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MID-OCEAN RIDGE SEISMIC STRUCTURE

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Introduction

New crust is created at midocean ridges as the oceanic plates separate and mantle material upwells and melts in response through pressure-release melting. Mantle melts rise to the surface and freeze through a variety of processes to form an internally stratified basaltic crust. Seismic methods permit direct imaging of structures within the crust that result from these magmatic processes and are powerful tools for understanding crustal accretion at ridges. Studies carried out since the mid 1980s have focused on three crustal structures; the uppermost crust formed by eruption of lavas, the magma chamber from which the crust is formed, and the Moho, which marks the crust-to-mantle boundary. Each of these three structures and their main characteristics at different midocean ridges will be described here and implications of these observations for how oceanic crust is created will be summarized. The final section will focus on how crustal structure changes at ridges spreading at different rates, and the prevailing models to account for these variations.

Seismic techniques employ sound to create cross-sectional views beneath the seafloor, analogous to how X-rays and sonograms are used to image inside human bodies. These methods fall into two categories; reflection studies, which are based on the reflection of near-vertical seismic waves from interfaces where large contrasts in acoustic properties are present; and refraction studies, which exploit the characteristics of seismic energy that travels horizontally as head waves through rock layers. Reflection methods provide continuous images of crustal boundaries and permit efficient mapping of small-scale variations over large regions. Locating these boundaries at their correct depth within the crust requires knowledge of the seismic velocity of crustal rocks, which is poorly constrained from reflection data. Refraction techniques provide detailed information on crustal velocity structure but typically result in relatively sparse measurements that represent large spatial averages. Hence the types of information obtained from reflection and refraction methods are highly complementary and these data are often collected and interpreted together.

Much of what we know about the seismic structure of ridges has come from studies of the East Pacific Rise. This is a fast-spreading ridge within the eastern Pacific that extends from the Gulf of California to south of Easter Island. Along this ridge, seafloor topography is relatively smooth and seismic studies have been very successful at imaging the internal structure of the crust. Comparatively little is known from other ridges, in part because fewer experiments have been carried out and in part because, with the rougher topography, imaging is more difficult.

Seismic Layer 2A

Early Studies

Seismic layer 2A was first identified in the early 1970s from analysis of refraction data at the Reykjanes Ridge south of Iceland. This layer of low compressional- or P-wave velocities ($< 3.5\,\mathrm{km\,s^{-1}}$), which comprises the shallowest portion of the oceanic crust (**Figure 1**) was attributed to extrusive rocks with high porosities due to volcanically generated voids and extensive crustal fracturing. In the late 1980s a bright event corresponding with the base of seismic layer 2A was imaged for the first time using multichannel seismic reflection data. This event is not a true reflection but rather is a refracted arrival resulting from turning waves within a steep velocity gradient zone that marks the base of seismic layer 2A. Within this gradient zone P-wave velocity rapidly increases to velocities typical of seismic layer 2B ($> 5.0\,\mathrm{km\,s^{-1}}$) over a depth interval of ~ 100–$300\,\mathrm{m}$ (**Figure 1A**). The 2A event is seen in the far offset traces of reflection data collected with long receiver arrays ($> 2\,\mathrm{km}$) and has been successfully stacked, providing essentially continuous images of the base of layer 2A at midocean ridges.

The Geological Significance of the Layer 2A/2B Transition: Is It a Lithological Transition from Extrusives to Dikes or a Porosity Boundary within the Extrusives?

In most recent studies, layer 2A near the ridge axis is assumed to correspond with extrusive rocks and the base of layer 2A with a lithological transition to the sheeted dike section of oceanic crust. The primary evidence cited for this lithological interpretation comes from studies at Hess Deep in the equatorial eastern Pacific. In this area, observations of fault exposures made from manned submersibles show that the extrusive rocks are ~ 300–$400\,\mathrm{m}$ thick, similar to the thickness of layer 2A measured near the crest of the East Pacific Rise (compare **Figures 1A** and **1B**).

Other researchers have suggested that the base of layer 2A may correspond with a porosity boundary within the extrusive section associated with perhaps a fracture front or hydrothermal alteration. This interpretation is based primarily on observations from a deep crustal hole located off the coast of Costa Rica, which was drilled as part of the Deep Sea Drilling Program (DSDP). Within this hole (504B) a velocity transition zone is found that is located entirely within the extrusive section (**Figure 1C**). Here, a thin high-porosity section of rubbly basalts and breccia with P-wave velocities of $\sim 4.2\,\mathrm{km\,s^{-1}}$ overlies a thick lower-porosity section of extrusives with higher P-wave velocities ($5.2\,\mathrm{km\,s^{-1}}$) (**Figure 1**). However, the relevance of these observations for the geological significance of ridge crest velocity structure is questionable. Crust at

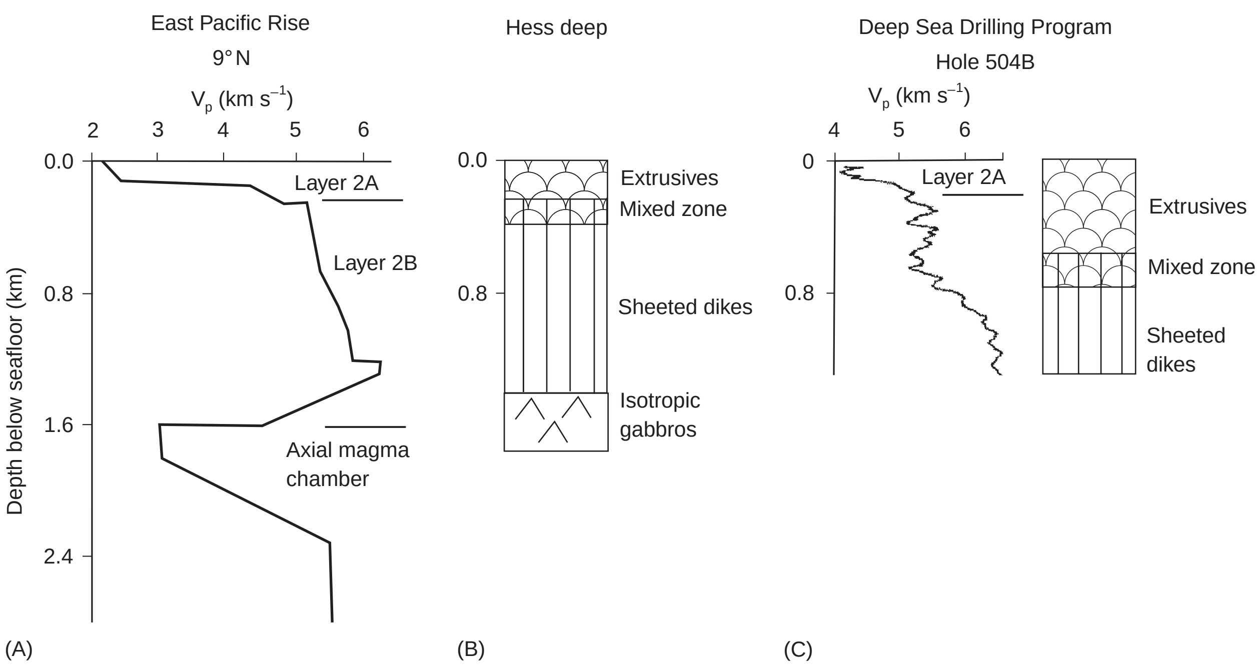

Figure 1 (A) Seismic velocity with depth for newly formed crust at the East Pacific Rise. Layer 2A, 2B, and the low velocities associated with the axial magma chamber (AMC) are identified. (Data from Vera EE, Buhl P, Mutter JC *et al.* (1990), *Journal of Geophysical Research* 95: 15529–15556). (B) Lithological cross section for the upper crust at Hess Deep derived from submersible observations. (Synthesis is from Francheteau J, Armijo R, Cheminee JL *et al.* (1992) *Earth and Planetary Sciences Letters* 111: 109–121. (C) Comparison of P-wave velocities from *in situ* sonic logging within Deep Sea Drilling Hole 504B and the lithological units observed within the hole. (From Becker K *et al.* (1988) *Proceedings of ODP, Initial reports, Part A, v.* 111, *Ocean Drilling Program.* College Station, TX).

DSDP hole 504B is 5.9 My old and it is well established that the seismic velocity of the shallow crust increases with age owing to crustal alteration (see below). Indeed, the velocities within the shallowest extrusives at DSDP 504B ($\sim 4\,\text{km s}^{-1}$) are much higher than observed at the ridge crest (2.5–$3\,\text{km s}^{-1}$), indicating that significant crustal alteration has occurred (compare **Figures 1A** and **1C**).

Conclusive evidence regarding the geological nature of seismic layer 2A will likely require drilling or observations of faulted exposures of crust at or near the ridge crest made where seismic observations are also available. At present, the bulk of the existing sparse information favors the lithological interpretation and layer 2A is commonly used as a proxy for the extrusive crust. If this interpretation is correct, mapping the layer 2A/2B boundary provides direct constraints on the eruption and dike injection processes that form the uppermost part of oceanic crust.

Characteristics of Layer 2A at Mid-ocean Ridges

Along the crest of the East Pacific Rise, layer 2A is typically 150–250 m thick (**Figures 2** and **3**). Only minor variations in the thickness of this layer are observed along the ridge crest except near transform faults and other ridge offsets where this layer thickens.

Across the ridge axis, layer 2A approximately doubles or triples in thickness over a zone $\sim$ 2–6 km wide indicating extensive accumulation of extrusives within this wide region (**Figures 4** and 5). This accumulation may occur through lava flows that travel up to several kilometers from their eruption sites at the axis, either over the seafloor or perhaps transported through subsurface lava tubes. Volcanic eruptions that originate off-axis may also contribute to building the extrusive pile. On the flanks of the East Pacific Rise the base of layer 2A roughly follows the undulating abyssal hill relief of the seafloor (**Figure 6**). Layer 2A is offset at the major faults that bound the abyssal hills. Superimposed on this undulating relief are smaller-scale variations in 2A thickness (50–100 m) that may reflect local build-up of lavas through ponding at and draping of seafloor faults (**Figures 5** and **6**).

Layer 2A is thicker and more variable in thickness (200–550 m) along the axis of the intermediate spreading Juan de Fuca Ridge, located in the northeast Pacific (see **Figure 9**). At this ridge, the sparse existing data suggest that layer 2A does not systematically thicken away from the ridge axis, and it appears that lavas accumulate within a narrower zone than at the East Pacific Rise. Along the slow spreading Mid-Atlantic Ridge, the extrusive section is built largely within the floor of the median valley. At all the ridges that have been surveyed to date, extrusive layer thicknesses measured beyond the axial region are very similar (350–600 m).

Evolution of Layer 2A with Age

Global compilations carried out in the mid-1970s showed that the velocity of layer 2A increases as the crust ages away from the ridge axis and that layer 2A velocities gradually increase to levels typical of layer 2B by 20–40 Ma. Recent compilations of modern seismic data suggest that layer 2A velocities increase abruptly and at quite young crustal ages ($<$ 5 Ma), rather than the gradual change evident in the early data. This increase in the velocity of layer 2A is the primary known change in the seismic structure of oceanic crust with age. This change is commonly attributed to precipitation of low-temperature alteration minerals within cracks and voids in the extrusive section during hydrothermal circulation of sea water through the crust. The detailed geochemical and physical processes associated with how hydrothermal precipitation of minerals affects seismic velocities is poorly understood. However, in-filling of voids with alteration minerals is believed to increase the mechanical competency of the crust sufficiently to account for the evolution of layer 2A with age.

Axial Magma Chamber

Early Studies

Drawing on observations of the crustal structure of ophiolites (sections of oceanic or oceanic-like crust exposed on land) and the geochemistry of seafloor basalts, geologists long believed that midocean ridges were underlain by large, essentially molten, magma reservoirs. However, until the last 15 years, few actual constraints on the dimensions of magma chambers at ridges were available. Early seismic studies on the East Pacific Rise detected a zone of lower seismic velocity beneath the ridge axis as expected for a region containing melt. A bright reflector was also found indicating the presence of a sharp interface with high acoustic impedance contrast within the upper crust. In the mid 1980s an extensive seismic reflection and refraction experiment was carried out on the northern East Pacific Rise by researchers at the University of Rhode Island, Lamont-Doherty Earth Observatory, and Scripps Institution of Oceanography. This study imaged a bright subhorizontal reflector located 1–2 km below seafloor along much of the ridge. In several locations this reflector was found to be phase-reversed relative to the seafloor reflection, indicating it

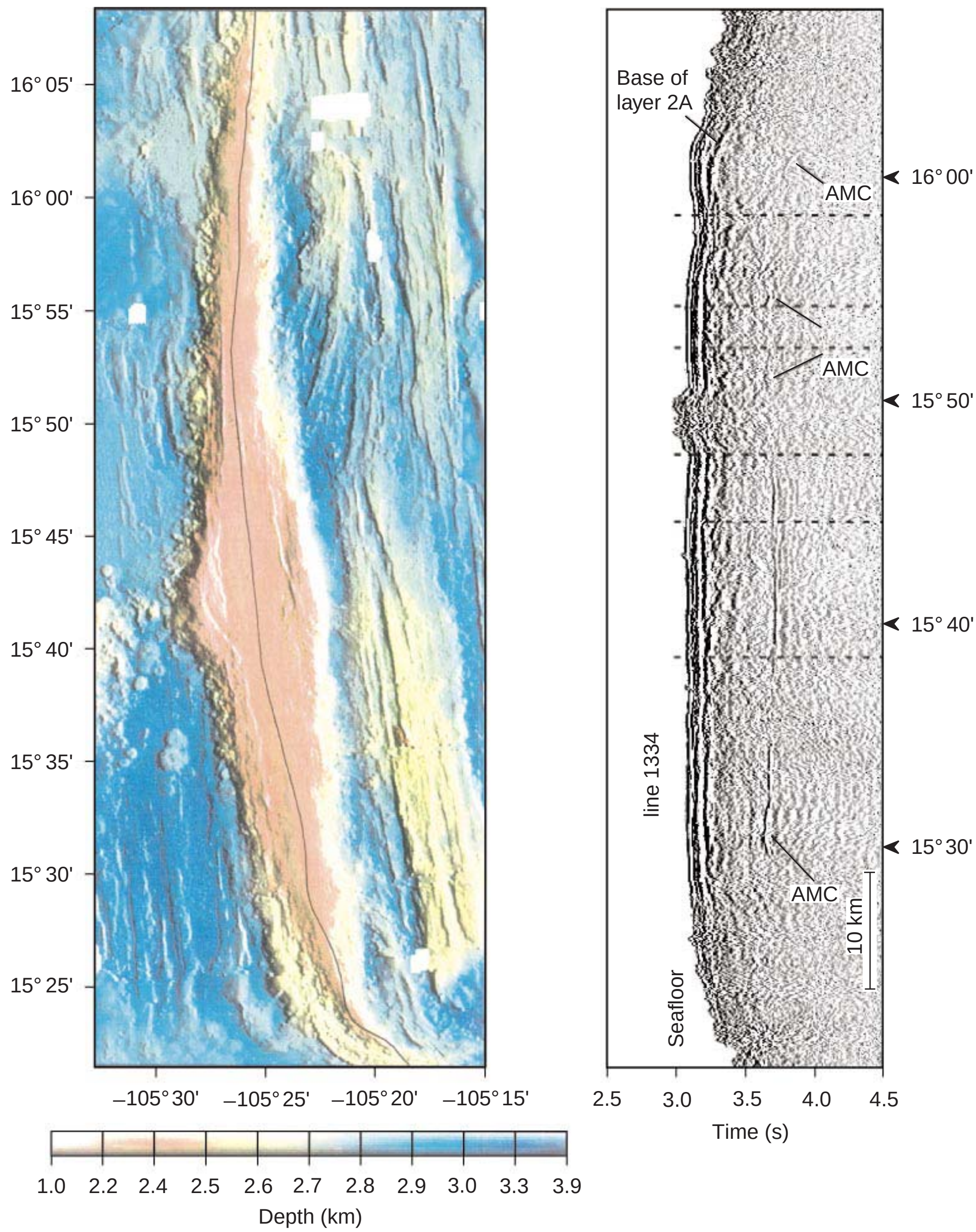

Figure 2 Example of a multichannel seismic line collected along the axis of the East Pacific Rise showing the base of the extrusive crust (layer 2A) and the reflection from the top of the axial magma chamber (AMC). Right-hand panel shows the bathymetry of the ridge axis with the location of the seismic profile in black line. The dashed lines on the seismic section mark the locations of very small offsets that are observed in the narrow depression along the axis where most active volcanism is concentrated.

resulted from an interface with an abrupt drop in seismic velocity. Based on its reversed phase and high amplitude, this event is now recognized as a reflection from a largely molten region located at the top of what is commonly referred to as an axial magma chamber.

Seismic refraction and tomography experiments show that this reflector overlies a broader zone that extends to the base of the crust within which seismic velocities are reduced relative to normal crust. At shallow depths this low-velocity zone is ~ 2 km wide. It broadens and deepens beneath the ridge flanks and is ~ 10 km wide at the base of the crust. Because of the relatively small velocity anomaly associated with much of this low-velocity zone ($< 1\,\text{km s}^{-1}$), this region is interpreted to be hot, largely solidified rock, and crystal mush containing only a few per cent partial melt.

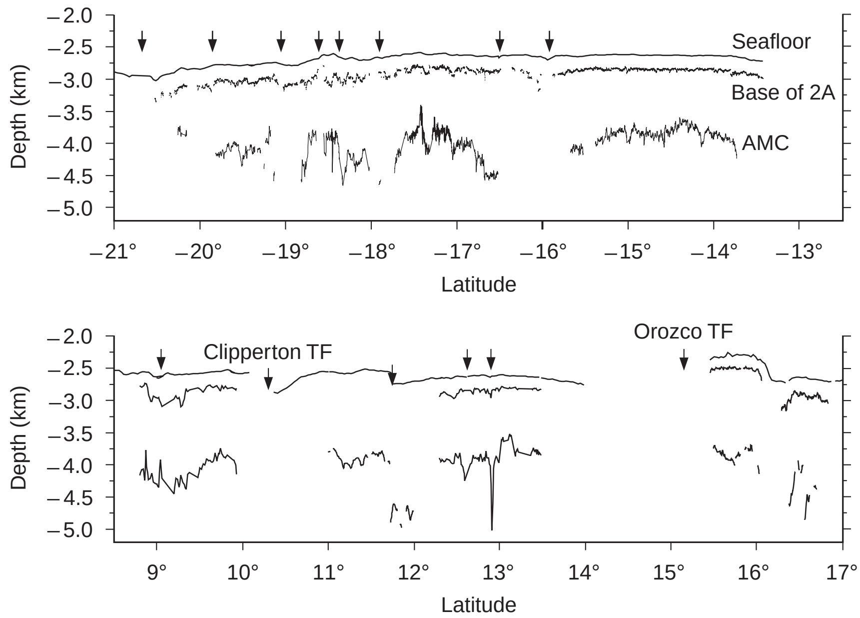

Figure 3 Cross section along the axis of the southern (top panel) and northern (bottom panel) East Pacific Rise showing depth to seafloor, the base of the extrusive crust, and the axial magma chamber reflection. This compilation includes results from all multichannel reflection data available along this ridge. Labeled arrows show the locations of transform faults. Other arrows mark the locations of smaller discontinuities of the ridge axis known as overlapping spreading centers. (Top panel, data from Hooft EE, Detrick RS and Kent GM (1997) *Journal of Geophysical Research* 102: 27319–27340. Bottom panel, data from Kent GM, Harding AJ and Orcutt JA (1993) *Journal of Geophysical Research* 98: 13945–13696; Detrick RS, Buhl P, Vera E *et al.* (1987) *Nature* 326: 35–41; Babcock JM, Harding AJ, Kent GM and Orcutt JA (1998) *Journal of Geophysical Research* 103: 30451–30467; Carbotte SM, Ponce-Correa G and Solomon A (2000) *Journal of Geophysical Research* 105: 2737–2759).

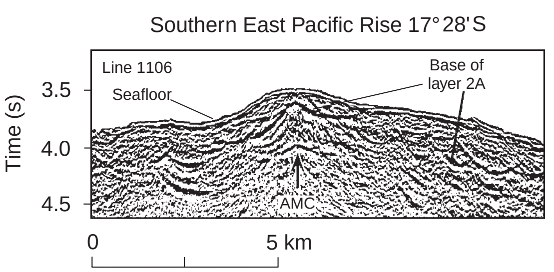

Figure 4 Example of a multichannel seismic profile shot across the ridge axis. Figure shows the magma chamber reflection and the event from the base of layer 2A. (Data from Carbotte SM, Mutter JC and Wu L (1997) *Journal of Geophysical Research* 102: 10165–10184).

The Characteristics of the Axial Magma Chamber at Mid-ocean Ridges

Several seismic reflection studies have now been carried out along the fast-spreading East Pacific Rise imaging over 1400 km of ridge crest (**Figure 3**). A reflection from the magma chamber roof is detected beneath $\sim 60\%$ of the surveyed region and can be traced continuously in places for tens of kilometers. This reflector is found at a depth of 1–2 km below seafloor and deepens and disappears toward major offsets of the ridge axis, including transform faults and overlapping spreading centers. Most volcanic activity along the East Pacific Rise is concentrated within a narrow depression, < 1 km wide, which is interrupted by small steps or offsets that may be the boundaries between individual dike swarms. In many places, the magma chamber reflector does not disappear beneath these offsets (**Figure 2**). However, changes in the depth and width of the reflector are often seen. Seismic tomography studies centered at 9°30′N on the East Pacific Rise shows that a broader region of low velocities within the crust pinches and narrows beneath two small offsets. These results suggest that segmentation of the axial magma chamber may be associated with the full range of ridge crest offsets observed on the seafloor.

Migration of seismic profiles shot perpendicular to the ridge axis reveals that the magma chamber reflection arises from a narrow feature that is typically less than 1 km in width (e.g., **Figure 4**). Refraction data and waveform studies of the magma chamber reflection suggest that it arises from a thin body of magma a few hundred to perhaps a few tens of meters thick, leading to the notion of a magma lens or sill. Initial studies assumed that this lens contained pure melt. However, recent

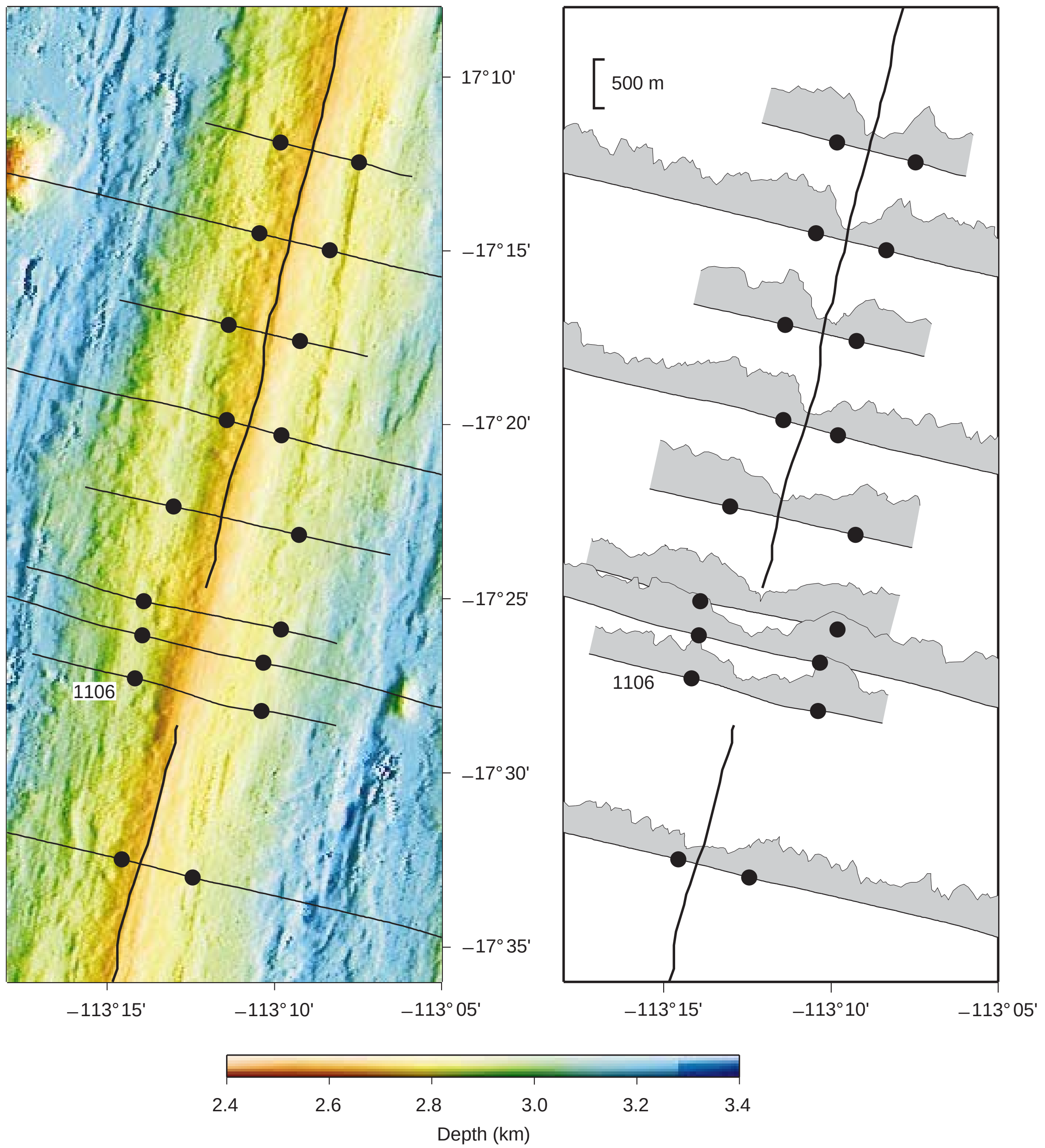

Figure 5 Illustration of the thickening of the seismically inferred extrusive crust (layer 2A) across the axis of the southern East Pacific Rise. Left-hand panel: Bathymetry map of the region with the location of cross-axis seismic lines shown in light line. The bold black line shows the location of the narrow depression along the ridge axis where most volcanic activity occurs. The black dots show the width of the region over which the seismically inferred extrusives accumulate as interpreted from the data shown in the right-hand panel. Right-hand panel: Thickness of the extrusive crust inferred from the seismic data along each cross-axis line. Black dots mark the location where 2A reaches its maximum thickness away from the axis. Seismic line 1106 shown in **Figure 4** is labeled. (Data from Carbotte SM, Mutter JC and Wu L (1997) *Journal of Geophysical Research* 102: 10165–10184).

research suggests that much of the magma lens may have a significant crystal content (> 25%) with regions of pure melt limited to pockets only a few kilometers or less in length along the axis.

Possible magma lens reflections, similar to those imaged beneath the East Pacific Rise, have also been imaged along the intermediate spreading Juan de Fuca Ridge and Costa Rica Rift and at the back-arc spreading center in the Lau Basin. In these areas, reflectors 1–2.5 km wide and at 2.5–3 km depth are detected (see **Figures 10** and **11**). Diffractions from the edges of these reflectors are shallower than

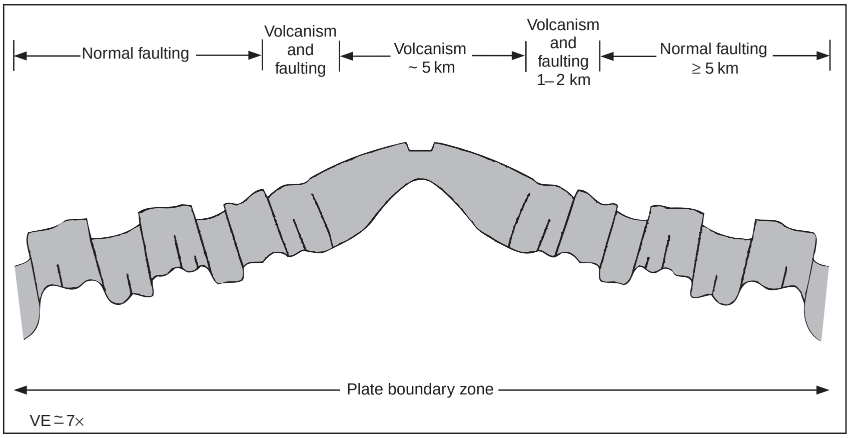

Figure 6 Schematic representation of the accumulation of the extrusive crust on the fast-spreading East Pacific Rise. The extrusive layer gradual increases in thickness within a wide zone centered on the narrow depression that marks the innermost axis. Normal faults begin to develop at the edges of this volcanic zone but may be buried by the occasional lava flow that reaches this distance. Beyond this zone, large-scale normal faulting occurs that gives rise to the fault-bounded abyssal hills and troughs found on the ridge flanks. (Reproduced from Carbotte SM, Mutter JC and Wu L (1997) *Journal of Geophysical Research* 102: 10165–10184).

diffractions due to seafloor topography, indicating that these events clearly lie within the crust. However, there is some debate whether these reflections correspond with magma bodies. Refraction studies along the northern Juan de Fuca show no evidence for a low-velocity zone coincident with the intracrustal reflection. In addition, the Juan de Fuca and Costa Rica Rift data are too noisy to allow determination of the polarity of the event. Hence we cannot rule out the possibility that the shallow crustal reflections observed at these ridges are due to an abrupt velocity increase within the crust, perhaps associated with a frozen magma lens or a cracking front, rather than a velocity decrease associated with the presence of melt.

Along the slow spreading Mid-Atlantic Ridge, evidence for magma lenses has been found in one location along the Reykjanes Ridge. Here an intracrustal reflection at a depth of ~ 2–5 km is observed, similar to the depths of magma lens events observed beneath portions of the intermediate spreading ridges. The absence of magma lens reflections in seismic data collected elsewhere along the Mid-Atlantic Ridge could be due to the imaging problems associated with the very rough topography of the seafloor typical at this ridge. However, there is also evidence from refraction data and seismicity studies that large, steady-state magma bodies are not present beneath this ridge. Microearthquake data show that earthquakes can occur to depths of 8 km beneath parts of the Mid-Atlantic Ridge, indicating that the entire crustal section is sufficiently cool for brittle failure. In other areas, slightly reduced velocities within the crust have been identified, indicating warmer temperatures and possibly the presence of small pockets of melt.

The prevailing model for magma chambers beneath ridges (**Figure 7**), incorporates the geophysical constraints on chamber dimensions described above as well as geochemical constraints on magma chamber processes. At fast-spreading ridges (**Figure 7A**), the magma chamber is composed of the narrow and thin melt-rich magma lens that overlies a broader crystal mush zone and surrounding region of hot but solidified rock. The dike injection events and volcanic eruptions that build the upper crust are assumed to tap the magma lens. The lower crust is formed from the crystal residuum within the magma lens and from the broader crystal mush zone. At slow-spreading ridges (**Figure 7B**) a short-lived dike-like crystal mush zone without a steady-state magma lens is envisioned. At these ridges volcanic eruptions occur and the crystal mush zone is replenished during periodic magma injection events from the mantle.

Moho

The base of the crust is marked by the Mohorovcic Discontinuity, or Moho, where P-wave velocities increase from values typical of lower crustal rocks (6.8–$7.0\,\mathrm{km\,s^{-1}}$) to mantle velocities ($>8.0\,\mathrm{km\,s^{-1}}$). The change in P-wave velocity is often sufficiently abrupt that a subhorizontal Moho reflection is observed from which the base of the crust can be mapped. Depth to seismic Moho provides our best estimates of crustal thickness and is used to study

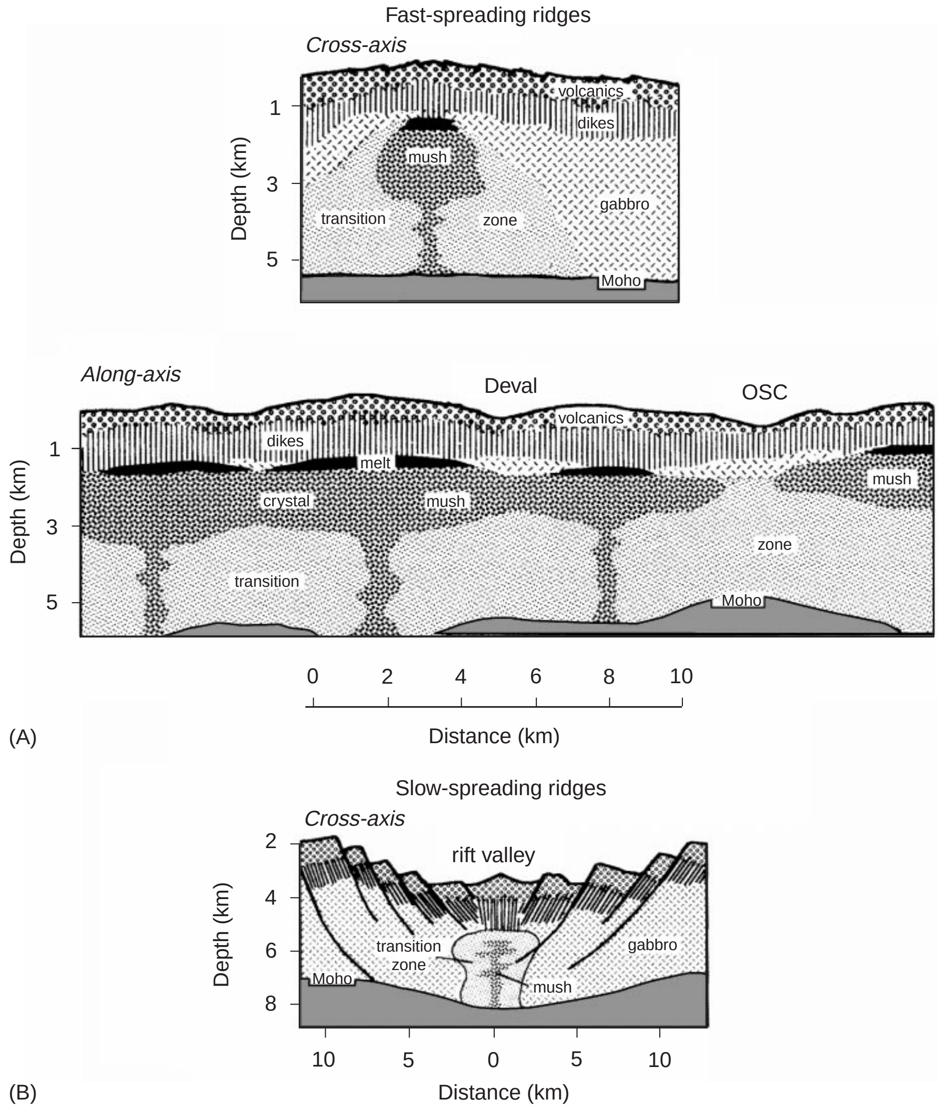

Figure 7 Schematic representation of the axial magma chamber beneath fast-spreading (A) and slow-spreading (B) ridges. At a fast-spreading ridge a thin zone of predominantly melt (black region) is located at 1–2 km below seafloor that grades downward into a partially solidified crystal mush zone. This region is in turn surrounded by a transition zone of solidified but hot rock. Along the ridge axis, the 'melt' sill and crystal mush zone narrows and may disappear at the locations of ridge discontinuities (labeled Deval and OSC in along-axis profile). At a slow-spreading ridge a steady-state melt region is not present. Here a dike-like mush zone forms small sill-like intrusive bodies that crystallize to form the oceanic crust. (Reproduced from Sinton JA and Detrick RS (1991) *Journal of Geophysical Research* 97: 197–216.)

how total crustal production varies in different ridge settings.

Characteristics of Moho at Midocean Ridges

Reflection Moho is often imaged in data collected at the East Pacific Rise (**Figure 8**). In places it can be traced below the region of lower crustal velocities found at the ridge and occasionally beneath the magma lens reflection itself. Depths to seismic Moho indicate average crustal thicknesses of 6–7 km. There is no evidence for thickening away from the ridge crest, indicating that the crust acquires its full thickness within a narrow zone at the axis. The Moho reflection has three characteristic appearances on the East Pacific Rise: as a single, a diffuse, or a shingled event. These variations presumably reflect changes in the structure and composition of the crust-to-mantle transition such as are observed in ophiolites, where the base of the crust can vary from a wide band of alternating lenses of mafic and ultramafic rocks to an abrupt and simple transition zone.

At the Mid-Atlantic Ridge, the base of the crust is not marked by a strong Moho reflection such as is

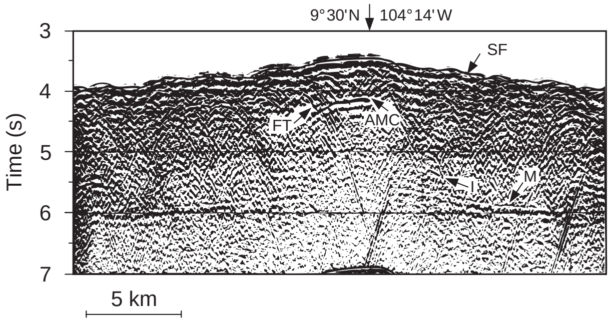

Figure 8 Multichannel seismic line crossing the East Pacific Rise at 9°30′N showing the Moho reflection (labeled M). The seafloor (SF) magma chamber reflection (AMC) and other intra-crustal reflections (FT, I) are labeled. (Reproduced from Barth GA and Mutter JC (1996) *Journal of Geophysical Research* 101: 17951–17975.)

imaged at the East Pacific Rise. Here an indistinct boundary is found that is absent in many places. Hence most of our information on crustal thickness at this ridge has come from seismic refraction studies. Detailed refraction surveys are available within a number of locations that show a clear pattern of thinner crust (by 1–4 km) toward transform faults and smaller ridge offsets. These results are interpreted to reflect focused mantle upwelling and greater crustal production within the central regions of ridge segments away from ridge offsets.

Significant variations in crustal thickness are also observed along the East Pacific Rise. However, in the region with the best data constraints (9°–10°N) the spatial relationships are the opposite of those observed on the Mid-Atlantic Ridge. Within this region, crust is ~ 2 km thinner, not thicker, within the central portion of the segment where a range of ridge crest observations indicate that active crustal accretion is focused. At this fast-spreading ridge the presence of a steady-state magma chamber and broad region of hot rock (**Figure 7**) may permit efficient redistribution of magma away from regions of focused delivery from the mantle. The absence of a steady-state magma chamber beneath the slow-spreading Mid-Atlantic Ridge may prohibit significant along-axis transport of magma such that at this ridge thicker crust accumulates at the site of focused melt delivery.

Variations in Crustal Structure with Spreading Rate

Spreading rate has long been recognized as a fundamental variable in the crustal accretion process. At slow-spreading ridges new crust is formed within a pronounced topographic depression, whereas at fast spreading ridges a smooth and broad topographic high is found. Gravity anomalies indicate significant variations in crustal and mantle properties along the axis of slow-spreading ridges, whereas they are subdued and quite uniform at fast-spreading ridges. Magnetic anomalies are more complex and often difficult to identify at slow-spreading ridges and seafloor basalts are typically more primitive. These observations indicate that spreading rate plays an important role in how magma is segregated from the mantle and delivered to form new oceanic crust. Seismic techniques provide direct constraints on the significance of spreading rate for the distribution of magma within the crust, total crustal production, and the internal stratification of the crust resulting from the magmatic processes of crustal creation.

Some aspects of the seismic structure of ridges are surprisingly similar at all spreading rates. The thickness of the extrusive layer away from the ridge axis is similar (~ 350–600 m), indicating that the total volume of extrusives produced by seafloor spreading is independent of spreading rate. Average crustal thickness is also comparable at all spreading ridges (6–7 km) and total crustal production does not appear to depend on spreading rate.

However, the characteristics of crustal magma lenses and the pattern of accumulation of the extrusive layer are different at fast and slow ridges. Throughout the fast-spreading range (85–150 mm y^{-1}) the extrusive section is thin (~ 200 m) at the ridge axis (**Figure 9**) and accumulates away from the axis within a zone 2–6 km wide. At these rates, magma lenses are imaged beneath much of the axis and have similar widths (**Figure 10**) and are located at similar depths within the crust (**Figure 11**).

At slower-spreading ridges (< 70–80 mm y^{-1}) magma lenses appear to be present only intermittently. Where they are observed they lie at a deeper level within the crust (> 2.5 km) and form a second distinct depth population (**Figure 11**). The extrusive layer is thicker along the axis and does not systematically thicken away from the ridge. At these ridges the extrusive section appears to acquire its full thickness within the innermost axial zone. These differences in the accumulation of extrusives at fast-spreading and slow-spreading ridges could reflect differences in lava and eruption parameters (e.g., eruptive volumes, lava flow viscosity, and morphology) that govern flow thicknesses and the distances lavas may travel from their eruption sites.

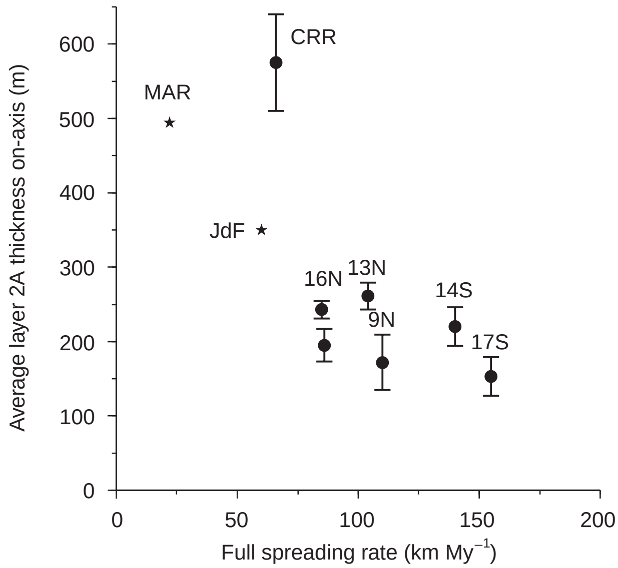

Figure 9 Thickness of the extrusive crust at the ridge axis versus spreading rate. For data obtained from detailed reflection surveys, average thickness is shown with black dots and standard deviations. East Pacific Rise data are labeled by survey location and are from (16N) Carbotte SM, Ponce-Correa G and Solomon A (2000) *Journal of Geophysical Research* 105: 2737–2759; (13N) Babcock JM, Harding AJ, Kent GM and Orcutt JA (1998) *Journal of Geophysical Reseach* 103: 30451–30467; (9N) Harding AJ, Kent GM and Orcutt JA (1993) *Journal of Geophysical Research* 98: 13925–13944; (14S) Kent GM, Harding AJ, Orcutt JA *et al.* (1994) *Journal of Geophysical Research* 99: 9097–9116; (17S) Carbotte SM, Mutter JC and Wu L (1997) *Journal of Geophysical Research* 102; 10165–10184. Costa Rica Rift (CRR) data are from Buck RW, Carbotte SM, Mutter CZ (1997) *Geology* 25: 935–938. Data from other ridges are derived from other seismic methods and are shown in stars. Data for the Mid-Atlantic Ridge (MAR) are from Hussenoeder SA, Detrick RS and Kent GM (1997), *EOS Transactions AGU*, F692.Data for Juan de Fuca Ridge (JdF) are from McDonald MA, Webb SC, Hildebrand JA, Cornuelle BD and Fox CG (1994) *Journal of Geophysical Research* 99: 4857–4873.

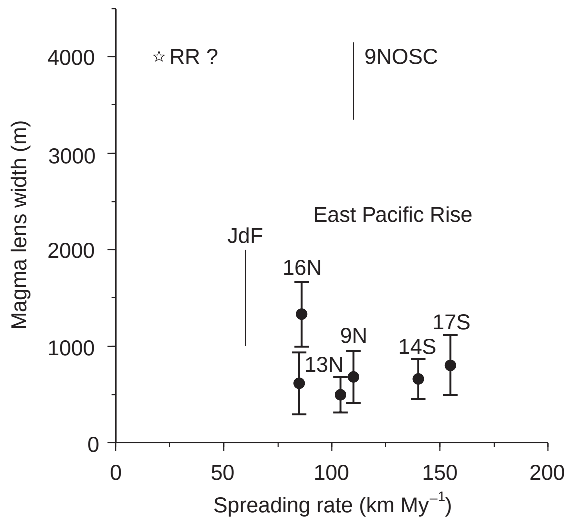

Figure 10 Width of magma lens reflections beneath ridges versus spreading rate. Average widths (black dots) and standard deviations are shown for regions where detailed reflection surveys have been carried out. East Pacific Rise data are labeled by survey location and are from (16N) Carbotte SM, Ponce-Correa G and Solomon A (2000) *Journal of Geophysical Research* 105: 2737–2759; (13N) Babcock JM, Harding AJ, Kent GM and Orcutt JA (1998) *Journal of Geophysical Research* 103: 30451–30467; (9N and 9NOSC) Kent GM, Harding AJ and Orcutt JA (1993) *Journal of Geophysical Research* 98: 13945–13970, 13971–13996 (the data labeled 9NOSC correspond with an unusually wide lens mapped near an overlapping spreading center); (14S) and (17S) from compilation of Hooft EE, Detrick RS and Kent GM (1997) *Journal of Geophysical Research* 102: 27319–27340. An estimate of lens width from wide-angle seismic data along the Reykjanes Ridge (RR) is shown in open star: Sinha MC, Navin DA, MacGregor LM *et al.* (1997) *Philosophical Transactions of the Royal Society of London* 355 (1723): 233–253. The Juan de Fuca (JdF) estimate is from Morton JL, Sleep NH, Normark WR and Tompkins DH (1987) *Journal of Geophysical Research* 92: 11315–11326.

What Controls the Depth at Which Magma Chambers Reside at Ridges?

Two main hypotheses have been put forward to explain the depths at which magma chambers are found at ridges. One hypothesis is based on the concept of a level of neutral buoyancy for magma within oceanic crust. This model predicts that magma will rise until it reaches a level where the density of the surrounding country rock equals that of the magma. However, at ridges, magma lenses lie at considerably greater depths than the neutral bouyancy level predicted for magma if its density is equivalent to that of lavas erupted onto the seafloor ($2700\,kg\,m^{-3}$). Either the average density of magma is greater, or mechanisms other than neutral buoyancy control magma lens depth.

The prevailing hypothesis is that magma chamber depth is controlled by spreading rate-dependent variations in the thermal structure of the ridge. In this model, a mechanical boundary such as a freezing horizon or the brittle–ductile transition acts to prevent magma from rising to its level of neutral buoyancy. Both of these horizons will be controlled by the thermal structure of the ridge axis. Compelling support for this hypothesis was provided by the inverse relation between spreading rate and depth to low-velocity zones at ridges apparent in early datasets. Numerical models of ridge thermal structure have been developed that predict systematic changes in the depth to the 1200°C isotherm (proxy for basaltic melts) with spreading rates that match the first-order depth trends for magma lenses. This model predicts a minor increase in lens depth within the fast-spreading rate range and an abrupt trans-

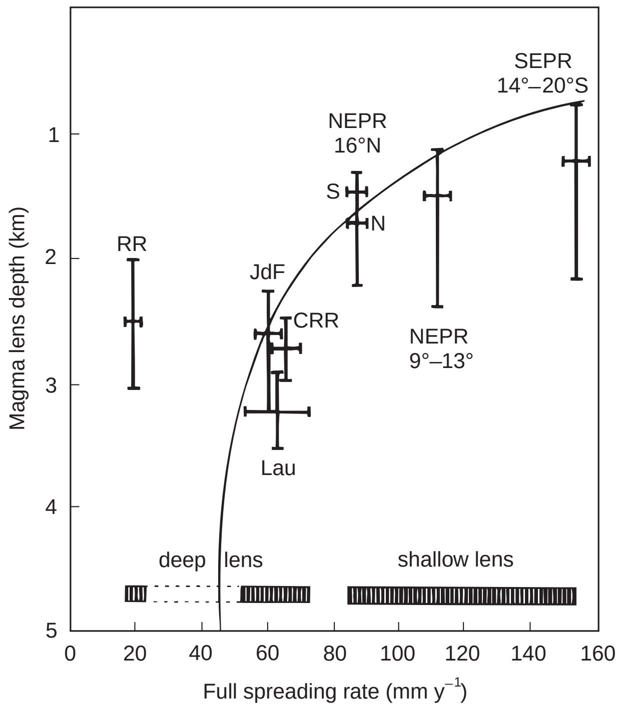

Figure 11 Average depth of magma lens reflections beneath ridges versus spreading rate. The curved line shows the depth to the 1200°C isotherm calculated from the ridge thermal model of Phipps Morgan J and Chen YJ (1993) *Journal of Geophysical Research* 98: 6283–6297. Data from different ridges are labeled Reykjanes Ridge (RR), Juan de Fuca Ridge (JdF), Costa Rica Rift (CRR), Lau Basin (Lau), northern and southern East Pacific Rise (NEPR and SEPR, respectively). (Reproduced from Carbotte SM, Mutter CZ, Mutter J and Ponce-Correa G (1998) *Geology* 26: 455–458.)

ition to deeper lenses at intermediate spreading rates, consistent with the present dataset (**Figure 11**).

However, there is no evidence for the systematic deepening of magma lenses within the intermediate to slow spreading range that is predicted by the numerical models (**Figure 11**). Instead, where magma lenses have been observed at these ridges, they cluster at 2.5–3 km depth. At these spreading rates there may be large local variations in the supply of magma from the mantle to the axis that control ridge thermal structure and give rise to shallower magma lenses than predicted from spreading rate alone. In light of recent observations, the role of neutral buoyancy may need to be reconsidered. If the magma lens is not a region of 100% melt, magma densities may be considerably higher than used in previous neutral buoyancy calculations. The magma lens may indeed lie at its correct neutrality depth, and the observed variation in magma lens depth may reflect changes in the density of the melt and crystal aggregate found within the lens.

See also

Mid-ocean Ridge Geochemistry and Petrology. Mid-ocean Ridge Tectonics, Volcanism and Geomorphology. Seamounts and Off-ridge Volcanism. Seismic Structure.

Further Reading

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MID-OCEAN RIDGE TECTONICS, VOLCANISM AND GEOMORPHOLOGY

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Introduction

The midocean ridge is the largest mountain chain and the most active system of volcanoes in the solar system. In plate tectonic theory, the ridge is located between plates of the earth's rigid outer shell that