Influence of magma supply and spreading rate on crustal magma bodies and emplacement of the extrusive layer: Insights from the East Pacific Rise at lat 16°N

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ABSTRACT

Seismic reflection data from the East Pacific Rise at lat 16°N, which is spreading at the high end of intermediate rates, suggest that the depths at which axial magma chambers reside do not vary smoothly as a function of spreading rate. Rather, magma-chamber depths form two distinct populations, each associated with a distinct axial morphology and with an abrupt transition occurring within the intermediate-spreading-rate range. Our data (1) show that the melt lens at high-intermediate-spreading ridges lies at a shallow level similar to lens depths at faster-spreading ridges, and (2) provide further support for the spreading-rate invariance of ridges with axial highs noted in other ridge properties. The axial morphology of the two ridge segments within the study area differs markedly, and a large contrast in magma supply is inferred. The ridge segment with greater magma supply is associated with a broader and more continuous melt lens, a wider region over which the extrusive crust accumulates, and a thicker extrusive layer off-axis where supply to the ridge segment appears to be centered. However, on-axis, the extrusive layer is thinnest where magma supply is robust and a shallower melt lens is observed, consistent with a model in which magma pressure controls the thickness of the extrusive layer accumulated above the magma lens.

INTRODUCTION

At fast-spreading ridges, variations in the depth and width of the axis, basalt geochemistry, hydrothermal vent distribution, and seafloor fracturing (e.g., Macdonald et al., 1984; Scheirer and Macdonald, 1993; Langmuir et al., 1986; Haymon et al., 1991) have lead to the hypothesis that the morphology of the axial high reflects the local supply of magma (magma production and delivery), with enhanced magma supply beneath shallow and broad parts of the ridge (e.g., Macdonald and Fox, 1988). Gravity data show that lower sub-sea-floor densities are associated with the shallow, broad parts of the ridge (Scheirer and Macdonald, 1993; Hooft et al., 1997), consistent with the magma supply model. However, from recent seismic studies, the relationship between the distribution of magma within the crust and the supply of magma inferred from axial morphology is not clear. A horizon marking the magma lens at the top of the axial magma chamber (AMC) is typically detected in seismic reflection data beneath shallow parts of the East Pacific Rise; this horizon deepens and disappears as the ridge deepens toward ridge-axis discontinuities (Macdonald and Fox, 1988; Detrick et al., 1993; Scheirer and Macdonald, 1993). However, large local variations in AMC depth and width are also observed along the East Pacific Rise which give rise to little overall correlation between AMC characteristics and axial morphology (Hooft et al., 1997). The thickness of the extrusive layer (the eruptive product of the crustal magma chamber) inferred from seismic studies appears to increase where the axis deepens near discontinuities, and does not appear simply related to magma supply (Harding et al., 1993; Hooft et al., 1997). Gravity studies show that the isostatic root for the axial high lies primarily below the crust (e.g. Wilson, 1992), and variations in magma supply inferred from axial morphology may largely reflect changes within the mantle.

The inverse correlation between magma chamber depth and spreading rate apparent in Purdy et al. (1992) has provided evidence for a spreading-rate-controlled thermal influence on the depths at which crustal magma bodies reside. Assuming the magma lens imaged in reflection studies is situated at a level within the crust corresponding to the freezing horizon for melt, Phipps Morgan and Chen (1993a) present a model for crustal accretion that can account for the spreading-rate variations in magma chamber depths. In their model, the thermal structure of the axis is governed by the balance between heat input to the crust through magma injection, and heat removed through hydrothermal circulation. The model predicts an abrupt transition in the depth to the magma lens within a narrow range of intermediate-spreading rates. However, data have not been available to adequately constrain the model within the intermediate-rate range where the steep gradient in magma-chamber depths is predicted.

In this contribution we present results from a seismic reflection study of two segments of the East Pacific Rise north of the Orozco Fracture Zone (hereafter referred to as the southern and northern segments, Fig. 1). These observations provide new constraints on the spreading-rate dependence of and the influence of magma supply on ridge structure. Spreading in the region is at a high intermediate rate (85 mm/yr, DeMets et al., 1994) that has not been studied previously. The southern segment, located directly north of the fracture zone (Fig. 1), is the shallowest and broadest segment along the entire length of the East Pacific Rise from lat 23°S to 23°N. Axial depths rise to 2200 m within a flat, plateaulike summit that broadens from approximately 3–4 km wide to 10 km at its widest point. A prominent seamount chain with depths as shallow as 1300 m extends within ~20 km of the ridge on its west flank. The ridge axis is broadest just north of the seamount chain, and the currently inflated morphology of the axis may reflect enhanced magma supply associated with the seamount-

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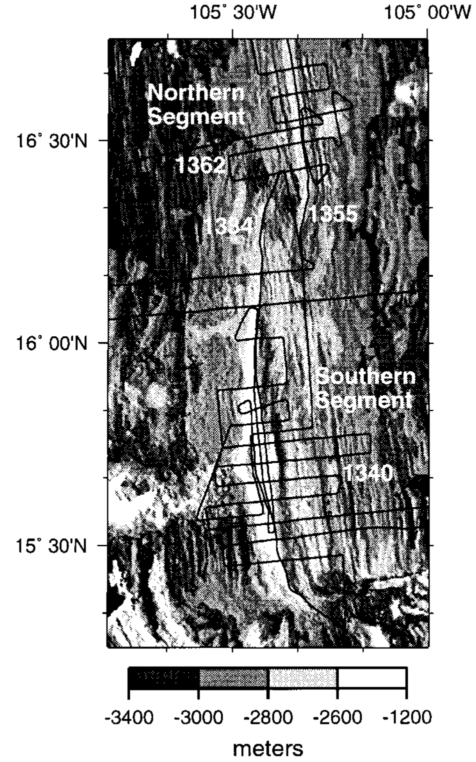

Figure 1. Bathymetry of study region showing track coverage for seismic reflection survey. Numbered lines are seismic profiles referred to in text and in Figures 2 and 3.

chain melt source. Enhanced magma supply within this region is supported by gravity studies which indicate thicker crust or hotter mantle beneath the central part of the ridge segment (Weiland and Macdonald, 1996). Axial morphology suggests that enhanced magma supply is largely confined to the southern segment. Along the northern segment, located north of a small 8-km-offset discontinuity at lat 16°20′N, the axial high is much narrower and more than 300 m deeper, with a morphology similar to that of the East Pacific Rise elsewhere. With the approximately constant spreading rate through the region, these two ridge segments provide an ideal site to evaluate the influence of magma supply inferred from axial morphology on crustal magma bodies and the accretion of the extrusive layer.

Along a series of axis-parallel and cross-axis lines within both ridge segments, seismic reflection data were obtained with a tuned 10-gun array of 3005 in^3 (49.25 dm^3) and a 4-km-long, 160-channel digital streamer. With this configuration, a bright AMC reflection was imaged as well as a refracted arrival from the base of seismic layer 2A (Fig. 2). The layer 2A event arises from a steep velocity gradient in the shallow crust within which P-wave velocities rapidly increase from ~2.4 to 5 km/s (e.g., Vera et al., 1990; Christeson et al., 1994). The velocity transition at the base of layer 2A has been variously interpreted as the lithologic boundary between low-density extrusive rocks and higher-density dikes, or as a porosity horizon within the extrusive layer (e.g., Christeson et al., 1994). The bulk of the available evidence supports the lithologic model, and in most recent seismic studies layer 2A is used as a proxy for the extrusive crust (e.g. Carbotte et al., 1997; Hooft et al., 1997). Two-way traveltimes (twtt) to the AMC and the layer 2A event are digitized and converted to depth by using crustal-velocity information derived from sonobuoy data collected in the region and expanding spread profile data from the East Pacific Rise at lat 9°N (Vera et al., 1990) (Fig. 3).

AMC CHARACTERISTICS

An along-axis profile that approximately follows the axial summit caldera of the southern segment shows a bright AMC event, clearly phase reversed relative to sea floor and located at a quite constant depth of 0.59 ± 0.043 s twtt below sea floor (Fig. 2A). On the northern segment, a bright AMC is also observed but only beneath the shallowest part of the ridge (Fig. 2B). Beneath this segment, the AMC is discontinuous and varies considerably in depth (average 0.74 ± 0.081 s twtt). The AMC is deeper on average beneath the northern segment, although the shallowest AMC lies at a two-way traveltime comparable to that observed for the inflated southern segment. The AMC is also narrower in the northern segment, with a width of 0.6 km measured from a migrated profile crossing the shallowest part of the ridge (Fig. 3D), compared to a width of 1.6 km near the broadest part of the southern segment (Fig. 3C).

Converting traveltimes to depth, we obtain average AMC depths of 1.47 and 1.75 km for the southern and northern segments, respectively (Fig. 3A). Average depths at both ridge segments are comparable to those observed for the East Pacific Rise at lat 9°N, where spreading rates are 30% faster (Kent et al., 1993) and are only ~300–400 m deeper than those for the superfast-spreading ridges. Our results are approximately consistent with Phipps Morgan and Chen (1993a) and show that if the change in magma-chamber depths about the intermediate-spreading-rate range is controlled by spreading rate as predicted by their model, this transition occurs at rates less than 85 mm/yr (Fig. 4). However, Phipps Morgan and Chen (1993a) predict more variation in AMC depth for fast ridges (~800 m decrease in depth for ridges spreading from 85 to 155 mm/yr) than we observe (Fig. 4). Other recently collected data show less variation in AMC depth than predicted for slower spreading ridges as well (Fig. 4). Shallow magma chambers (1.2–1.8 km below sea floor) appear to characterize ridges spreading at a wide range of rates from high-intermediate (~85 mm/yr) to superfast (~155 mm/yr). Magma lenses detected at slow- to intermediate-spreading ridges (<85 mm/yr) lie at a deeper level within the crust (2.5 to 3 km) and appear to form a second distinct depth population.

Global compilations of ridge-axis topography and gravity show that a marked change occurs within the intermediate-spreading-rate range (Small and Sandwell, 1992; Small, 1994). An axial high characterizes ridges spreading at rates above 55–80 mm/yr, whereas an axial valley is found at slower-spreading ridges which systematically increases in relief as spreading rate decreases. Wang and Cochran (1995) pointed out that ridges with axial highs have similar relief (~200–400 m) and along-axis gravity gradients, irrespective of spreading rate. Our results, in the context of the previous work, indicate that the AMC is located at a very similar depth range

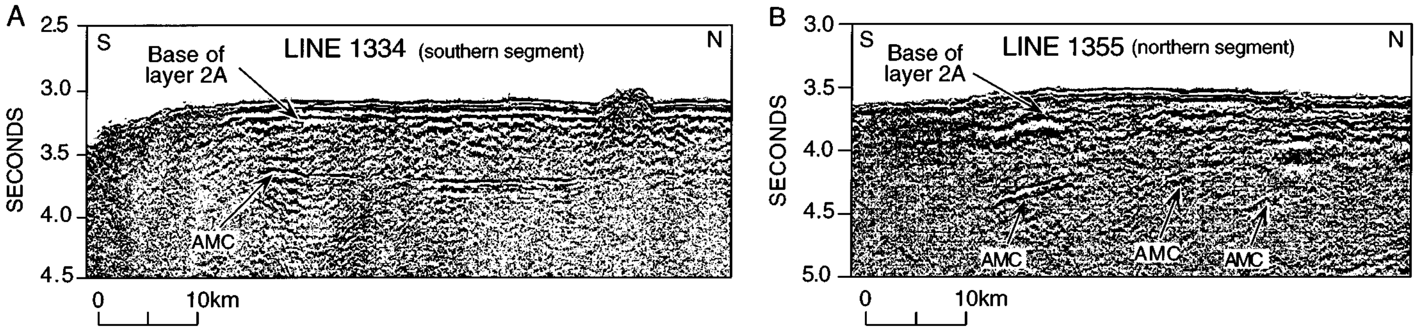

Figure 2. Representative migrated seismic images showing axial magma chamber (AMC) reflector and base of seismic layer 2A beneath part of the axis of the southern (A) and northern (B) segments. To image the layer 2A event, detailed velocity analysis is carried out along closely spaced common midpoint gathers as described in Carbotte et al. (1997).

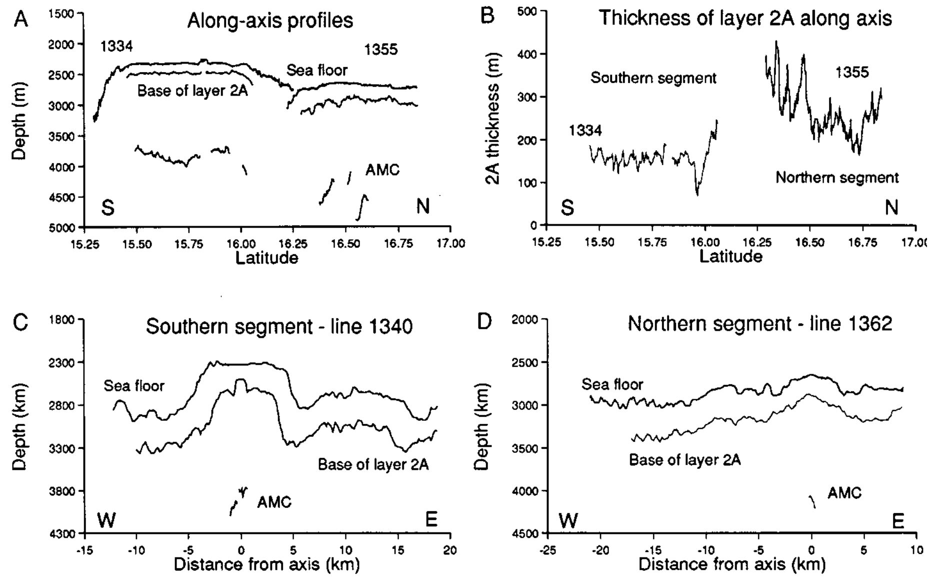

Figure 3. A: Line drawing interpretation of along-axis seismic profiles (portions of which are shown in Fig. 2) showing depth to sea floor, base of layer 2A, and axial magma chamber (AMC) reflector. B: Thickness of layer 2A along axis of both segments. C: Interpretation of migrated cross axis profile 1340 from southern segment. D: Profile 1362 across northern segment.

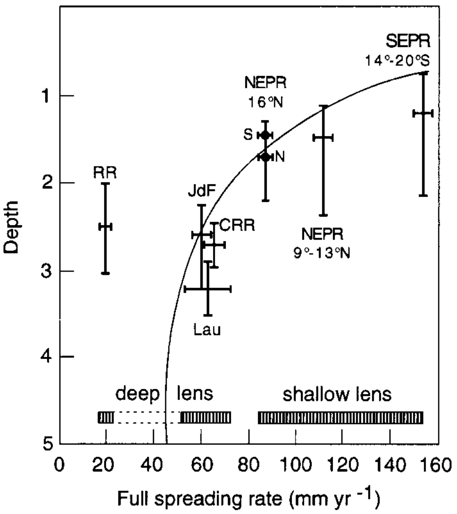

Figure 4. Depth to axial magma chamber (AMC) reflector imaged in seismic reflection surveys at mid-ocean ridges plotted vs. spreading rate with data from our recent survey included (NEPR 16°N, large dots; S and N indicate southern and northern segments, respectively). Total range in AMC depths observed beneath innermost axis is shown. Figure is modified from Phipps Morgan and Chen (1993b) and includes their model prediction (solid line) and range in AMC depth from the northern and southern East Pacific Rise (NEPR, SEPR), Juan de Fuca Ridge (JdF), and Lau Basin (Lau). New data from the intermediate spreading Costa Rica Rift (CRR; Mutter, 1995) and Reykjanes Ridge (RR; Sinha et al., 1997) are also shown.

beneath ridges with axial highs, consistent with the spreading-rate-independent axial topographic and gravity characteristics.

Phipps Morgan and Chen (1993b) extended their model of crustal accretion to include the effects of varying magma supply (modeled as crustal thickness) and found that at any one spreading rate, small variations in supply around a "threshold" level result in large changes in axial thermal structure and, hence, in melt lens depth. The pattern of magma-chamber depths now evident (Fig. 4) suggests that spreading rate is not the only important control on AMC depth. Within the intermediate- to slow-spreading-rate range, local changes in magma supply, as modeled by Phipps Morgan and Chen (1993b), could play the key role in axial thermal structure. Hooft et al. (1997) suggested that local variations in AMC depth and width along the fast- and superfast-spreading East Pacific Rise reflect dike injection and eruptive events. Magma lenses may be dynamic features residing at different levels within the crust depending on local variations in both magma delivery to the melt lens (i.e., magma supply) and magma removal from the lens by dike intrusion and eruption.

AMC widths at the shallowest, broadest parts of both the southern and northern segments (i.e., AMC widths of 1.6 and 0.6 km, respectively) are within the range observed on the faster-spreading parts of the East Pacific Rise (typically ≤1 km, range <500 m to 4 km, Kent et al., 1994), and show no indication of dependence on spreading rate. However, AMC width does appear correlated with magma supply. A wider AMC is found beneath the inflated southern segment than that observed beneath the broadest region of the northern segment. The AMC is also more continuous and uniform in depth beneath the southern segment and a broad, more continuous lens may characterize ridge segments with greater supply.

STRUCTURE OF THE UPPERMOST CRUST

Along the axis of the southern segment, seismic layer 2A is only 160 m thick (0.121 s twtt) with little variation (standard deviation is ±47 m, ±0.035 s twtt, Fig. 3, A and B). Beneath the northern segment, layer 2A is thicker on average and varies more in thickness (260 ± 69 m, 0.196 ± 0.052 s twtt, Fig. 3, A and B). Cross-axis lines show that the thin layer 2A beneath the axis of the southern segment is confined to a narrow region ~1 km wide centered above the AMC (Fig. 3C). Beyond the innermost zone, layer 2A increases in thickness in a step-wise jump near the edges of the AMC event, remains markedly uniform in thickness beneath the rest of the flat-topped axial plateau (300–340 m), and then thickens again at the plateau edges (650–800 m, Fig. 3C). Along the northern segment, the thickness of 2A across the axial high is relatively uniform (average 256 ± 38 m along line 1362, Fig. 3D) and comparable to the average thickness within the innermost zone, indicating a very narrow 2A thickening region. On the ridge flanks, 2A thicknesses are very similar for both ridge segments (averages of 380 ± 80 m and 354 ± 62 m for lines 1340 and 1362, respectively).

The layer 2A thicknesses we observe on the ridge axis and flanks of both ridge segments are within the range reported for the faster-spreading East Pacific Rise (values from multichannel seismic studies are typically 150–300 m on-axis and 350–600 m off-axis: Harding et al., 1993; Kent et al., 1994; Carbotte et al., 1997; Hooft et al., 1997) and indicate that the thickness of the extrusive crust does not vary with spreading rate for ridges spreading from high-intermediate to superfast rates. Comparison of 2A thicknesses at the two segments in our study area indicates that increased magma supply to a ridge does not result in accumulation of a thicker extrusive layer within the innermost axial region. Buck et al. (1997) suggested that magma pressure within the melt lens controlled by the thickness and density structure of the overburden—not magma supply—governs the thickness of the extrusive layer that can accumulate above a melt lens. Their model predicts that a thicker extrusive layer will form at ridges where the magma lens is deeper, as found at intermediate-spreading ridges, and perhaps in areas of reduced magma supply. Beneath the northern segment of our study area the melt lens, on average, is several hundred meters deeper, and the extrusive pile above the lens is thicker (by 60% on average) than at the southern segment, consistent with the model of Buck et al. (1997).

The influence of magma pressure on extrusive thickness modeled in Buck et al. (1997) will be a very localized effect, confined to extrusive accumulation directly above the magma lens.

Beyond the innermost axial region, our data suggest that magmatic budget does influence the longer-term accumulation of this layer, with enhanced magma supply associated with a thicker total accumulation of extrusive rocks and a wider zone over which this layer accumulates. The greatest thicknesses of layer 2A measured in the region are found in the central part of the southern segment (up to 800 m at the edge of the axial plateau, line 1340, Fig. 3C) where the ridge is broadest and where the current enhanced melt supply to the ridge appears to be centered (Weiland and Macdonald, 1996). Layer 2A thickens over a very wide region (from ~4 to 10 km) along the length of the southern segment with the widest accumulation zone also located in the central, broad part of the ridge. In comparison, along the northern segment, the seismically inferred extrusive layer attains nearly its complete thickness within the innermost axial region.

SUMMARY

The marked contrast in axial morphology for two ridge segments north of the Orozco Fracture Zone allows us to assess, for a single spreading rate, the influence of magma supply on extrusive-layer and magma-chamber characteristics. Our observations are consistent with a model in which the on-axis accumulation of extrusive rocks is controlled by magma pressure within the melt lens, and not magmatic budget to a ridge segment. However, beyond the innermost axial zone, greater supply to a segment is associated with a wider region over which the extrusive layer forms and with greater off-axis accumulations. Axial morphology is related to magma-chamber characteristics: A broad and more continuous magma lens is associated with shallow and broad ridge segments.

Our results suggest that the thickness of the extrusive layer, and the width and depth of the magma lens show little dependence on spreading rate for ridges spreading at a wide range of rates from high-intermediate to superfast. This pattern is consistent with the spreading-rate-invariant characteristic of ridges with axial highs noted in topography and gravity data. The depths of crustal magma chambers form two distinct populations; at intermediate spreading rates an abrupt transition occurs within which local magma supply may play the key role.

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