Earth and Planetary Science Letters 468 (2017) 51–61

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

Radial viscous fingering of hot asthenosphere within the Icelandic plume beneath the North Atlantic Ocean

C.M. Schoonman [a], N.J. White [a,*], D. Pritchard [b]

[a] Bullard Laboratories, Department of Earth Sciences, University of Cambridge, Madingley Rise, Madingley Road, Cambridge, CB3 0EZ, UK
[b] Department of Mathematics and Statistics, University of Strathclyde, Livingstone Tower, 26 Richmond Street, Glasgow, G1 1XH, Scotland, UK

ARTICLE INFO

Article history:
Received 21 November 2016
Received in revised form 28 March 2017
Accepted 29 March 2017
Available online xxxx
Editor: P. Shearer

Keywords:
viscous fingering
Iceland
mantle plumes
dynamic topography

ABSTRACT

The Icelandic mantle plume has had a significant influence on the geologic and oceanographic evolution of the North Atlantic Ocean during Cenozoic times. Full-waveform tomographic imaging of this region shows that the planform of this plume has a complex irregular shape with significant shear wave velocity anomalies lying beneath the lithospheric plates at a depth of 100–200 km. The distribution of these anomalies suggests that about five horizontal fingers extend radially beneath the fringing continental margins. The best-imaged fingers lie beneath the British Isles and beneath western Norway where significant departures from crustal isostatic equilibrium have been measured. Here, we propose that these radial fingers are generated by a phenomenon known as the Saffman–Taylor instability. Experimental and theoretical analyses show that fingering occurs when a less viscous fluid is injected into a more viscous fluid. In radial, miscible fingering, the wavelength and number of fingers are controlled by the mobility ratio (i.e. the ratio of viscosities), by the Péclet number (i.e. the ratio of advective and diffusive transport rates), and by the thickness of the horizontal layer into which fluid is injected. We combine shear wave velocity estimates with residual depth measurements around the Atlantic margins to estimate the planform distribution of temperature and viscosity within a horizontal asthenospheric layer beneath the lithospheric plate. Our estimates suggest that the mobility ratio is at least 20–50, that the Péclet number is $O(10^4)$, and that the asthenospheric channel is 100 ± 20 km thick. The existence and planform of fingering is consistent with experimental observations and with theoretical arguments. A useful rule of thumb is that the wavelength of fingering is 5 ± 1 times the thickness of the horizontal layer. Our proposal has been further tested by examining plumes of different vigor and planform (e.g. Hawaii, Cape Verde, Yellowstone). Our results support the notion that dynamic topography of the Earth's surface can be influenced by fast, irregular horizontal flow within thin, but rapidly evolving, asthenospheric fingers.

1. Introduction

It is generally agreed that a substantial convective upwelling or plume centered beneath Iceland has had a significant effect on the stratigraphic evolution of the North Atlantic Ocean (White and McKenzie, 1989; Jones et al., 2012). This plume developed during Early Cenozoic times and its inception is usually linked with the appearance of basaltic magmatism at 64 Ma. It is bisected by a mid-oceanic ridge which provides a helpful window into the detailed temporal evolution of this globally significant feature (Parnell-Turner et al., 2014). Fluctuations in plume activity over the last 50 Ma are recorded in the pattern of diachronous V-shaped ridges that are imaged in the oceanic basins on either side of the Reykjanes Ridge. During the Neogene period, regional bathymetric changes associated with these fluctuations appear to have moderated overflow of Northern Component Water, the ancient precursor of North Atlantic Deep Water (Poore et al., 2011).

The present-day planform of the Icelandic plume is determined from a combination of three different sets of observations (Fig. 1). The simplest and most striking manifestation is the pattern of long wavelength (700–2500 km) free-air gravity anomalies. A positive anomaly of 30–50 mGal is centered on Iceland. Together, other anomalies form an irregular planform that reaches from Baffin Island to western Scandinavia, and from the Charlie-Gibbs fracture zone to Svalbard. The inference that this pattern of long wavelength anomalies is a manifestation of mantle convective upwelling is strengthened by the existence of significant residual depth anomalies throughout adjacent oceanic basins. Hoggard et al. (2017) built a database of seismic reflection and wide-angle profiles that they used to accurately calculate water-loaded depths

---

* Corresponding author.
E-mail address: njw10@cam.ac.uk (N.J. White).

http://dx.doi.org/10.1016/j.epsl.2017.03.036
0012-821X/

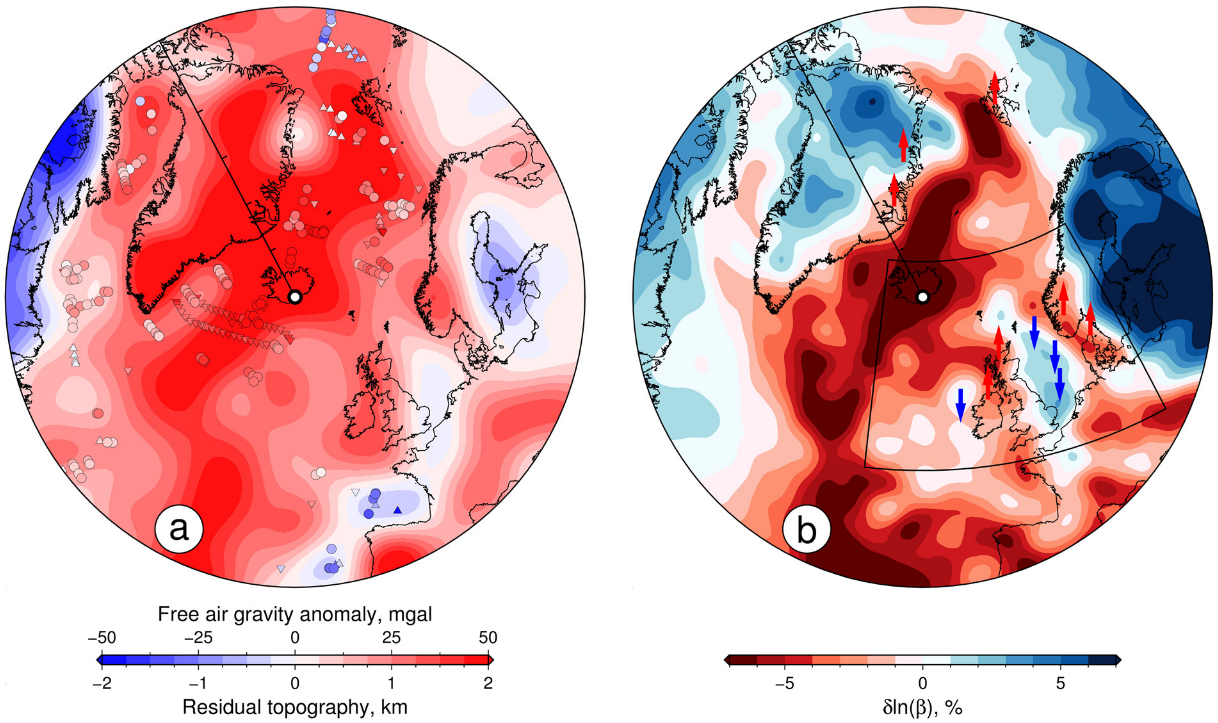

Fig. 1. Residual topography and velocity structure. (a) Map of residual topography of North Atlantic Ocean calculated from long wavelength (700–2500 km) free-air gravity anomalies using water-loaded admittance of $Z = 25$ mGal km^{-1}. Circles = residual depth anomaly measurements on oceanic crust with both sedimentary and crustal corrections (Hoggard et al., 2017); upward-/downward-pointing triangles = upper/lower limits for residual depth anomaly measurements with sedimentary corrections only; white circle = center of Icelandic plume (Shorttle et al., 2010); ticks on scale bar plotted every 500 km. Azimuthal polar projection centered on Iceland where radius = 2800 km. (b) Map of shear wave velocity anomaly, V_s, with respect to Preliminary Reference Earth Model (PREM) at depth of 150 km (Rickers et al., 2013). Red/blue arrows = loci of anomalous Neogene uplift/subsidence events (Kooi et al., 1991; Anell et al., 2009; Davis et al., 2012); box = location of Fig. 2. For interpretation of colors in this figure, reader is referred to web version of this article.

to oceanic basement as a function of plate age. In this way, residual depth anomalies are determined that build upon previous analyses (White, 1997; Marquart and Schmeling, 2004). These combined results show that oceanic crust surrounding Iceland is considerably shallower than expected (Fig. 1a). For example, residual depth anomalies of up to 2 km are recorded adjacent to Iceland. This regional shallowing dies out gradually with increasing distance from Iceland. The match between residual depth measurements and long wavelength gravity anomalies is reasonable, although a notable exception is observed north of Greenland. The relationship between the gravity field and residual depth measurements suggests that the water-loaded admittance is $Z \sim +25$ mGal km^{-1}, in agreement with global studies (Crosby and McKenzie, 2009).

Finally, the presence of a mantle convective anomaly is corroborated by earthquake tomographic models which suggest that an extensive and irregular patch of low shear wave velocity lies beneath the lithospheric plates (Bijwaard and Spakman, 1999; Ritsema et al., 2011). The most striking of these studies is that of Rickers et al. (2013) who use full-waveform tomography to build a high resolution shear wave velocity model of the North Atlantic region from the surface to a depth of 1300 km (Fig. 1b). A significant negative velocity anomaly of >10% with respect to their reference model is centered beneath Iceland, in agreement with earlier studies. One notable feature of their model is the existence of narrow, slow velocity fingers that protrude beneath the fringing continental margins. Two prominent fingers reach beneath the British Isles and western Norway. In both cases, the associated negative shear wave velocity anomalies are >2% and sit within a 100 ± 20 km thick horizontal layer immediately beneath the lithospheric plate (Fig. 2). Rickers et al. (2013) show that there is a reasonable match between the loci of these fingers and long wavelength gravity anomalies. Significantly, both fingers also coincide with crustal isostatic anomalies and with the general pattern of Neogene vertical movements observed across the northwest shelf of Europe (Anell et al., 2009; Davis et al., 2012). In the southern North Sea, the fast (i.e. cooler) region between these fingers has a water-loaded subsidence anomaly of ∼500 m that grew in Neogene times and represents a significant departure from the expected thermal subsidence trajectory (Fig. 2b–d; Kooi et al., 1991). This region probably subsided as a result of small-scale convective downwelling between the two warm fingers.

Here, we combine these different geologic and geophysical observations to investigate the causes and consequences of radial fingering within the asthenospheric mantle. In a series of contributions pioneered by Weeraratne et al. (2003), it has been suggested that some combination of rectilinear viscous fingering instabilities, small-scale convection, and shear-driven upwelling may play a role in explaining the observed pattern of seismic velocity anomalies beneath the southern portion of the East Pacific Rise (Weeraratne et al., 2007; Harmon et al., 2011; Ballmer et al., 2013). Although there are significant geometric and mechanical differences, our analysis evidently builds upon these previous contributions and upon the analysis of Morgan et al. (2013).

Our approach is divided into three steps. First, we present the physical characteristics of the Icelandic plume, such as its size, shape and vigor. By combining the correlation between shear wave velocity anomalies and the pattern of regional Neogene epeirogeny with a global empirical relationship between shear wave velocity and temperature, we estimate how viscosity within the plume head spatially varies. Secondly, we compare these observations of plume behavior beneath Iceland and elsewhere with published laboratory experiments that investigate the development of radial miscible viscous fingering. Thirdly, the development of radial fingering is discussed using a suite of theoretical and heuristic arguments. We conclude by exploring the implication of our hypothesis for a small selection of well-known plumes.