

A Continuous 55 Million Year Record of Transient Mantle Plume Activity Beneath Iceland

Ross Parnell-Turner¹, Nicky White¹, Tim Henstock², Bramley Murton³, John MacLennan¹ & Stephen M. Jones⁴

¹*Department of Earth Sciences, University of Cambridge, Cambridge, CB3 0EZ, UK*

²*National Oceanography Centre Southampton, University of Southampton, Southampton SO17 1BJ, UK*

³*National Oceanography Centre, European Way, Southampton, SO14 3ZH, UK*

⁴*School of Geography, Earth and Environmental Sciences, University of Birmingham, B15 2TT, UK*

1 **In the North Atlantic Ocean, a mid-oceanic ridge bisects the Icelandic mantle plume, pro-**
2 **viding a window into the temporal evolution of this major convective upwelling¹⁻³. It is gen-**
3 **erally accepted that this plume's transient behavior is indirectly recorded within the fabric**
4 **of oceanic floor south of Iceland⁴⁻⁷. Despite its significance, the structure of this region is**
5 **poorly known. Here, we present long seismic reflection profiles that traverse the oceanic**
6 **basin between northwest Europe and Greenland. A diachronous pattern of V-shaped ridges**
7 **is imaged beneath a thickening blanket of sediment, revealing a complete record of tran-**
8 **sient periodicity that can be traced continuously back to ~55 Myrs— the longest record of**
9 **its kind. This periodicity increases from ~3 to ~8 Myr with clear evidence for minor, but**
10 **systematic, asymmetric crustal accretion. V-shaped ridges grow with time and reflect small**

11 (e.g. 5–30°C) fluctuations of mantle temperature, consistent with quasi-periodic generation
12 of hot solitary waves triggered by growth of thermal boundary layer instabilities within the
13 mantle⁸. Our continuous record of convective activity predicts a history of regional elevation
14 change which moderated overflow of the Neogene precursor of North Atlantic Deep Water
15 and which controlled the growth and decay of multiple Paleogene buried landscapes.

16 Spatial and temporal patterns of convective circulation beneath lithospheric plates cause re-
17 gional elevation changes at the Earth’s surface which have important— but poorly understood—
18 implications for the development of dynamic topography on geologic timescales. Since the Rayleigh
19 number of convecting mantle is 10^6 – 10^8 , this circulation is expected to be transient, varying on
20 timescales of 1–100 Myr and on length scales of 100s–1000s of kilometers^{3,9}. A global network
21 of mid-oceanic ridges provides a useful means of estimating the temperature of underlying as-
22 thenospheric mantle^{10,11}. At spreading mid-oceanic ridges, accretion of oceanic crust is sensitive
23 to small temperature fluctuations that change the thickness of newly formed crust by kilometers².

24 In the North Atlantic ocean, the Reykjanes Ridge crosses the Icelandic plume, a hot convec-
25 tive upwelling with a radius of at least 1200 km¹². Within the region influenced by this plume,
26 average thickness of oceanic crust increases from 7 to 14 km and the seabed is anomalously shal-
27 low by up to 2 km. Both observations are consistent with an average temperature anomaly of
28 150°C². Several different timescales of transient behavior are sampled by the mid-oceanic ridge’s
29 interaction with this plume. On the shortest timescale, the most obvious and best-known features
30 are diachronous V-shaped ridges (VSRs) that are visible on either side of the ridge axis where sed-

31 imentary cover is minimal (Figure 1). These VSRs probably reflect minor changes in the thickness
32 and composition of oceanic crust and are generated when hotter than average parcels of plume
33 material travel radially away from the plume's conduit^{13,14}. On a much longer timescale, there is a
34 transition from smooth crust without fracture zones, accreted over hotter asthenosphere, to rough
35 crust with fracture zones, accreted over colder asthenosphere (Figure 1). This observation suggests
36 that the plume's planform has changed through time. Today, the plume's thermal (as opposed to
37 chemical) influence extends to the intersection between the mid-oceanic ridge and the Bight Frac-
38 ture Zone at 57°N and 33°W^{2,5,15}. Despite their importance in providing otherwise inaccessible
39 insights into convective processes, the structure and extent of these VSRs are poorly known and
40 their origin is still debated^{16,17}. It is especially unclear how many VSRs exist and how far back in
41 time their history can be traced.

42 To address these general issues, we acquired two regional (>1200 km) seismic reflection pro-
43 files that traverse the oceanic basin south of Iceland (Figure 1). Crucially, these profiles provide
44 conjugate images of the Iceland and Irminger basins, since each one of them is oriented parallel
45 to plate spreading flowlines¹⁸. Acquisition and processing details are provided in the Methods
46 Summary. We have two significant findings. First, we have mapped the sediment-basement inter-
47 face, which demonstrates that VSR activity can be continuously traced back to 55 Myr. Secondly,
48 this activity has been used to build a detailed chronology of asthenospheric potential temperature,
49 T_p . This continuous record provides a reference frame for analyzing relationships between plume
50 activity and other geologic observations.

51 Profile 2 resolves the detailed structure of the Iceland and Irminger basins (Figure 1a). Away
52 from a prominent mid-oceanic ridge, the top of oceanic crust is clearly imaged beneath layered
53 sediments, which thicken in either direction. A sediment-basement interface can easily be traced,
54 despite being cut by minor faults (Figure 1b). The sedimentary pile is dominated by contourite
55 drift deposits that record the history of deep-water overflow across the Greenland-Scotland Ridge.
56 For example, Eirik Drift records 7 Myr of overflow through the Denmark Strait and is visible at
57 the northwestern end of the profile¹⁴. This overflow caused incision of older contourite deposits
58 northwest of the mid-oceanic ridge. The sediment-basement interface is deformed into a series of
59 prominent ridges and troughs that are imaged out to ~500 km on either side of the mid-oceanic
60 ridge. These ridges and troughs are 20–40 km wide with amplitudes of up to 1 km and they
61 correlate with small free-air gravity anomalies (Figure 1c,d). Detailed interpretation shows that
62 these ridges and troughs are broken up, but not controlled, by normal faulting (Figure 1e,f).

63 Average crustal thickness along the Reykjanes Ridge is primarily controlled by astheno-
64 spheric temperature within the plume head¹³. Smallwood et al.¹⁸ demonstrated that V-shaped
65 ridges and troughs are maintained by minor changes in oceanic crustal thickness, which in turn are
66 generated by temperature fluctuations within the plume. Changes in the composition of basaltic
67 rocks and in the geometry of active faults along the Reykjanes Ridge suggest that these temperature
68 fluctuations are $\pm 25^\circ\text{C}$ ^{13,14,19}. Here, we exploit residual depth anomalies as a proxy for tracking
69 crustal thickness and asthenospheric temperature fluctuations (Figure 1a). Residual depth is the
70 water-loaded depth to oceanic crust that has been corrected for sediment loading, plate age and
71 present-day dynamic support⁶. South of Iceland, residual depth varies by ± 400 m and is con-

72 trolled by changes in crustal thickness. If crust is generated at the mid-oceanic ridge by isentropic
73 decompression of anhydrous mantle^{11,13}, T_p can be estimated from residual depth measurements
74 using

$$T_p \approx 16 \left[t_c + \left(\frac{\rho_a - \rho_w}{\rho_a - \rho_c} \right) d_r \right] + 1200 \quad (1)$$

75 where $t_c = 8.4$ km is a reference crustal thickness¹⁸, d_r is residual depth, $\rho_a = 3.2$ Mg m⁻³ is den-
76 sity of asthenospheric mantle, $\rho_c = 2.8$ Mg m⁻³ is density of oceanic crust, and $\rho_w = 1$ Mg m⁻³ is
77 the density of seawater. We have projected our T_p estimates into age-distance space and combined
78 them with satellite gravity observations (Figure 1b). There is excellent agreement between these
79 estimates and free-air gravity anomalies on young, smooth oceanic crust (<20 Myr). On the oldest
80 crust, VSRs are also visible and correlate with weak linear gravity anomalies whose significance
81 was not previously recognized due to variable thicknesses of sedimentary cover (Figure 1). Parkin
82 and White²⁰ demonstrated that some of the oldest VSRs are manifest by resolvable crustal thick-
83 ness changes of ± 1 km. At radial distances of >500 km from the plume center, symmetric lobes
84 of rough crust are intersected by profile 1 between 20 and 35 Myr (Figure 3b). Within these highly
85 fractured lobes, coherent VSRs are not clearly observed and legacy seismic refraction data suggest
86 that the crust is only 6.1 km thick^{5,21}. This observation suggests that the rough-smooth boundary
87 represents the lateral extent of the plume.

88 VSRs are not exactly symmetric about the Reykjanes Ridge. For example, an old and promi-

89 nent VSR occurs at a distance of 350 km from the ridge axis on the eastern side of profile 2 (Figure
90 2b). On the western side of the same profile, this VSR occurs at 370 km, which corresponds to
91 a cumulative offset of 20 km. Over the last 30 Myrs, a systematic pattern of increasing offset
92 is consistent with a history of asymmetric crustal accretion documented using magnetic anomaly
93 profiles located closer to Iceland^{16,17}. At distances of <250 km from the ridge axis, estimates of
94 asymmetry made from magnetic anomalies and VSRs agree within error (Figure 3c). Increasing
95 asymmetry corresponds to a series of well-known eastward ridge jumps on Iceland which reflect
96 the fact that the mid-oceanic ridge gradually drifts westward with respect to the plume center, pe-
97 riodically relocating itself at the center of the plume²². VSR asymmetry between 300 and 500 km
98 corresponds to a much older westward switching in seafloor spreading from the now-extinct Aegir
99 Ridge to the active Kolbeinsey Ridge located north of Iceland^{15,23}.

100 Growth and decay of asymmetry enables us to synchronize VSR chronology on either side
101 of the Reykjanes Ridge (Figures 3a,d). The optimal result is obtained by adjusting a sub-set of
102 poorly constrained magnetic anomaly picks (i.e. magnetic chrons 8–17 corresponding to 20–40
103 Myrs) along profile 2 by ± 1 Myrs, which is within the range of uncertainty¹⁵. The resultant match
104 between eastern and western portions of this profile implies that VSRs were generated by radially
105 expanding temperature fluctuations that were generated deep within plume's conduit^{7,14,16}. Growth
106 and decay of asymmetric spreading correlate with plume activity which suggests a causal relation-
107 ship. In the North Atlantic Ocean, it is known that the mid-oceanic ridge drifts northwestward
108 with respect to the center of the plume¹⁵. Our results indicate that the cumulative amount of drift
109 increases when the plume is quiescent (compare Figures 3c and d). Greater plume activity sub-

110 stantially increases the distal radial force that probably acts to inhibit plate spreading, encouraging
111 the mid-oceanic ridge to switch back to the plume center. If elevation at the plume center goes up
112 by 200 m, the distal radial force increases by a minimum of $2 \times 10^8 \text{ N m}^{-1}$.

113 We have combined analysis of both profiles with the results of Parkin and White²⁰ to calculate
114 an average history of plume temperature fluctuations (Figure 3d). Between 55 and 35 Myrs, small
115 ($\sim 5\text{--}10^\circ\text{C}$) fluctuations of plume temperature have a periodicity of ~ 3 Myrs. These fluctuations
116 are superimposed upon a rapidly cooling temperature structure that is also manifest by a northward
117 shift in the transition from smooth to rough crust. Both observations are consistent with wholesale
118 shrinkage of the plume²⁰. After 35 Myrs, the radius of the convective planform rapidly expanded
119 from 400 to at least 1200 km. This growth was accompanied by larger ($\sim 25\text{--}30^\circ\text{C}$) fluctuations of
120 plume temperature that have a periodicity of up to 8 Myrs (Figure 3d). This changing periodicity
121 is probably caused by boundary layer perturbations within the convecting mantle^{4,5,20,24}. Scaling
122 analysis suggests that VSR activity is compatible with perturbations which form either at the 670
123 km mantle discontinuity or at the core-mantle boundary (Supplementary Information).

124 Using values from Supplementary Table 1, the geometry of the youngest VSR confirms
125 that the present-day buoyancy flux of the plume is $B = 18 \pm 7 \text{ Mg s}^{-1}$ if plume material flows
126 radially away from the plume center within an asthenospheric layer that is 125 ± 25 km thick
127 with an excess temperature of $\Delta T = 150 \pm 50^\circ\text{C}$ ^{6,7}. Independent values of B can be obtained
128 by exploiting two separate observations. First, the changing boundary between smooth and rough
129 crust, d , is controlled by a combination of plate spreading rate, u , and B where

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

130 which yields $B = 26 \pm 9 \text{ Mg s}^{-1}$ for the last 2 Myrs. Secondly, the present-day planform of
 131 the plume swell constrains its excess volume²⁵. If a plume radius of $1200 \pm 100 \text{ km}$ grew over
 132 the last 25–35 Myrs, $B = 17 \pm 5 \text{ Mg s}^{-1}$. All three estimates of buoyancy flux are consistently
 133 large, indicating that the Iceland plume is probably the biggest convective upwelling on Earth. In
 134 contrast, the Hawaiian plume has a buoyancy flux of only 8.7 Mg s^{-1} (ref. 26).

135 Our seismic reflection interpretations suggest that buoyancy flux has changed through time.
 136 For example, the oldest VSRs within the Irminger and Iceland basins have weak linear gravity
 137 anomalies that yield $B = 73 \pm 15 \text{ Mg s}^{-1}$ and $66 \pm 14 \text{ Mg s}^{-1}$, respectively. Such high values are
 138 consistent with the oldest smooth lobes of crust that extend at least 1400 km away from the center
 139 of the plume, implying that $B \geq 70 \text{ Mg s}^{-1}$ (Figure 3b).

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

147 In summary, we have presented observations that document a continuous record of transient
148 behaviour of the Icelandic plume between 55 Myrs and the present day. Transient thermal anoma-
149 lies occur every 3–8 Myr and are generated by boundary layer instabilities. Present-day buoyancy
150 flux of the Iceland plume suggests that it is the largest convective upwelling on Earth. Fluctuating
151 dynamic support during the Cenozoic Era provides a general mechanism for proposed changes
152 in deep-water oceanic circulation¹⁴, for sedimentary drift accumulation²⁷, and for the carving of
153 ancient ephemeral landscapes²⁸. Establishing these connections between convective chronologies
154 and surface observations has helped to yield novel insights into the coupled nature of Earth's deep
155 and surficial realms.

156 **Methods**

157 **Seismic data acquisition and processing.** Seismic profiles were acquired onboard the RRS *James*
158 *Cook* during July–August 2010 by the Universities of Cambridge, Southampton and Birmingham.
159 This cruise, JC50, was financially supported by the Natural Environmental Research Council.
160 Acoustic energy was generated using a single generator-injector airgun with a total volume of
161 5.82 litres (generator pulse = 4.1 litres, injector pulse = 1.72 litres) and a frequency bandwidth of
162 10–400 Hz. The airgun was towed at a depth of 5.5 m behind the vessel, which steamed at ~ 9.3 km
163 hr^{-1} . This airgun was primed with compressed air (20.7 MPa) and fired every 15 s (~ 40 m). Re-
164 flected acoustic energy was recorded on a 1600 m-long streamer towed at 7 m depth. This streamer
165 consisted of 132 groups of hydrophones located every 12.5 m. Distance from the airgun to the first
166 group (i.e. near-trace offset) was 163 m. The digital sampling interval of recorded signals was 1

167 ms. During the survey, impulses of acoustic energy are transmitted and reflected at discontinuities
168 within the Earth, where changes in acoustic impedance are generated by density and velocity con-
169 trasts. The geometry of this survey was designed to repeatedly record signals every 6.25 m along
170 the profile. This redundancy improves signal to noise since reflections from different shotpoint-
171 receiver pairs can be stacked together. Before stacking, acoustic velocity is carefully picked as a
172 function of two-way travel time to correct for the travel-time delay (that is, normal move-out) of
173 different raypaths within a single common mid-point (CMP) gather. Here, velocity functions were
174 hand-picked every 100 CMPs (i.e. every 625 m). The resultant 21-fold stacked image has a vertical
175 and horizontal resolution of 10–20 m. Signal processing techniques also included application of a
176 12 Hz high-pass filter with a roll-off of 24 dB per octave, and a post-stack Stolt migration with a
177 constant acoustic velocity of 1500 m s^{-1} .

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature

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Author Information Reprints and permissions information is available at www.nature.com/reprints. The authors declare that they have no competing financial interests. Correspondence and requests for material should be addressed to N.W. and R.P-T. (email: njw10@cam.ac.uk, rep52@cam.ac.uk).

1 Figure Captions

Figure 1 Location of seismic experiment. **a**, Bathymetric map showing location of seismic reflection profiles. Emboldened portion of profile 2 is shown in Figure 1. Red line = plate-spreading axis along Reykjanes Ridge. **b**, Map of short (<250 km) wavelength free-air gravity anomalies²⁹. Red/blue circles at A = ridge/trough crustal thicknesses¹⁸; blue circle at B = crustal thickness²¹; blue line at C = crustal thickness profile²⁰; arrows = weak linear anomalies.

Figure 2 Interpreted seismic images. **a**, Profile 2 (Figure 1). Red line = free-air gravity anomaly²⁹. **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 Myr) and associated gravity anomalies. **d**, Structure of three older VSRs (35–40 Myr) and associated free-air gravity anomalies. **e**, Geologic interpretation. Solid line = normally faulted sediment-basement interface; yellow shading = plastered contourite drifts. **f**, Geologic interpretation. VSRs have steeper flanks facing toward mid-oceanic ridge.

Figure 3 Analysis of VSR chronology and asymmetric crustal accretion. **a**, Line = water-loaded basement depth⁵; gray line = mirror image; dashed lines = best-fitting relationships ($d = 580 + 430a^{1/2}$ and $d = 770 + 360a^{1/2}$ for western/eastern portions; d = depth; a = age); red circles/lines = VSRs (Figure 2); red/blue circles = crustal thicknesses^{18,21}. **b**, Gravity anomaly as function of age and distance from plume center (63.95°N, 17.4°W)³⁰.

Lines and blue band = calculated T_p from this study and from wide-angle data²⁰; red/blue circles = crust-derived T_p ¹⁸; dashed/dotted lines = smooth-rough transition from magnetic/gravity picks⁶; blue dots = V-shaped troughs; arrows = weak linear anomalies. **c**, Asymmetry of crustal accretion. Circles = asymmetry from magnetic picks^{5,16}; red circles = VSR-derived asymmetry; line = best-fitting curve; bars = ridge-jump episodes¹⁵. E/W = jump direction; S-NVZ = Snaefellsnes-Húnaflói paleo-rift toward Northern Volcanic Zone. **d**, Line with gray band = mean $\pm 1\sigma$ of T_p as function of time at plume center. Red circles/lines = sets of VSRs; red/blue circles = crust-derived T_p ^{18,21}.

Figure 4 Cut-away cartoon 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; gray 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. Gray 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.







