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Crustal manifestations of a hot transient pulse at 60°N beneath the Mid-Atlantic Ridge

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ABSTRACT

Since its inception at 62 Ma, mantle convective upwelling beneath Iceland has had a significant influence on Cenozoic vertical motions, magmatism and paleoceanography in the North Atlantic Ocean. Crucially, intersection of the Reykjanes Ridge with the Icelandic Plume provides us with a useful window into the transient activity of this plume. Here, the spreading ridge acts as a linear sampler of plume activity, which is recorded as a series of time-transgressive V-shaped ridges and troughs. We present the results of a detailed study of the spreading ridge close to 60°N, where the youngest V-shaped ridge of thickened oceanic crust is forming today. A combination of multibeam bathymetry and seismic reflection profiles, acquired along and across the ridge axis, is used to map the detailed pattern of volcanism and normal faulting. Along the ridge axis, the density of volcanic seamounts varies markedly, increasing by a factor of two between 59°N and 62°N. Within this zone, seismic imaging shows that there is enhanced acoustic scattering at the seabed. These observations are accompanied by a decrease in mean fault length from ~12 km to ~6 km. A 1960–2009 catalog of relocated teleseismic earthquake hypocenters indicates that there is a pronounced gap in seismicity between 59°N and 62°N where the cumulative moment release is two orders of magnitude smaller than that along adjacent ridge segments. A steady-state thermal model is used to show that a combination of increased melt generation and decreased hydrothermal circulation accounts for this suite of observations. The predicted decrease in the thickness of the brittle seismogenic layer is consistent with geochemical modeling of dredged basaltic samples, which require hotter asthenospheric material beneath the spreading axis. Thus, along-axis variation in melt supply caused by passage of a pulse of hot material modulates crustal accretion processes and rheological properties.

1. Introduction

It is widely accepted that convective circulation of the Earth's mantle modifies surface elevation (e.g. Schubert et al., 2001). Elevation change produced in this way is referred to as dynamic topography in order to distinguish it from isostatic topography which is maintained by changes in the density structure of the lithosphere (Hager et al., 1985; Hager and Richards, 1989; Cazenave et al., 1989). Spatial and temporal variations in dynamic topography play an important role in sculpting terrestrial landscapes and in moderating deep-water overflow at oceanic gateways (Wright and Miller, 1996; Jones et al., 2001; Poore et al., 2006). The North Atlantic Ocean is an important natural laboratory where the behavior of time-dependent convective circulation can be investigated in diverse ways. Here, hot plume material is thought to rise within a conduit located beneath Iceland and spread outward beneath the lithospheric plate (White, 1997; Delorey et al., 2007). Marine geophysical observations combined with a fluid dynamical understanding of convective upwelling suggest that periodic oscillations within the plume's conduit trigger transient temperature fluctuations which spread out horizontally over large distances (Schubert and Olson, 1989; White et al., 1995; Ito, 2001; Jones et al., 2002b). These fluctuations are manifest in different ways: variations in the thickness and composition of oceanic crust; changes in the overflow of North Atlantic Deep Water across the Greenland–Scotland Ridge; and periodic development of ancient ephemeral landscapes (Jones et al., 2002b; Poore et al., 2011; Hartley et al., 2011).

South of Iceland, the Reykjanes Ridge is an oblique and slow spreading axis, which is uninterrupted by fracture zones (Fig. 1). This ridge is flanked by a series of diachronous V-shaped ridges, which was first described by Vogt (1971). At 60.3°N, the youngest

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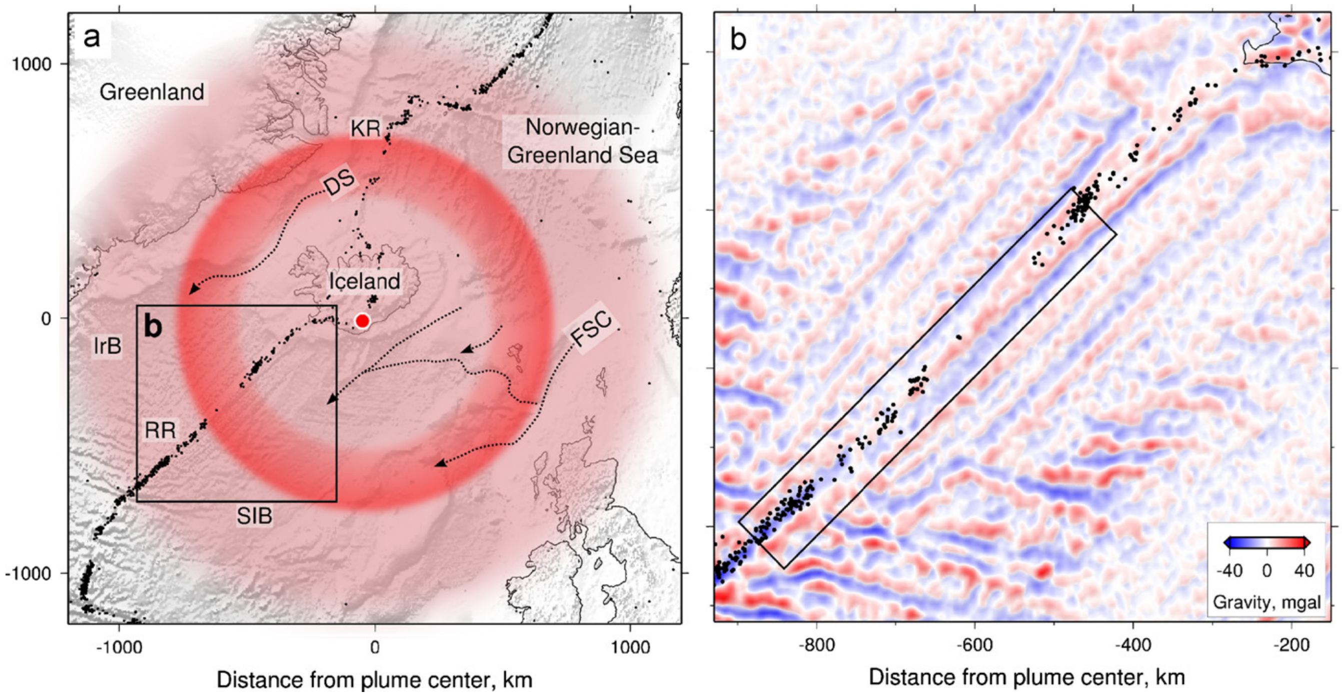

Fig. 1. (a) Bathymetric map of North Atlantic Ocean showing idealized extent of Icelandic Plume (projection centered on 63.95°N, 17.4°W). Transparent red disk, present-day extent of plume; red ring, radial locus of transient thermal anomaly inferred at intersection of youngest V-shaped ridge with RR; small red circle, plume center (Shorttle et al., 2010); black circles, relocated earthquakes for 1960–2009 (magnitude >4; Engdahl et al., 1998). IrB, Irminger Basin; RR, Reykjanes Ridge; SIB, South Iceland Basin; KR, Kolbeinsey Ridge; labeled dashed lines, deep-water pathways (FSC, Faroe–Shetland Channel overflow; DS, Denmark Straits overflow); black box, location of Fig. 1b. (b) Short wavelength free-air gravity map of North Atlantic Ocean calculated from satellite-derived data by removing wavelengths greater than 100 km (Sandwell and Smith, 2009). Box, location of Figs. 2a and 3. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

V-shaped ridge meets the ridge axis where the crustal thickness measured in a wide-angle seismic experiment is 10.0 ± 0.5 km (Smallwood and White, 1998). At 58.5°N, the adjacent trough has a projected crustal thickness of 7.8 ± 0.5 km. Along the ridge axis itself, systematic variations in major, trace and rare earth elemental compositions from dredged basaltic rocks correspond to the intersections of V-shaped ridges and troughs (Murton et al., 2002; Jones et al., 2010; Poore et al., 2011). These crustal thickness and geochemical variations are best explained by 25–30 °C fluctuations in the asthenospheric potential temperature (White et al., 1995; Poore et al., 2011). A suite of different geophysical, geochemical and paleoceanographic observations support the existence of transient thermal anomalies which are generated within the plume conduit and flow outward within a horizontal channel (e.g. Vogt, 1971; White, 1997; Ito, 2001; Jones et al., 2002b). Closer to Iceland, high resolution magnetic and bathymetric profiles imply that asymmetric spreading occurs over the last 15 Ma (Hey et al., 2010; Benediktsdóttir et al., 2012). This asymmetry could be accounted for by progressive eastward stepping of the propagating Reykjanes Ridge. In the last 6 Ma, there is little evidence for asymmetry within the uncertainty of the magnetic anomaly picks (Benediktsdóttir et al., 2012). Crustal thickness and geochemical variations along the spreading axis itself cannot be easily accounted for by the effects of ridge propagation.

A V-shaped ridge is currently forming at the spreading axis and its tip occurs at 60°N, ~ 760 km southwest of Iceland (Fig. 1). The detailed structure of this nascent V-shaped ridge implies that a hot, transient anomaly is propagating away from Iceland at the present day (Searle et al., 1998). A combination of multibeam bathymetric and seismic reflection profiles acquired on this segment of the Reykjanes Ridge enables us to investigate how this anomaly has influenced the structure and evolution of the brittle crust. By combining this analysis with the distribution of teleseismically recorded earthquakes and with the geochemistry of dredged basaltic rocks, we develop a better understanding of how horizontally advecting thermal anomalies modify oceanic crust. A steady-state thermal model of the spreading axis is used to explore the relationship between brittle deformation, hydrothermal circulation, rheological structure, and crustal accretion processes at this slow-spreading ridge (e.g. Chen, 2003; Buck et al., 2005; Behn and Ito, 2008; Ito and Behn, 2008).

2. Multibeam bathymetry

Bathymetric surveys were acquired during Cruise JC50 on the RRS *James Cook* during July–August 2010. At the Reykjanes Ridge, bathymetric profiles were collected along four flowlines which straddle the ridge centered at 60°N and 61.5°N (Fig. 2). Additional profiles were collected along the ridge crest itself. These data were acquired using a hull-mounted Kongsberg EM120 multibeam echo sounder operating at a frequency of 12 kHz with a swath width which is ~ 6 times the average water depth.

Processing was carried out using the Caris HIPS software and a gridded dataset that covers $>28{,}000$ km^2 was generated. Here, we exploit a subset that consists of 1293 km^2 acquired at the ridge crest. The horizontal resolution is ~ 30 m. This survey overlaps with regionally extensive surveys acquired on Cruise EW9008 (RV *Maurice Ewing*; Searle et al., 1994) and on Cruises CD81 and CD87 (RRS *Charles Darwin*; Keeton et al., 1997). The average horizontal resolution of these earlier surveys is ~ 100 m.

2.1. Volcanism

Morphology of the Reykjanes Ridge is dominated by an axial high which is characterized by a series of *en echelon* axial volcanic