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Mantle flow and melting beneath oceanic ridge–ridge–ridge triple junctions

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ABSTRACT

Plate boundary geometry likely has an important influence on crustal production at mid-ocean ridges. Many studies have explored the effects of geometrical features such as transform offsets and oblique ridge segments on mantle flow and melting. This study investigates how triple junction (TJ) geometry may influence mantle dynamics. An earlier study [Georgen, J.E., Lin, J., 2002. Three-dimensional passive flow and temperature structure beneath oceanic ridge-ridge-ridge triple junctions. Earth Planet. Sci. Lett. 204, 115–132.] suggested that the effects of a ridge–ridge–ridge configuration are most pronounced under the branch with the slowest spreading rate. Thus, we create a three-dimensional, finite element, variable viscosity model that focuses on the slowest-diverging ridge of a triple junction with geometry similar to the Rodrigues TJ. This spreading axis may be considered to be analogous to the Southwest Indian Ridge. Within 100 km of the TJ, temperatures at depths within the partial melting zone and crustal thickness are predicted to increase by ~40 °C and 1 km, respectively. We also investigate the effects of differential motion of the TJ with respect to the underlying mantle, by imposing bottom model boundary conditions replicating (a) absolute plate motion and (b) a three-dimensional solution for plate-driven and density-driven asthenospheric flow in the African region. Neither of these basal boundary conditions significantly affects the model solutions, suggesting that the system is dominated by the divergence of the surface places. Finally, we explore how varying spreading rate magnitudes affects TJ geodynamics. When ridge divergence rates are all relatively slow (i.e., with plate kinematics similar to the Azores TJ), significant along-axis increases in mantle temperature and crustal thickness are calculated. At depths within the partial melting zone, temperatures are predicted to increase by ~150 °C, similar to the excess temperatures associated with mantle plumes. Likewise, crustal thickness is calculated to increase by approximately 6 km over the 200 km of ridge closest to the TJ. These results could imply that some component of the excess volcanism observed in geologic settings such as the Terceira Rift may be attributed to the effects of TJ geometry, although the important influence of features like nearby hotspots (e.g., the Azores hotspot) cannot be evaluated without additional numerical modeling.

1. Introduction

The geometry of plate boundaries may play a significant role in the style of magmatic production along mid-ocean ridges. For example, studies have focused on the importance of transform offsets in suppressing melting (Phipps Morgan and Forsyth, 1988; Shen and Forsyth, 1992) and the effects of obliquity on ridge tectonics and crustal accretion (Dauteuil and Brun, 1993; Okino et al., 2002; Dick et al., 2003). This study uses three-dimensional numerical modeling to investigate mantle processes at another distinct type of plate boundary geometry, the triple junction.

Triple junctions, defined as locations where three plate boundaries meet at a single point, are likely to mark regions of unusual mantle geodynamics. This study examines the particular case where all three boundaries of a triple junction are divergent ridges. Such ridge–ridge–ridge (RRR) triple junctions are observed in a number of locations, including the Rodrigues Triple Junction (RTJ) in the Indian Ocean (Tapscott et al., 1980; Sclater et al., 1981; Mitchell and Parson, 1993; Patriat et al., 1997), the Azores Triple Junction (ATJ) in the north Atlantic Ocean (Krause and Watkins, 1970; Searle, 1980), the Bouvet Triple Junction in the south Atlantic Ocean (Sclater et al., 1976; Ligi et al., 1999), and the Galapagos Triple Junction (GTJ) in the Pacific Ocean (Searle and Francheteau, 1986; Lonsdale, 1988). Neglecting factors such as segment-scale melt focusing, the flow fields and thermal patterns along single ridges are predicted to be principally two-dimensional, with upwelling underneath the ridge axis transitioning to dominantly horizontal plate-driven flow away from the spreading center (e.g., Reid and Jackson, 1981; Spiegelman and McKenzie, 1987; Phipps Morgan and Forsyth, 1988). However, near a triple junction, the flow fields of three ridges are likely to interact, producing a complex, three-dimensional pattern of mantle motion and gradients of crustal thickness along ridge axes.

An earlier study (Georgen and Lin, 2002) presented a simplified model of mantle geodynamics for the three ridges of an RRR triple junction with geometry similar to the RTJ. Their investigation used a model in which

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upwelling of an isoviscous mantle was driven by divergence of three surface plates away from a fixed triple junction point. In this way, the calculations of Georgen and Lin (2002) represent a passive, relative plate motion model. Georgen and Lin (2002) predicted strong along-axis flow, as well as significant gradients in mantle temperature and upwelling velocity, along the slowest-spreading of the three ridges. In contrast, the geodynamics of the two faster-spreading ridges differed little from the single-ridge case. Therefore, in this investigation we will focus on calculating mantle velocity, mantle temperature, and crustal thickness for the slowest-spreading ridge, the branch predicted to be most affected by the triple junction geometry. We will incorporate factors not considered in Georgen and Lin (2002), such as variable viscosity, thermal buoyancy, and differential motion of the triple junction with respect to the underlying mantle. We will also compare model predictions to bathymetry, gravity, and geochemical data collected along spreading centers most analogous to the modeled systems, the Southwest Indian Ridge (SWIR) and Terceira Rift, to draw inferences about mantle processes in these two settings.

2. Geometry of RRR triple junctions

More than twenty triple junctions currently exist, and considerably more have operated throughout Earth's history. Many of these present and paleo triple junctions have been the subject of studies focusing on their plate kinematics and seafloor morphology. For example, Searle (1980) used bathymetric and GLORIA sidescan data to investigate seafloor fabric and rift propagation at the ATJ. The GTJ has been the focus of extensive surveys and plate motion studies, including Searle and Francheteau (1986), Lonsdale (1988), and Klein et al. (2005). Larson et al. (2002) and Pockalny et al. (2002) explored the now-extinct Tongareva triple junction in the western Pacific, and Sager et al. (1999) examined the creation and evolution of the Pacific–Izanagi–Farallon triple junction.

2.1. Rodrigues Triple Junction

This study focuses primarily on a plate kinematic configuration similar to that of the RTJ (also known as the Indian Ocean Triple Junction) (Fig. 1). This triple junction is comprised of the ultra-slow-spreading SWIR (half-rate ~0.7–0.8 cm/yr), and the intermediate-spreading Central (CIR) and Southeast Indian (SEIR) ridges, with half-rates of ~2.3 cm/yr and ~2.8 cm/yr, respectively. The RTJ is a good candidate for numerical modeling because of its relatively simple geometry. For example, the kinematics of the RTJ are not complicated by the presence of a microplate. Additionally, upwelling patterns at the RTJ are not expected to be influenced by features such as mantle plumes, as the nearest hotspot to the triple junction, Reunion, is presently located more than 1000 km away. Moreover, the RTJ is a relatively stable feature. Plate kinematic and seafloor morphology studies suggest that the triple junction has been stable for perhaps as long as 40 Myr (Tapscott et al., 1980; Sclater et al., 1981). For the last ~80 Myr, the triple junction has been migrating eastward in the hotspot reference frame, accommodated by lengthening of the CIR and the SEIR by 1.3 and 2.7 cm/yr, respectively (Tapscott et al., 1980). Thus, because of its long-term stability, large distance from hotspot influence, and relatively simple plate boundary

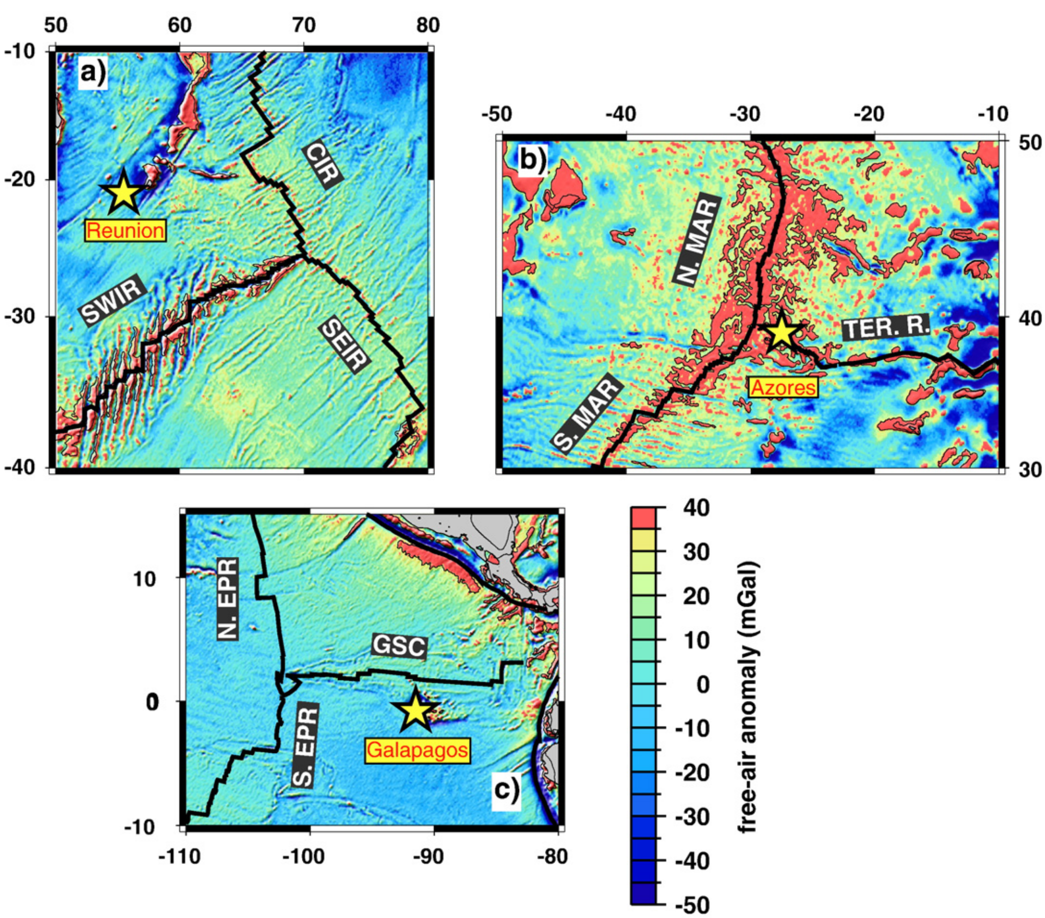

Fig. 1. Location maps for the (a) Rodrigues, (b) Azores, and (c) Galapagos triple junctions. Black lines indicate plate boundaries, and yellow stars mark the locations of the nearest hotspot to each triple junction. SWIR = Southwest Indian Ridge, SEIR = Southeast Indian Ridge, CIR = Central Indian Ridge, N. MAR = Mid-Atlantic Ridge north of the Azores Triple Junction, S. MAR = Mid-Atlantic Ridge south of the Azores Triple Junction, Ter. R. = Terceira Rift, N. EPR = East Pacific Rise north of the Galapagos Triple Junction, S. EPR = East Pacific Rise south of the Galapagos Triple Junction, and GSC = Galapagos Spreading Center. Free-air gravity data are from Sandwell and Smith (1997), and ridge coordinates are from Mueller et al. (1997). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)