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Interaction of a mantle plume and a segmented mid-ocean ridge: Results from numerical modeling

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ABSTRACT

Previous investigations have proposed that changes in lithospheric thickness across a transform fault, due to the juxtaposition of seafloor of different ages, can impede lateral dispersion of an on-ridge mantle plume. The application of this "transform damming" mechanism has been considered for several plume–ridge systems, including the Reunion hotspot and the Central Indian Ridge, the Amsterdam–St. Paul hotspot and the Southeast Indian Ridge, the Cobb hotspot and the Juan de Fuca Ridge, the Iceland hotspot and the Kolbeinsey Ridge, the Afar plume and the ridges of the Gulf of Aden, and the Marion/Crozet hotspot and the Southwest Indian Ridge. This study explores the geodynamics of the transform damming mechanism using a three-dimensional finite element numerical model. The model solves the coupled steady-state equations for conservation of mass, momentum, and energy, including thermal buoyancy and viscosity that is dependent on pressure and temperature. The plume is introduced as a circular thermal anomaly on the bottom boundary of the numerical domain. The center of the plume conduit is located directly beneath a spreading segment, at a distance of 200 km (measured in the along-axis direction) from a transform offset with length 100 km. Half-spreading rate is 0.5 cm/yr. In a series of numerical experiments, the buoyancy flux of the modeled plume is progressively increased to investigate the effects on the temperature and velocity structure of the upper mantle in the vicinity of the transform. Unlike earlier studies, which suggest that a transform always acts to decrease the along-axis extent of plume signature, these models imply that the effect of a transform on plume dispersion may be complex. Under certain ranges of plume flux modeled in this study, the region of the upper mantle undergoing along-axis flow directed away from the plume could be enhanced by the three-dimensional velocity and temperature structure associated with ridge–transform–ridge geometry. It is suggested that, for a setting where a plume–ridge system has one or more transforms, a location-specific model with appropriate plate boundary geometry be used to assess the importance of ridge offsets on upper mantle geodynamics

1. Introduction and motivation

Approximately 20% of the global mid-ocean ridge system has geophysical or geochemical anomalies that can be attributed to a nearby mantle plume (Ito et al., 2003), making the study of plume–ridge interactions critical to understanding crustal accretion processes (Fig. 1). Plumes may generate significant variations in bathymetry, isotope geochemistry, melt production, and other crustal and mantle properties. Some well-studied examples of plume–ridge interaction include the Iceland/Mid-Atlantic Ridge system (e.g., Schilling, 1973; Ito et al., 1996; Searle et al., 1998; Breivik et al., 2008), the Galapagos/Galapagos Spreading Center system (e.g., Ito et al., 1997; Canales et al., 2002; Sinton et al., 2003; Gibson and Geist, 2010), and the Azores/Mid-Atlantic Ridge system (e.g., Schilling, 1975; Detrick et al., 1995; Cannat et al., 1999; Gente et al., 2003).

It has long been recognized that axial discontinuities are near-universal features of divergent plate boundaries (e.g., Macdonald, 1982; Schouten et al., 1985; Lin and Phipps Morgan, 1992). The lithosphere cools and thickens as a function of age away from a spreading segment. Thus, variations in the thickness of the lithosphere occur across transform faults (Fig. 2(a)). Generally, the greatest lithospheric thickness variations are expected where age offsets are large (e.g., where transform length is long and spreading rate is slow). Early analytical work (e.g., Vogt and Johnson, 1975; Vogt, 1976) suggested that transform faults might act as a type of "dam" to along-axis plume flow. These studies posited that variations in lithospheric thickness across transforms offsets could impede the lateral transport of plume material in the upper mantle.

The possible effects of discontinuity-related variations in lithospheric thickness on plume dispersion in the upper mantle have been considered for a number of on-axis and off-axis ridge–hotspot systems. Some examples include the Reunion hotspot

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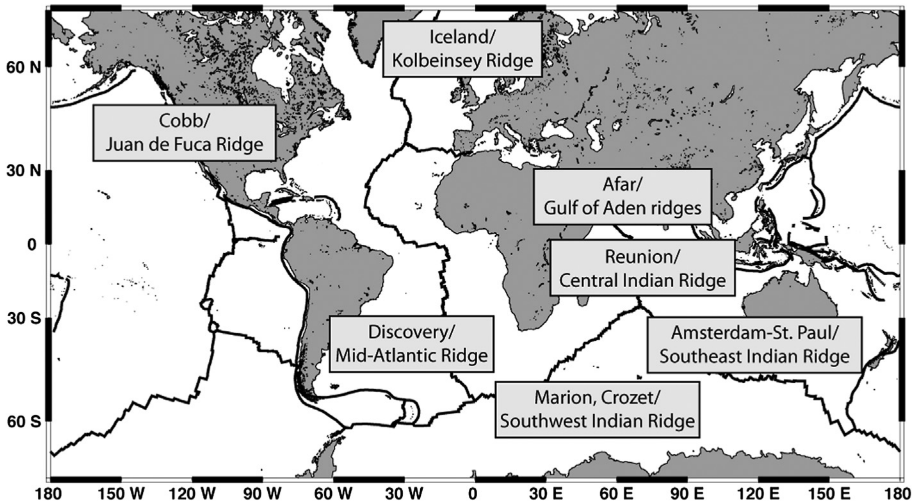

Fig. 1. Selected mid-ocean ridge offsets for which the importance of the transform damming mechanism has been considered.

and the Central Indian Ridge (Mahoney et al., 1989; Sleep, 2002; Murton et al., 2005), the Amsterdam-St. Paul hotspot and the Southeast Indian Ridge (Graham et al., 1999; Scheirer et al., 2000), the Discovery hotspot and the southern Mid-Atlantic Ridge (Douglass et al., 1999; Sleep, 2002), the Iceland hotspot and the Kolbeinsey Ridge (Sleep, 2002; Hooft et al., 2006), the Cobb hotspot and the Juan de Fuca Ridge (Carbotte et al., 2008), the Afar plume and the ridges of the Gulf of Aden (Leroy et al., 2010), and the Marion/Crozet hotspots and the Southwest Indian Ridge (Georgen et al., 2001; Georgen and Lin, 2003; Sauter et al., 2009; Takeuchi et al., 2010) (Fig. 1). Each of these studies addressed the potential role of lithosphere–asthenosphere boundary topography in controlling the three-dimensional dispersion of upper mantle plume material.

The purpose of this investigation is to use a fully dynamic, three-dimensional finite element model of a simplified plume–ridge system to study the geodynamical interaction between a plume and a transform-offset spreading center. A series of plumes with increasing buoyancy flux are modeled to investigate the effects on the temperature and velocity structure of the upper mantle in the vicinity of the transform. This study addresses the fundamental question of how plume material disperses along a segmented ridge. Importantly, it has implications for the supposition that transform offsets act as a simple barrier to along-axis flow.

2. Prior geodynamic studies

Generally speaking, the dispersion of a plume along a mid-ocean ridge can be described as taking a form between two end member types, radial or channelized flow. Channel number is a measure of lithospheric thickness variations compared to a characteristic thickness and width of a plume head (Ribe, 1996; Albers and Christensen, 2001; Ito et al., 2003). High channel number is predicted to occur when the base of the lithosphere has relatively large slope (i.e., when spreading rates are slow) and when plume viscosity is relatively low (e.g., Ribe, 1996; Albers and Christensen, 2001). High channel numbers are associated with more pipe-like plume flow under the ridge axis, guided by the inverted duct formed by the cooling lithospheric plates. Off-axis plumes can be preferentially guided toward the divergent plate boundary because of buoyancy forces, depending on a balance of factors including ridge spreading rate, plume flux, and plume–ridge separation distance (e.g., Kincaid et al., 1995; Ribe, 1996; Ito et al., 1997). If plume material is channelized along the ridge axis, then it is possible that ridge offsets may influence its dispersion. As mentioned above, Vogt and Johnson (1975) and Vogt (1976) first suggested that transforms could effectively act as dams to along-axis upper mantle plume flow. Transform offsets juxtapose cooled lithospheric material of different ages, resulting in lithospheric thickness variations along the ridge axis (Fig. 2(a)). Under the transform damming mechanism, lateral flow away from the plume conduit is impeded by these lithospheric thickness con-

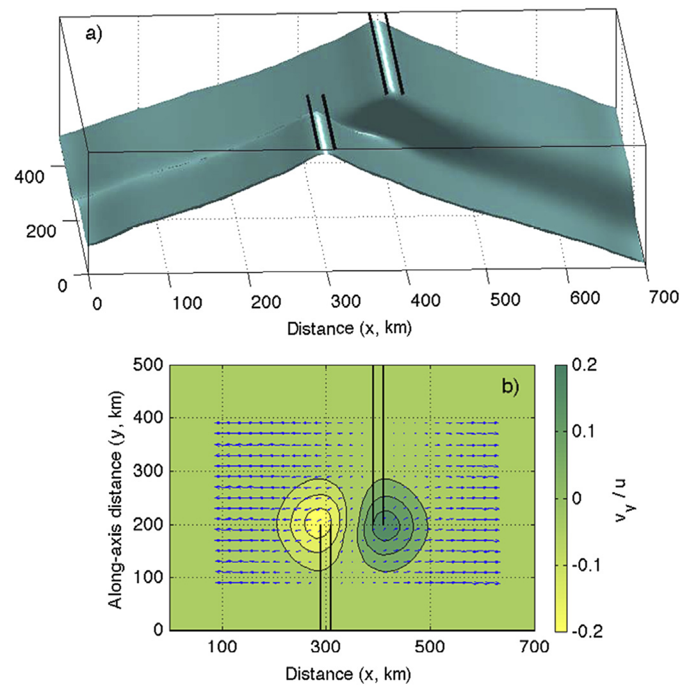

Fig. 2. (a) Green surface shows calculated depth to 800 °C isotherm for a section of ridge with two segments (indicated with double black lines) and an intervening transform fault. Calculations include thermal buoyancy and pressure- and temperature-dependent viscosity, but do not include a thermal mantle plume. An artificial illumination has been applied to highlight how the depth to the isothermal surface changes across the transform offset. (b) Calculated horizontal velocity field at a depth of 80 km below the top surface of the model domain. Double black lines indicate ridge segments, with an intervening transform at $y = 200$ km. Contour plot normalizes along-axis velocity (v_y) to the half-spreading rate (u). Along-axis velocities are generally positive in the vicinity of the ridge-transform intersection at ($x = 400$ km, $y = 200$ km) and negative in the vicinity of the ridge-transform intersection at ($x = 300$ km, $y = 200$ km) with a maximum amplitude of approximately 20% of the half-spreading rate, consistent with previous studies (e.g., Phipps Morgan and Forsyth, 1988; Shen and Forsyth, 1992). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)