Mantle upwelling, magmatic differentiation, and the meaning of axial depth at fast-spreading ridges

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ABSTRACT

Since the first systematic mapping of the East Pacific Rise, its axial depth profile has been used to infer variability in magma supply or mantle temperature. Here, however, we show that segment-scale, rise-parallel undulations of both on- and off-axis seafloor depth result primarily from variations in the bulk density of oceanic crust. Using seismic images of crustal and upper mantle structure combined with gravity data and lava chemistry, we demonstrate that segment-scale variations in crustal density are caused by magmatic differentiation. Rise-parallel changes in magmatic differentiation are attributed to a skew between the axes of mantle upwelling and plate spreading. We conclude that segmentation of axial depth along fast-spreading ridges is controlled primarily by the geometry of mantle upwelling.

Keywords: East Pacific Rise, mid-ocean ridges, segmentation, mantle upwelling.

INTRODUCTION AND BACKGROUND

Tectonic offsets of the East Pacific Rise define ridge segments. Within ridge segments, axial depth typically shoals away from tectonic offsets toward intrasegment highs (Francheteau and Ballard, 1983; Macdonald et al., 1988). Axial depth minima are commonly associated with broad axial summits, intense volcanic and seafloor hydrothermal activity, and the eruption of MgO-rich lavas (Langmuir et al., 1986; Macdonald et al., 1988; Scheirer and Macdonald, 1993) (Fig. 1). A popular concept for explaining these characteristics is that the supply of magma from the mantle to the crust is increased beneath intrasegment highs (Carbotte et al., 2004; Francheteau and Ballard, 1983; Macdonald et al., 1988; Whitehead et al., 1984). If this view were correct, we would expect to observe either thickened crust beneath axial depth minima or evidence for the segment-scale redistribution of magma.

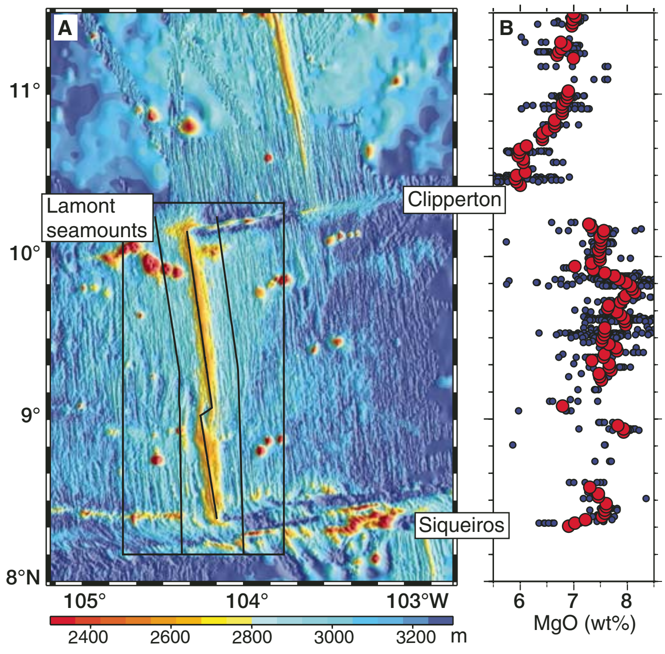

Figure 1. Map of the northern East Pacific Rise and plot of along-axis variations in lava chemistry. A: Bathymetric map showing changes in axial depth and seafloor morphology. The box outlines the area of the UNDERSHOOT experiment. Black lines show the location of profiles shown in Figure 3. B: Plot of weight percent MgO (from PetDB, www.petdb.org) by latitude for samples recovered near the ridge axis (blue dots) and the running average determined every 1 km along axis using a triangular filter with a 4 km half-width (red circles).

Crustal thickness, however, does not correlate with seafloor depth for the ridge segment bounded by the Clipperton and Siqueiros transforms (Barth and Mutter, 1996; Canales et al., 2003). Figure 2A shows the crustal thickness map derived from wide-angle refraction data (Canales et al., 2003). Excluding the area near the Lamont seamounts, the thickest crust (7.4 km) is located in the wake of the 9°03′N overlapping spreading center (OSC), whereas crust is generally thinner (5.9–6.2 km) toward 10°N where seafloor depth is shallower (crustal thickness values are from east of the rise axis). A similar result is obtained if we compare axial depth to the average crustal thickness within 25 km of the rise (Figs. 3A and 3B). Even when including the anomalously thick crust beneath the Lamont seamounts, the amount of crustal material found near the intrasegment highs north and south of the 9°03′N OSC is significantly less than the average crustal thickness in the wake of the 9°03′N OSC.

Why does axial depth not correlate with crustal thickness variations along the East Pacific Rise? A common interpretation is that axial depth is a signature of mantle density. In this view, axial depth minima are supported by anomalously low-density mantle that is localized beneath intrasegment highs. Such mantle is assumed to be hotter, to contain more melt, and to supply more magma to the ridge crest in comparison with mantle beneath regions where the rise axis is deeper. Previous studies of topography and gravity assume that the excess supply of magma beneath axial highs is redistributed in the rise-parallel direction, an issue we address further below, and that intrasegment highs are underlain by segment-scale mantle diapirs (Barth and Mutter, 1996; Macdonald, 1998; Macdonald et al., 1988; Wang et al., 1996). The residual mantle Bouguer anomaly (RMBA, the free air gravity anomaly corrected for the topography of both the seafloor and the seismically measured Moho, and for the mantle thermal structure due to the ridge geometry; see the GSA Data Repository[1]) for the East Pacific Rise between the Siqueiros and Clipperton transforms

[1]GSA Data Repository item 2008174, mantle Bouguer and residual mantle Bouguer anomalies calculated by removing both 6-km-thick crust and the seismically measured crust, is available online at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

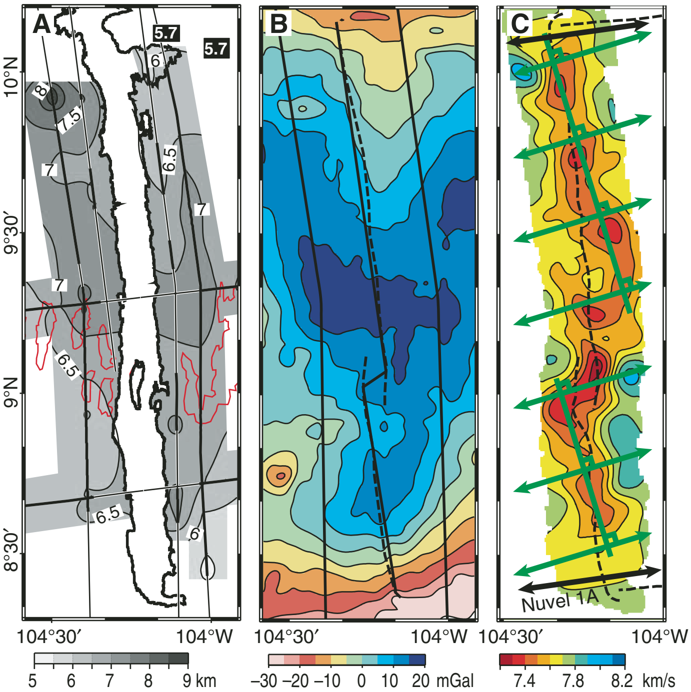

Figure 2. Geophysical results from the UNDERSHOOT experiment between the Clipperton and Siqueiros transforms. A: Crustal thickness map interpolated from seismic refraction data (Canales et al., 2003). The map is masked where no data are available; contour interval is 0.5 km. Light black lines show the location of refraction profiles; heavy black lines show where crustal thickness was measured. Also shown are two crustal thickness measurements south of the Clipperton transform (black rectangles) from Van Avendonk et al. (2001). Red lines show bathymetric trace of overlapping spreading center (OSC). B: The residual mantle Bouguer anomaly (RMBA) is calculated using the seismically measured crustal thickness; contour interval is 5 mgal. The solid black lines show the locations of along-axis profiles shown in Figure 3. C: Compressional wave velocity model of the topmost mantle (Toomey et al., 2007). Contour interval for the isotropic component of the model is 0.1 km/s; section is 9 km beneath the seafloor. Green lines with arrowheads indicate the orientation of the fast axis of seismic anisotropy. Green lines without arrowheads are perpendicular to seismic anisotropy and indicate locations of en echelon segments of the mantle low-velocity zone. The dashed line in B and C shows the ridge axis.

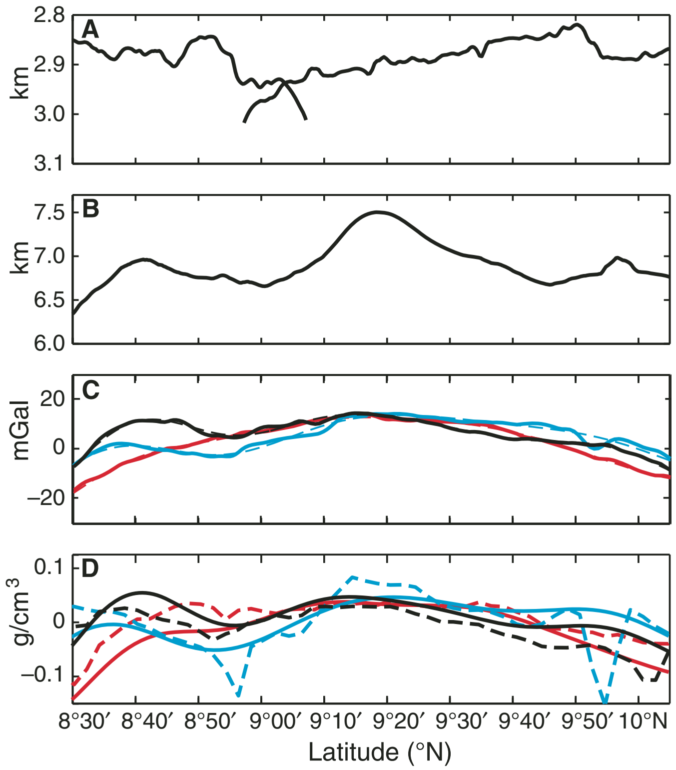

Figure 3. Axis-parallel profiles of bathymetry, average crustal thickness, gravity, and crustal density between the Clipperton and Siqueiros transforms. A: Depth of the ridge axis. B: Average crustal thickness by latitude. Each value is an average of crustal thickness within a 25 km × 20 km region that extends across and along axis, respectively. Thicker crust does not correlate with shallower axial depth. C: Observed RMBA (solid lines) for the profiles shown in Figure 2B and predicted RMBA (dashed lines) from the downward continuation for crustal density. Ridge axis profiles in black; profiles from the east and west rise flanks are red and blue, respectively. D: Crustal density variations predicted first by downward-continuing the RMBA into the crust (solid lines) and second by assuming all axis-parallel changes in bathymetry are isostatically supported by the crust alone (dashed lines). Line colors same as in C. For these calculations, the topography and crustal thickness are averaged 20 km perpendicular to the ridge, and the density anomalies are relative to an average crustal density (2.8 g/cm^3). When downward-continuing the RMBA, the observed RMBA is band-pass filtered from 50 to 500 km in order to prevent amplification of short-wavelength signal.

argues against this interpretation. Figures 2A and 2B show a V-shaped region of thick crust in the wake of the 9°03′N OSC that is also a region of anomalously high densities (high RMBA). The V-shaped RMBA high is difficult to explain in the context of either hotter or more melt-rich mantle localized beneath the intrasegment high near 9°50′N, because such an interpretation would also imply that the southern, off-axis edges of the V-shaped anomaly mark a transition to increased mantle temperature or melt content. Furthermore, the similarity in the rise-parallel amplitude of the on- and off-axis RMBA implies that the anomalous density structure is similar on- and off-axis. We conclude that there is no compelling evidence for anomalously low mantle densities localized beneath and uplifting the axial depth minimum near 9°50′N.

Here we propose an alternative interpretation of seafloor depth and gravity along the East Pacific Rise. We attribute rise-parallel changes in on- and off-axis seafloor depth to changes in both the density and thickness of the crust, including the Moho transition zone. By this view, the V-shaped region of relatively higher RMBA and thicker crust shown in Figure 2 is also more dense.

METHODS

We evaluate the magnitude of crustal density variations following two approaches: (1) We determine the variations in crustal density that fit the along-axis gravity, bathymetry, and crustal thickness data, and (2) we isostatically estimate the variations in crustal density required to locally support seafloor depth anomalies. We first extract the RMBA along three profiles parallel to the ridge (Fig. 3C) and then downward-continue the gravity anomalies into the crust to estimate crustal density variations (Parker, 1972). Two of the profiles are from the rise flanks where crustal thickness is measured directly; the crustal thickness for the axial profile is interpolated from the rise flank measurements. Figure 3D (solid lines) shows that between the transforms the on- and off-axis variations in the RMBA (20–25 mgal) can be explained by crustal density variations with a range of ~0.12 g/cm^3; if the density anomaly is restricted to crust more than 2 km beneath the seafloor, its range is ~0.16 g/cm^3. We exclude the immediate regions of the transforms in our discussion because in those areas seismic velocities are reduced throughout the crust and uppermost mantle, indicating that local cracking and fracturing decrease densities at these depths (e.g., Van Avendonk et al., 2001). We next calculate the crustal density variations required to isostatically support rise-parallel changes in seafloor topography along each of the three profiles. Figure 3D (dashed lines) shows that the crustal densities predicted from isostasy are in good overall agreement with those predicted by downward continuation of the RMBA, particularly for the profiles along the axial high and on its eastern flank; the isostatically estimated crustal densities predict more local variability for the western profile due to the presence of seamounts that may not be supported by local isostasy.

Our analyses show that variations in the density of oceanic crust are consistent with segment-scale, rise-parallel variations in seafloor depth, crustal thickness, and gravity near the East Pacific Rise. As there is no evidence for either thicker crust or anomalously low-density mantle beneath the axial depth minimum at 9°50′N (Fig. 2), we conclude that crustal density plays a more important role in determining the axial depth profile than heretofore thought possible. Deeper on- and off-axis seafloor depth thus corresponds to more dense crust, whereas average crustal densities are expected to be less near axial depth minima or where off-axis seafloor depth shoals in the rise-parallel direction.

ORIGIN OF CRUSTAL DENSITY ANOMALIES

We now consider possible causes for the origin of rise-parallel, segment-scale variations in crustal density and seafloor depth. Crustal thermal structure cannot contribute significantly to rise-parallel variations in depth because the volumetric coefficient of thermal expansion for crustal rocks is small (1.6×10^{-5} °C^{-1}). Bathymetry would shoal by only ~15 m for a thermal anomaly of 350 °C that occurs throughout the middle to lower crust. Moreover, to reduce crustal densities by the range required (~0.1 g/cm^3; Fig. 3D) implies a crustal-wide temperature anomaly in excess of the solidus. Similarly incongruous conclusions are arrived at when considering partial melt. Since basaltic melt is 0.1–0.2 g/cm^3 less dense than solid basalt, crust in both on- and off-axis regions must vary between completely solid to 50%–100% molten in order to explain gravity and seafloor depth. These calculations belie a common assumption, which is that realistic variations in the temperature or partial melt content of oceanic crust are readily evident in seafloor bathymetry.

The average density of oceanic crust is also affected by porosity, alteration, and the degree of magmatic differentiation. Porosity includes the effects of cracking, as well as changes in the thickness of lithologic units (e.g., the extrusive section). With increasing porosity or alteration—characteristics found primarily in the upper crust—there is a resultant decrease in both density and compressional wave seismic velocity. These relations predict that shallower seafloor should be associated with a decrease in upper crustal seismic velocities and an increase in cracking or alteration, a trend opposite of what is observed (Canales et al., 2003; Van Avendonk et al., 2001).

By contrast, an increase in the degree of magmatic differentiation increases bulk density but decreases compressional wave velocity (Iturrino et al., 1991; Korenaga et al., 2002). Deepening of the seafloor in the rise-parallel direction would thus be associated with a transition to more differentiated lavas (lower mean MgO) and slower average crustal seismic velocities. An inverse relation between axial depth and the mean MgO content of lavas is well known (Fig. 1) (Hooft et al., 1997; Langmuir et al., 1986; Scheirer and Macdonald, 1993). Because upper crustal velocities are strongly influenced by porosity, they cannot be used to infer composition. However, seismic observations of lower crustal velocities are in general agreement with the predictions of magmatic differentiation. Between the Siqueiros and Clipperton transforms, average off-axis, lower crustal velocities are greater near the intrasegment high (see Figs. 4 and 5 of Canales et al., 2003). We conclude that the most likely cause of segment-scale variations in crustal density and axial depth is magmatic differentiation. While this possibility was considered previously (Canales et al., 2003), it was rejected because the origin of segment-scale variations in magmatic differentiation could not be explained, an issue we discuss next.

Previous studies have suggested that the along-axis redistribution of magma can cause segment-scale variations in magmatic differentiation (Batiza and Niu, 1992; Macdonald et al., 1988, 1991). Geological and geophysical studies, however, are incompatible with segment-scale redistribution of magma. Eruptive events along the East Pacific Rise show no evidence for segment-scale diking (Gregg et al., 1996; Tolstoy et al., 2006). Seismic images of the axial magma chamber (AMC) reflector show that the upper crustal sill is both too small and too discontinuous to transport magma over segment-scale distances (Kent et al., 1993). Tomographic imaging further shows that beneath the AMC reflector, melt fractions decrease with depth and that lower crustal segmentation compares well with offsets of the AMC reflector and segmentation of seafloor geology (Dunn et al., 2000; Toomey et al., 1990). These results are inconsistent with segment-scale redistribution of magma at lower crustal depths.

Tomographic imaging of mantle structure is also incompatible with segment-scale, along-axis transport of magma beneath the crust. Between the Siqueiros and Clipperton transforms, the mantle low-velocity zone (MLVZ) is composed of two en echelon trends that are skewed beneath the rise axis and offset in a right-lateral sense in the vicinity of the 9°03′N OSC (Toomey et al., 2007). The MLVZ intersects the rise axis near the intrasegment high and is located farther from the spreading axis toward the south (Fig. 2C). Along-axis transport of magma at mantle depths would imply that magma upwelling beneath the intrasegment high is transported in the off-axis direction, a scenario that we consider unlikely.

We propose that rise-parallel undulations in on- and off-axis seafloor depth and gravity are related to a skew between the axis of mantle upwelling and the axis of plate spreading. As a consequence of this skew there are systematic along-axis changes in the across-axis offset between the MLVZ and the axial magmatic system (Toomey et al., 2007). Away from tectonic discontinuities, this offset correlates well with less differentiated lavas and lower-density crust near regions of rise-centered mantle melt delivery and more differentiated lavas and higher-density crust at sites of off-axis delivery. As mantle melt migrates from an off-axis site of melt delivery toward the ridge, we suggest that it differentiates at pressures typical of the Moho transition zone, forming magmas (and subsequently crust) with lower mean MgO and higher density. Rise-parallel variations in the extent of near-Moho differentiation thus contribute to rise-parallel changes in bulk crustal composition and density that are preserved as the crust moves off axis.

We note that crustal-level crystallization also affects the extent of magmatic differentiation and that the importance of this process is likely to increase with magma residence time. While many processes can contribute to magma residence time, we mention two here. First, as magma moves riseward from a site of off-axis upwelling, it will undergo cooling, magmatic differentiation, and the exsolution of magmatic volatiles. Such changes in the properties of magma are likely to decrease its eruptibility, thereby increasing crustal residence time. Secondly, in the immediate vicinity of OSCs the rapidly decreasing rates of extension toward the tips of opposing limbs, along with known variations in mantle and crustal magma plumbing (Kent et al., 2000; Toomey et al., 2007), are likely to affect the frequency of eruptions and thus the residence time of crustal melt. In this setting we would expect considerable variation in the MgO content of lavas over relatively short distances. We thus suggest that segment-scale variations in magmatic differentiation are related to processes occurring near the Moho, whereas smaller-scale variability in fractional crystallization occurs at pressures typical of crustal magma bodies.

DISCUSSION

Segmentation of hydrothermal, volcanic, and tectonic processes along fast-spreading ridges is commonly attributed to variations in magma supply. An often-used proxy for inferring magma supply is the axial depth profile of the East Pacific Rise (Carbotte et al., 2004; Francheteau and Ballard, 1983; Macdonald et al., 1988). On the basis of our results, we conclude that axial depth is not a reliable proxy for either magma supply or mantle temperature. Consequently, determining the actual variations in either characteristic will require measurements of crustal production and mantle structure.

Between the Siqueiros and Clipperton transforms, rise-parallel variations in seafloor depth, crustal structure, gravity data, and lava chemistry are consistent with a skew between the axes of mantle upwelling and plate spreading (Figs. 1 and 2). Rise-centered delivery of mantle melt (near 9°50′N) is observed to be associated with the formation of crust that is both less dense and less evolved, whereas off-axis delivery of mantle melt results in the formation of denser and more evolved crust (south of 9°35′N). We thus predict that observations from the flanks of the East Pacific Rise constrain the past geometry of mantle upwelling. For example, we attribute the V-shaped region of anomalously dense crust found in the wake of the 9°03′N OSC (Fig. 2) to en echelon mantle upwelling that has persisted near the OSC throughout its known existence. Similarly, the formation of less dense crust to the north of this region is consistent with rise-centered upwelling beneath an intrasegment high that has existed for the past 10^5–10^6 years, implying that the associated sites of intense volcanic and hydrothermal activity have persisted for similar time scales.

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