picks (that is, magnetic chrons 8–17 corresponding to 20–40 Ma) along profile 2 by ±1 Myr, which is within the range of uncertainty[15]. The resultant match between eastern and western portions of this profile implies that VSRs were generated by radially expanding temperature fluctuations that were generated deep within the plume's conduit[7,14,16]. Growth and decay of asymmetric spreading correlate with plume activity, which suggests a causal relationship. In the North Atlantic Ocean, it is known that the mid-ocean ridge drifts northwestward with respect to the centre of the plume[15]. Our results indicate that the cumulative amount of drift increases when the plume is quiescent (compare Fig. 3c and d). Greater plume activity substantially increases the distal radial force that probably acts to inhibit plate spreading,

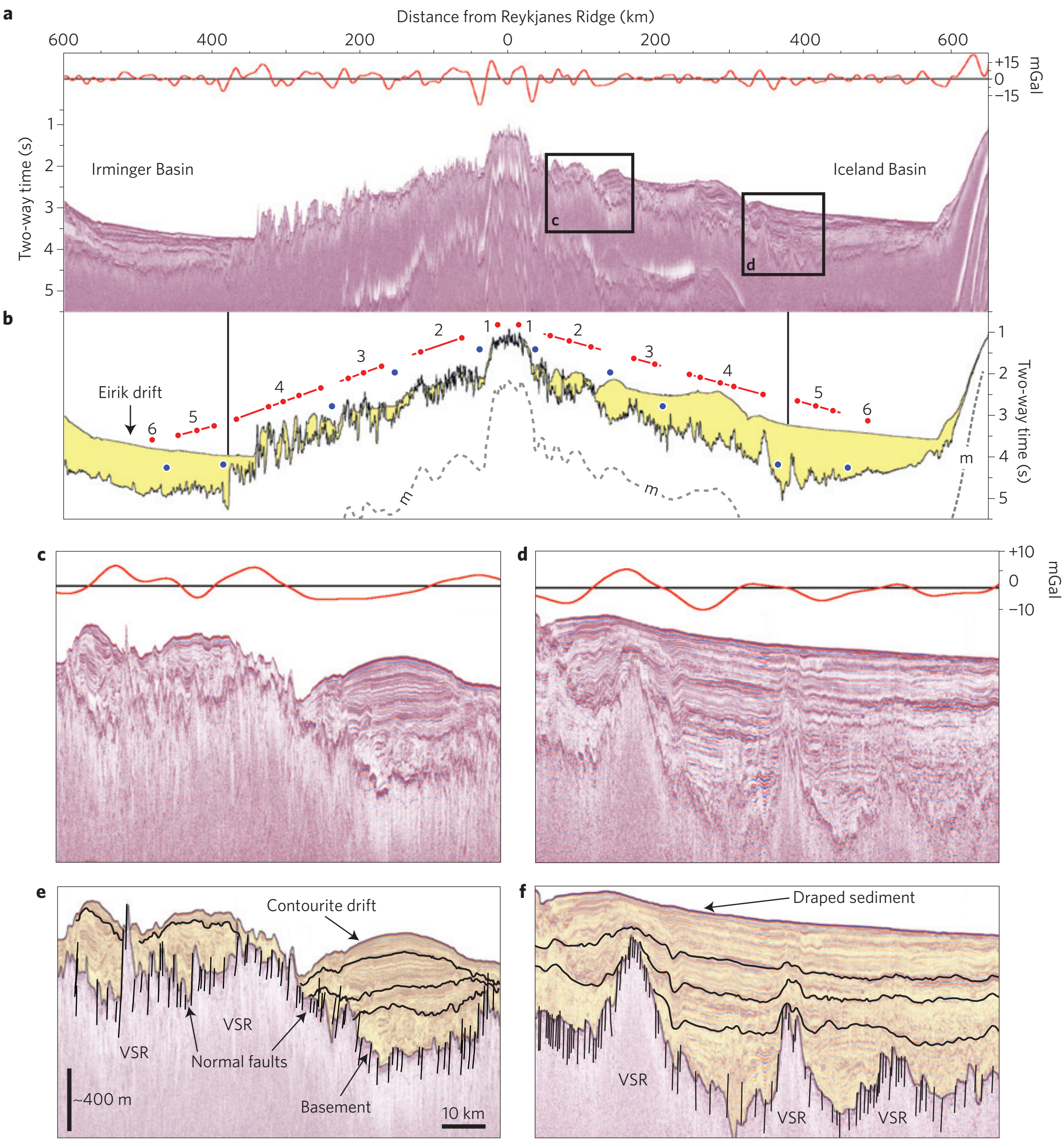

Figure 2 | Interpreted seismic images. a, Profile 2 (Fig. 1). Red line, free-air gravity anomaly[29]. **b**, Geologic interpretation. Solid lines, seabed and sediment–basement interface; yellow shading, sedimentary cover; dashed line, seabed multiple; red circles/lines, sets of VSRs; blue circles, intervening V-shaped troughs; vertical lines, locus of azimuthal changes along flowline. **c**, Young VSR (~12 Ma) and associated gravity anomalies. **d**, Structure of three older VSRs (35–40 Ma) and associated free-air gravity anomalies. **e**, Geologic interpretation of **c**. Solid line, normally faulted sediment–basement interface; yellow shading, plastered contourite drifts. **f**, Geologic interpretation of **d**. VSRs have steeper flanks facing towards mid-ocean ridge.

encouraging the mid-ocean ridge to switch back to the plume centre. If elevation at the plume centre goes up by 200 m, the distal radial force increases by a minimum of $2\times10^{8}\ \mathrm{N\,m^{-1}}$.

We have combined analysis of both profiles with the results of ref. 20 to calculate an average history of plume temperature fluctuations (Fig. 3d). Between 55 and 35 Ma, small (~5–10 °C) fluctuations of plume temperature have a periodicity of ~3 Myr. These fluctuations are superimposed on a rapidly cooling temperature structure that is also manifested by a northward shift in the transition from smooth to rough crust. Both observations are consistent with wholesale shrinkage of the plume[20]. After 35 Ma, the radius of the convective planform rapidly expanded from 400 to at least 1,200 km. This growth was accompanied by larger (~25–30 °C) fluctuations of plume temperature that have a periodicity of up to 8 Myr (Fig. 3d). This changing periodicity is probably caused by boundary layer perturbations within the convecting mantle[4,5,20,24]. Scaling analysis suggests that VSR activity is compatible with perturbations that form either at the 670 km mantle discontinuity or at the core–mantle boundary (Supplementary Information).

Using values from Supplementary Table 1, the geometry of the youngest VSR confirms that the present-day buoyancy flux of the plume is $B = 18 \pm 7\ \mathrm{Mg\,s^{-1}}$ if plume material flows radially away from the plume centre within an asthenospheric layer that is 125 ± 25 km thick with an excess temperature of $\Delta T = 150 \pm 50$ °C (refs 6,7). Independent values of B can be obtained by exploiting

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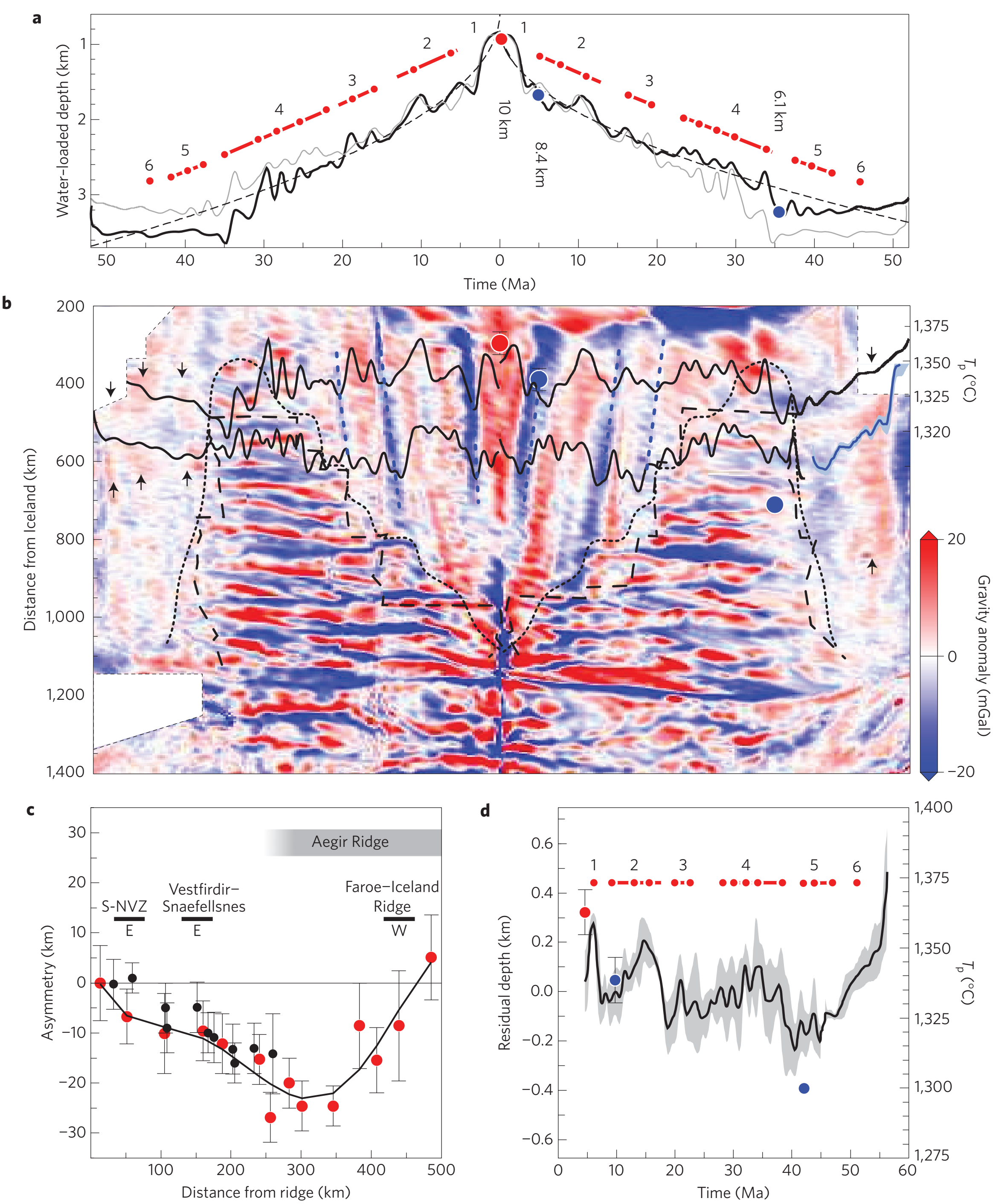

Figure 3 | Analysis of VSR chronology and asymmetric crustal accretion. **a**, Line, water-loaded basement depth[5]; grey line, mirror image; dashed lines, best-fitting relationships ($d = 580 + 430a^{1/2}$ and $d = 770 + 360a^{1/2}$ for western and eastern portions respectively; d, depth; a, age); red circles/lines, VSRs (Fig. 2); red/blue circles, crustal thicknesses[18,21]. **b**, Gravity anomaly as a function of age and distance from plume centre (63.95° N, 17.4° W; ref. 30). Lines and blue band, calculated T_p from this study and from wide-angle data[20]; red/blue circles, crust-derived T_p (ref. 18); dashed/dotted lines, smooth-rough transition from magnetic/gravity picks[6]; blue dashed lines, V-shaped troughs; arrows, weak linear anomalies. **c**, Asymmetry of crustal accretion. Black circles with error bars, asymmetry from magnetic picks $\pm 1\sigma$ (refs 5,16); red circles with error bars, VSR-derived asymmetry; line, best-fitting curve; bars, ridge-jump episodes[15]. E/W, jump direction; S-NVZ, Snaefellsnes–Húnafloí palaeo-rift towards Northern Volcanic Zone. **d**, Line with grey band, mean $\pm 1\sigma$ of T_p as a function of time at plume centre. Red circles/lines, sets of VSRs; red/blue circles, crust-derived T_p (refs 18,21).

two separate observations. First, the changing boundary between smooth and rough crust, d, is controlled by a combination of plate-spreading rate, u, and B where

$$B = \pi u d^2 \rho_m \alpha \Delta T$$

which yields $B = 26 \pm 9\ \mathrm{Mg\,s^{-1}}$ for the past 2 Myr. Second, the present-day planform of the plume swell constrains its excess volume[25]. If a plume radius of $1{,}200 \pm 100$ km grew over the past 25–35 Myr, $B = 17 \pm 5\ \mathrm{Mg\,s^{-1}}$. All three estimates of buoyancy flux are consistently large, indicating that the Iceland plume is probably

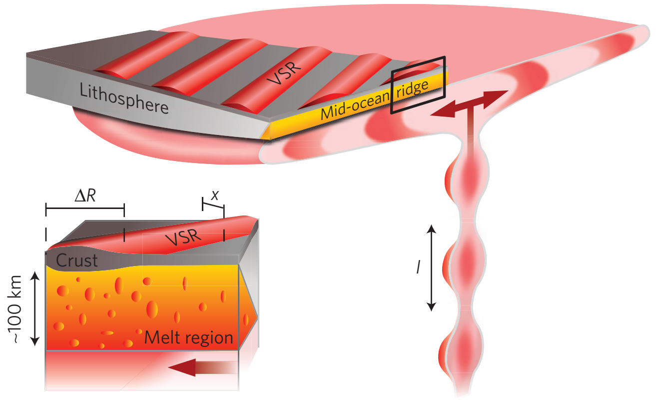

Figure 4 | Cut-away schematic diagram showing plume geometry. Red body, idealized plume spreading outward beneath lithosphere; darker patches, periodic blobs of hotter than average plume material flowing outward at ∼40 cm yr^{-1}; grey block, cooling/thickening lithosphere; red ribs, VSRs generated by plate spreading over plume; cut-away yellow prism, melting region beneath which hot annuli pass; red arrows indicate flow; l, length of solitary wave. Inset: relationship between thickened crust beneath VSR and underlying temperature structure. Grey block, crust, where x is width of VSR parallel to flowline and ΔR is along-axis width of VSR; cut-away yellow prism, melting region; red base, top of asthenosphere.

the biggest convective upwelling on Earth. In contrast, the Hawaiian plume has a buoyancy flux of only 8.7 Mg s^{-1} (ref. 26).

Our seismic reflection interpretations suggest that buoyancy flux has changed through time. For example, the oldest VSRs within the Irminger and Iceland basins have weak linear gravity anomalies that yield $B = 73 \pm 15$ Mg s^{-1} and 66 ± 14 Mg s^{-1}, respectively. Such high values are consistent with the oldest smooth lobes of crust that extend at least 1,400 km away from the centre of the plume, implying that $B \geq 70$ Mg s^{-1} (Fig. 3b).

Finally, our observations help to bound the dimensions of solitary waves that are generated at putative thermal boundary layers and travel up deformable conduits of plumes (Fig. 4)[8]. In the plate-spreading direction, the youngest VSRs are 25–30 km wide whereas older ones are 15–20 km wide. The youngest VSR is ∼730 km from the plume centre and has a width $x = 25 \pm 3$ km. Assuming a present-day plume flux of $\sim 18 \pm 4$ Mg s^{-1}, the width of the VSR in the direction of the mid-ocean ridge, ΔR, is expected to be 244 ± 44 km. This value is consistent with a 250-km-long segment of increased volcanism and reduced seismicity along the ridge crest near 60° N (ref. 19).

We have presented observations that document a continuous record of transient behaviour of the Icelandic plume between 55 Ma and the present day. Transient thermal anomalies occur every 3–8 Myr and are generated by boundary layer instabilities. Present-day buoyancy flux of the Iceland plume suggests that it is the largest convective upwelling on Earth. Fluctuating dynamic support during the Cenozoic era provides a general mechanism for proposed changes in deep-water oceanic circulation[14], for sedimentary drift accumulation[27], and for the carving of ancient ephemeral landscapes[28]. Establishing these connections between convective chronologies and surface observations has helped to yield new insights into the coupled nature of Earth's deep and surficial realms.

Methods

Seismic data acquisition and processing. Seismic profiles were acquired onboard the RRS *James Cook* during July–August 2010 by the universities of Cambridge, Southampton and Birmingham. This cruise, JC50, was financially supported by the Natural Environmental Research Council. Acoustic energy was generated using a single generator–injector airgun with a total volume of 5.82 l (generator pulse = 4.1 l, injector pulse = 1.72 l) and a frequency bandwidth of 10–400 Hz. The airgun was towed at a depth of 5.5 m behind the vessel, which steamed at ∼9.3 km h^{-1}. This airgun was primed with compressed air (20.7 MPa) and fired every 15 s (∼40 m). Reflected acoustic energy was recorded on a 1,600-m-long streamer towed at 7 m depth. This streamer consisted of 132 groups of hydrophones located every 12.5 m. Distance from the airgun to the first group (that is, near-trace offset) was 163 m. The digital sampling interval of recorded signals was 1 ms. During the survey, impulses of acoustic energy are transmitted and reflected at discontinuities within the Earth, where changes in acoustic impedance are generated by density and velocity contrasts. The geometry of this survey was designed to repeatedly record signals every 6.25 m along the profile. This redundancy improves signal to noise because reflections from different shotpoint–receiver pairs can be stacked together. Before stacking, acoustic velocity is carefully picked as a function of two-way travel time to correct for the travel-time delay (that is, normal move-out) of different raypaths within a single common midpoint gather. Here, velocity functions were hand-picked every 100 common midpoints (that is, every 625 m). The resultant 21-fold stacked image has a vertical and horizontal resolution of 10–20 m. Signal processing techniques also included application of a 12 Hz high-pass filter with a roll-off of 24 dB per octave, and a post-stack Stolt migration with a constant acoustic velocity of 1,500 m s^{-1}.

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Author contributions

This project was conceived and managed by N.W. and co-authors. R.P-T. processed and interpreted seismic data with guidance from N.W. and T.H. The paper was written by R.P-T. and N.W. with contributions from co-authors.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to R.P-T. or N.W.

Competing financial interests

The authors declare no competing financial interests.