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Propagating buoyant mantle upwelling on the Reykjanes Ridge

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A B S T R A C T

Crustal features of the Reykjanes Ridge have been attributed to mantle plume flow radiating outward from the Iceland hotspot. This model requires very rapid mantle upwelling and a "rheological boundary" at the solidus to deflect plume material laterally and prevent extreme melting above the plume stem. Here we propose an alternative explanation in which shallow buoyant mantle upwelling instabilities propagate along axis to form the crustal features of the ridge and flanks. As only the locus of buoyant upwelling propagates this mechanism removes the need for rapid mantle plume flow. Based on new geophysical mapping we show that a persistent sub-axial low viscosity channel supporting buoyant mantle upwelling can explain the current oblique geometry of the ridge as a reestablishment of its original configuration following an abrupt change in opening direction. This mechanism further explains the replacement of ridge-orthogonal crustal segmentation with V-shaped crustal ridges and troughs. Our findings indicate that crustal features of the Reykjanes Ridge and flanks are formed by shallow buoyant mantle instabilities, fundamentally like at other slow spreading ridges, and need not reflect deep mantle plume flow.

1. Introduction

The Iceland hotspot has long been viewed as formed by a mantle plume (Morgan, 1971) and as the Reykjanes Ridge intersects this feature its axial and flanking tectonic and crustal characteristics have been assumed to reflect mantle plume flow and temperature (Vogt, 1971). As proposed in conceptual models by Vogt (1971), thermal pulses rapidly rise within a plume stem beneath Iceland and then either spread radially or are channeled along-axis to form V-shaped crustal ridges as they flow beneath the Reykjanes Ridge. The geometry of the V-shaped ridges implies that mantle plume flow is at least ten times the spreading rate (Vogt, 1971). Of Vogt's two alternative flow models, current geodynamic models favor radial pancake-like expansion of the plume head that implies even faster upwelling in the plume stem as a result of radial spreading. Ito (2001) recognized that rapidly upwelling thermal pulses in the mantle plume stem would generate extreme crustal thickness variations (>200 km) if allowed to melt by decompression. To avoid these unobserved crustal thicknesses he proposed that a high viscosity "rheological boundary" formed by mantle dehydration (Hirth and Kohlstedt, 1996) above the solidus laterally deflects the plume before it melts (Ito, 2001). Because of the high viscosities above the solidus required in this model, ridge melting regime flow is purely plate-driven "corner flow" and only the component of upwelling required by passive plate spreading draws plume material into the sub-axial melting regime. In this model there is no sub-axial channeled plume flow and the V-shaped crustal ridges are generated as solid state plume material with embedded thermal pulses expands radially in annular rings beneath the high viscosity dehydration layer and solidus and are locally advected by ridge spreading. Thus excess crustal thicknesses beneath Iceland and the V-shaped ridges are generated thermally (not by enhanced upwelling) by a small component of plume material that is advected by passive plate spreading above the solidus into the high viscosity dehydration layer where it can melt by decompression. Mantle flow above the solidus has only corner flow trajectories (vertical beneath the axis curving to horizontal and spreading direction-parallel on the flanks) with no along-axis components and is radial beneath the solidus and high viscosity layer and centered beneath Iceland. We refer to this model hereafter as the pulsing plume model, as described by Ito (2001).

The pulsing plume model contrasts in fundamental ways with current models of slow spreading mid-ocean ridges wherein low mantle viscosity and buoyant upwelling instabilities are thought to be important in sub-axial mantle flow (Forsyth, 1992). In these models cells of buoyant mantle upwelling account for the segmented and focused nature of crustal accretion at slow spreading ridges. The buoyant upwelling cells generate crustal thickness variations from their centers to their ends forming fracture zones (FZs) or non-transform discontinuities (NTDs) whether or not ridge seg-

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ments are offset (Tucholke et al., 1997). The significant contribution of buoyant upwelling to melting distinguishes slow spreading ridges from fast spreading ridges where two-dimensional plate-driven "passive" mantle upwelling dominates and crustal segmentation can only occur at ridge segment offsets (Phipps Morgan and Forsyth, 1988). In the North Atlantic slow spreading (∼20 mm/yr, total rate) and regionally enhanced mantle melting should especially favor buoyant mantle upwelling. However, these general features of slow spreading ridges are precluded by the requirement of a high viscosity boundary layer in pulsing plume models. Together with other anomalous features, such as its 30° oblique spreading, linear geometry, and apparent lack of crustal segmentation, the Reykjanes Ridge presents a seeming contradiction to general models of slow spreading ridges. To examine these issues, we conducted a detailed marine geophysical survey of the southern Reykjanes Ridge and interpreted the results in the context of North Atlantic regional tectonics. We find that the reconfiguration of the ridge, elimination of segmentation, its present oblique linear geometry and formation of flanking crustal V-shaped ridges can be consistently explained by upper mantle buoyant upwelling, if such instabilities can propagate along a long linear axis.

1.1. Geologic background

Early seafloor spreading in the North Atlantic basin was partitioned between dual spreading centers. The Ran Ridge in the Labrador Sea between Greenland and North America initiated around 60 Ma (Vogt and Avery, 1974). The proto Reykjanes Ridge between Greenland and Eurasia initiated around 55 Ma (Vogt and Avery, 1974). These spreading centers joined the southward continuation of the Mid-Atlantic Ridge at a triple junction near what later became the Bight Fracture Zone. The proto Reykjanes Ridge formed an orthogonally spreading linear ridge without major offsets or FZs (Smallwood and White, 2002), as shown by the pattern of magnetic (Macnab et al., 1995) and gravity (Sandwell et al., 2014) anomalies in regional compilations (Fig. 1). Near Anomaly 17 (∼37 Ma) the opening direction abruptly changed by ∼30° from NW–SE to nearly E–W (Smallwood and White, 2002), probably related to cessation of spreading in the Labrador Sea and joining of Greenland to the North American plate (Vogt and Avery, 1974). This tectonic reconfiguration also converted the North America–Greenland–Eurasia triple junction into the Bight transform fault. As a result of the change in opening direction the Reykjanes Ridge abruptly became fragmented (Smallwood and White, 2002) forming a ridge-transform stair-step pattern with ∼50 km long ridges offset by transform faults on the order of 30 km long. Immediately after this segmented plate boundary was established it began to reconfigure again, but this time diachronously from north to south, so that a single linear but now obliquely spreading ridge replaced the orthogonally-spreading stair-step geometry (Hey et al., 2016). This reconfiguration occurred without further significant changes in opening direction (Smallwood and White, 2002) and was accompanied by the formation of diachronous V-shaped crustal ridges and troughs (Vogt, 1971), and the elimination of the previous ridge-orthogonal crustal segment offsets and boundaries (Fig. 1B).

1.2. Survey objectives

In order to investigate the elimination of transform faults, FZs and NTDs, the change from orthogonal to oblique spreading and the formation of V-shaped crustal ridges and troughs we surveyed the Reykjanes Ridge and flanks near its intersection with the Bight Transform Fault in August–September 2013 on *R/V Marcus G. Langseth*. In this area FZs and a transform fault still approach and intersect the ridge axis so that the process that eliminated them can be most clearly examined. Basement structure is well imaged in multibeam sonar mapping and closely spaced gravity and magnetic profiles resolve three-dimensional variations reflecting crustal thickness and deeper mantle density variations and magnetic isochrons. The magnetic isochrons together with seafloor basement fabric map the evolution of the plate boundary in sufficient detail to show how it reconfigured thereby allowing tests of proposed mantle plume-induced "thermal weakening" models (Vogt and Johnson, 1975; White, 1997) involving gradual ridge rotation vs. tectonic ridge propagation (Hey, 1977) and other ridge migration processes by asymmetric spreading. Mantle Bouguer anomalies map out changes in crustal thickness and underlying mantle density structure between the orthogonal segment south of the Bight FZ and the developing oblique ridge segments to the north providing insights into how the mode of mantle advection changed between these settings.

2. Methods

2.1. Multibeam data processing

Bathymetry and acoustic backscatter data were acquired with a 1° × 1° Simrad EM122 multibeam system on *R/V Marcus G. Langseth*. The multibeam system was calibrated daily with expendable bathy thermograph (XBT) water column sound velocity profiles. Tracks were run along flowlines calculated from Smallwood and White (2002) rotation poles for North America–Eurasia and mostly spaced at 7 km. The bathymetric data were gridded in .001 × .001 degree cells in latitude and longitude using Generic Mapping Tools (GMT) (Wessel et al., 2013) and MB-System (Caress and Chayes, 2008) software. The gridded bathymetric surface was illuminated from 045° and is shown with depths color coded in Fig. 2A. Acoustic backscatter data were extracted from the multibeam files and gridded at .0005 × .00025 degree cells in longitude and latitude. The acoustic backscatter data are shown in Fig. 2B as a gray-scale map with higher values in darker shades. The gridded multibeam data provide essentially complete coverage between tracks.

2.2. Magnetics data processing

Magnetic field data were acquired with a Geometrics G-882 Cesium magnetometer towed 200 m behind the ship during essentially all of the survey. The International Geomagnetic Reference Field (IGRF) was removed from the total field values to produce magnetic anomalies and gridded using GMT software. Extrapolated grid values were masked to the approximate extent of the multibeam data and plotted as a color-coded map in Fig. 3A. Isochrons (Fig. 3A) were identified from observed profile values by comparison with forward calculated two-dimensional magnetic profiles generated by block models of the geomagnetic reversal sequence scaled for the half-spreading rate of the Reykjanes Ridge (11 mm/yr) in Mirone Software (Luis, 2007). Three-dimensional magnetic anomaly and bathymetry grids were used to calculate seafloor magnetization, which removes field skewness and topographic effects. The magnetization inversion used magnetic grid (Macnab et al., 1995) and ship (Searle et al., 1998) and satellite-predicted (Sandwell et al., 2014) bathymetry to fill in areas outside of our survey coverage (gray areas in Fig. 3A). The grids were resampled to approximately 1 km spacings and mirrored for the magnetization inversion to minimize edge effects. The inversion used a three-dimensional implementation (Luis, 2007) of the Parker (1972) method in the Fourier domain. A 500 m source layer was assumed with magnetization direction given by an axial geocentric dipole. Five terms in the Fourier series were used. Data values were masked to the extent of the *Langseth* multibeam grid and are shown with color-coded values in Fig. 3B. As the resulting

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