Bending as a mechanism for triggering off-axis volcanism on the East Pacific Rise

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ABSTRACT

We propose that bending stresses play a key role in triggering volcanism on the flanks of the East Pacific Rise by simultaneously opening tensile cracks near the surface and increasing the pore pressure of melt bodies trapped in the lower crust. In addition, crack-tip stress intensities remain high during tensile opening, such that bending cracks propagate downward efficiently and thus have the potential to tap overpressured melt bodies trapped in the lower crust. We find that bending increases the vulnerability of the lithosphere to magmatic penetration out to distances of ~20 km from the rise axis, corresponding to the region of abyssal hill formation and isolated seamount generation.

Keywords: volcanism, bending, lithosphere, abyssal hills, seamounts.

INTRODUCTION

Abyssal hills and small isolated seamounts are predominant morphological features on the flanks of the East Pacific Rise. Sonar data from regions where detailed mapping has been conducted demonstrate that both of these features are distributed approximately symmetrically about the rise axis, and that they are formed within an interval extending from ~2 km to ~15 km from the rise axis (e.g., Bohnenstiehl and Carbotte, 2001; Macdonald, 1998; White et al., 1998). We propose that these similarities result from the fact that both abyssal hill growth and ridge flank seamount production are controlled by bending stresses from gravitational loading of cooling lithosphere.

The patterns of volcanism observed on Earth's surface are strongly influenced by the lithospheric stress state (e.g., Hieronymus and Bercovici, 2000; Vogt, 1974). Tensile stresses increase the vulnerability of the lithosphere to magmatic penetration, while compressive stresses have the opposite effect. The normal sense of displacement observed for abyssal hill faults provides evidence that they form under conditions of differential tension, indicating that the region of abyssal hill faulting is relatively vulnerable to magmatic penetration compared to lithosphere under hydrostatic or differential compression stress conditions.

Geochemical dating methods provide evidence that volcanic activity extends out to at least 10–20 km from the axis of the East Pacific Rise (Fig. 1). The U-series disequilibria data from lavas collected on either side of the East Pacific Rise from 9°30′–50′N exhibit a roughly symmetric pattern about the rise axis and provide evidence for volcanic activity extending to ~20 km off axis (Goldstein et al., 1994; Sims et al., 2003; Zou et al., 2002). These observations call into question the common assumption that crustal accretion at fast-spreading mid-ocean ridges is limited to a narrow zone extending a few kilometers from the rise axis. The apparent ridge normal symmetry of the U-series data also presents difficulties because the measurements cannot be explained by rise axis processes, as would commonly be invoked to explain most ridge symmetric features (e.g., magnetic stripes, propagator traces).

We use the "unbending" model of Buck (2001) along with analytical models of fracture mechanics to demonstrate that bending stresses from gravitational loading provide a means to trigger and localize off-axis volcanism, and to reconcile the geochemical and geophysical observations constraining faulting and volcanism on the flanks of fast-spreading ridges. We propose a geological model where melts migrate vertically in the mantle and then begin to crystallize as they enter a thermal boundary layer at the base of the lithosphere. Crystallization reduces the layer's permeability, which in turn impedes vertical melt migration. Melts accumulating beneath the permeability barrier will tend to move laterally in response to the lithospheric basal topology, which slopes up toward the rise axis (Sparks and Parmentier, 1991).

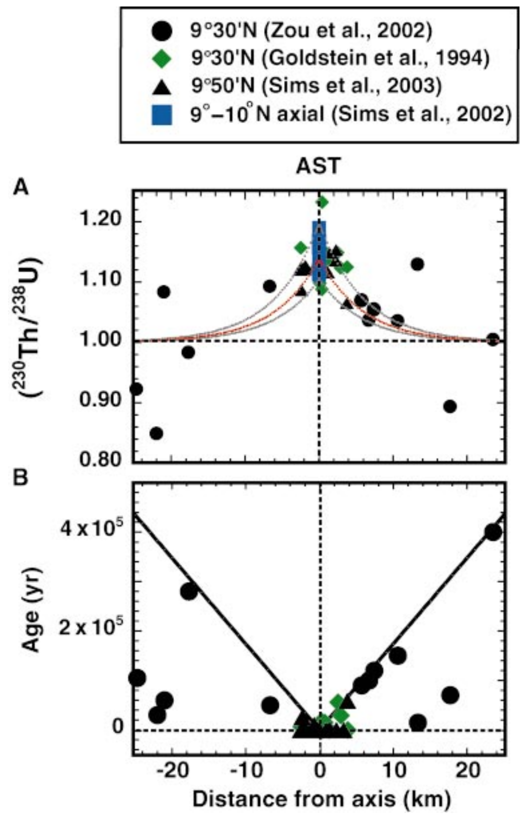

Figure 1. A: (^{230}Th/^{238}U) age vs. position relative to axial summit trough (AST) for lavas from 9°–10°N East Pacific Rise (EPR) (Goldstein et al., 1994; Sims et al., 2002, 2003; Zou et al., 2002). Also shown are decay curves for (^{230}Th/^{238}U) as function of distance from AST. Three decay curves are shown corresponding to initial "zero age" values from upper limit, lower limit, and average (red dots) for (^{230}Th/^{238}U) measured on rise axis (Sims et al., 2002) and assuming half-spreading rate of 55 km/m.y. (Carbotte and Macdonald, 1992). B: U-Th model ages versus position relative to AST for samples shown in A. Model ages are from Goldstein et al. (1994); Sims et al. (2003); and Zou et al. (2002). Model ages for samples with (^{230}Th/^{238}U) > 1 are calculated using average (^{230}Th/^{238}U) from 9°–10°N EPR axial lavas (Sims et al., 2002). Model ages for samples with (^{230}Th/^{238}U) < 1 are calculated using initial (^{230}Th/^{238}U) of 0.8. Model ages are compared to crustal age assuming half-spreading rate of 55 km/m.y. (solid lines).

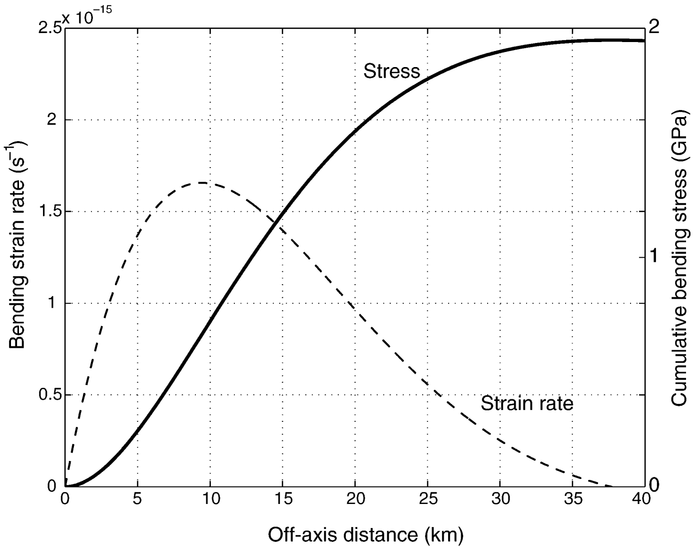

Figure 2. Bending stresses and strain rates at top of young, off-axis lithosphere assuming uniform lithosphere with mechanical properties shown in Table 1.

TABLE 1. LITHOSPHERIC MECHANICAL PROPERTIES USED FOR CALCULATIONS OF BENDING STRESS AND STRAIN

Parameter	Value
Plate deflection at rise axis, w_0	330 m
Lithospheric flexural parameter, α	12,000 m
Neutral depth of bending, h_n	4200 m
Young's modulus, E	90 GPa
Poisson's ratio, η	0.25
Plate half-spreading rate, U	50 mm/yr

The permeability barrier is leaky, however, such that some of the melts in the sublithospheric channel penetrate into the lithosphere on the rise flanks, and then erupt as seamounts when they are tapped by downward-propagating bending cracks.

VULNERABILITY OF OFF-AXIS LITHOSPHERE TO VOLCANISM

Off-axis volcanism can only occur if melt is present beneath the ridge flanks and if stress conditions in the off-axis lithosphere permit magmatic penetration. A few key geophysical measurements provide evidence for melt accumulations on the order of ~10 m thick at the base of the lithosphere at distances of 10–22 km from the rise axis (Crawford and Webb, 2002; Garmany, 1989). These observations, combined with the fact that the melting zone in the mantle under the East Pacific Rise is a few hundreds of kilometers wide (Toomey et al., 1998; Webb and Forsyth, 1998), and the fact that melt migration in the upper mantle is probably near vertical (assuming mantle viscosity is $<10^{21}$ Pa-s; Phipps Morgan, 1987; Spiegelman and McKenzie, 1987), lead to the conclusion that the young off-axis lithosphere is most likely underlain by significant quantities of melt. A variety of theoretical and observational evidence indicates that vertical melt ascent from the mantle is arrested near the base of the lithosphere, which leads to the formation of a decompacting melt-rich layer (Sparks and Parmentier, 1991). Lateral melt migration within this layer is a complex process that is not well understood, but lateral migration toward the rise axis is expected as the buoyant melts interact with the basal lithospheric topology, which slopes up toward the rise axis (e.g., Ghods and Arkani-Hamed, 2000; Sparks and Parmentier, 1991; Spiegelman, 1993a).

The mechanics of magma transport through the lithosphere depend on the thermal, chemical, mineralogical, textural, structural, and dynamic states of the rock volumes (Shaw, 1980). In general, it is not possible to constrain all of the relevant parameters in geological systems, and simplifying assumptions are required. From the perspective of fracture mechanics it follows that magma will be transported through the lithosphere when the melt reservoir achieves some critical fluid pressure, the value of which depends on the yield strength and stress state of the overlying rock column. Kelemen and Aharonov (1998) carefully considered this problem under conditions assumed appropriate for lower crustal melt bodies at fast-spreading ridges, and concluded that periodic formation of melt-filled fractures can result from magma accumulation beneath a permeability barrier in the lower crust, even under the conservative assumption of a lithostatic (i.e., unperturbed) stress field in the overlying elastic medium.

BENDING STRESSES AND FRACTURE MECHANICS

The possible role of plate bending stresses in the generation of abyssal hills at fast-spreading ridges was examined in detail by Buck (2001) and Shah and Buck (2003), who proposed that lithosphere at fast-spreading mid-ocean ridges is accreted with a concave-upward curvature, and that gravitational loading bends the lithosphere down as the plate cools and thickens. We use the conceptual framework and boundary conditions developed in those analyses to construct a simplified expression for bending stresses in a lithospheric plate with uniform mechanical properties. Bending strain, ε_{xx}, can be expressed as

$$\varepsilon_{xx}(x, z) = \Delta w''(x)h(z), \tag{1}$$

where $\Delta w''(x)$ is the change in curvature of the young plate, and $h(z)$ is the bending moment arm, defined as the vertical distance from the neutral depth of bending, h_n [i.e., $h(z) = h_n - z$, where z is positive downward from the seafloor]. The neutral depth of bending, h_n, is not the mid-plane in young oceanic crust because the yield strength envelope is not symmetric with depth (Hirth et al., 1998), but rather is ~4 km.

Using the incremental notation of Buck (2001), the change in plate curvature on the flanks of the East Pacific Rise can be expressed as

$$\begin{aligned}\Delta w''(x) &= w''(x) - w''(0)\\ &= \frac{2w_0}{\alpha^2}\left\{1 - e^{-x/\alpha}\left[\cos\left(\frac{x}{\alpha}\right) + \sin\left(\frac{x}{\alpha}\right)\right]\right\},\end{aligned} \tag{2}$$

where w_0 is the deflection at the ridge axis (typically ~330 m from observations), and α is the flexural wavelength parameter. The incremental unbending stress is therefore given by

$$\Delta\sigma_{xx}(x, z) = \Delta w''(x)h(z)\frac{E}{1 - \eta^2}, \tag{3}$$

where E is Young's modulus, and η is Poisson's ratio (Shah and Buck, 2003). In this model bending stresses are zero at the rise axis, and accumulate as the plate progressively moves off axis. If the lithosphere were infinitely strong the bending stress profile would resemble that shown in Figure 2 (using parameters shown in Table 1), reaching maximum tensile values of ~1.8 GPa at the top of the plate in the far field. Bending also generates compressive stresses in the lower portion of the plate (not shown) that are about twice as large as the tensile stresses (i.e., ~4 GPa) because the vertical asymmetry of the yield strength profile moves the neutral depth of bending toward the bottom of the plate.

Bending stresses will never reach the maximum values shown in Figure 2 because the plate will fail when the stresses approach the yield strength of young lithosphere, which is not very well constrained, but is probably <100 MPa (e.g., Hirth et al., 1998). Anelastic failure perturbs the stress field and also introduces heterogeneities that may exert a significant impact on future deformation (e.g., Behn et al., 2002;

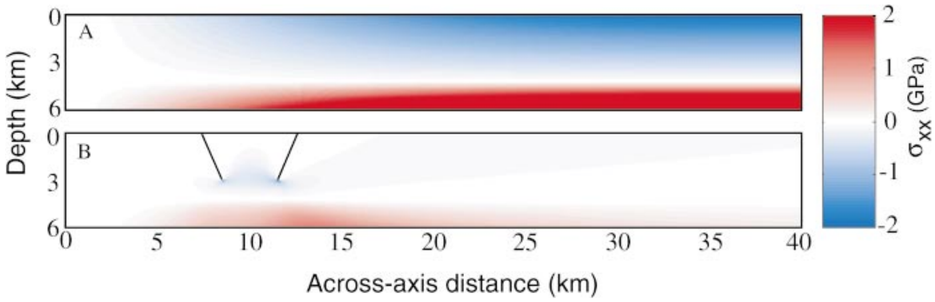

Figure 3. Effect of opening cracks on bending stress field. A: Horizontal cross section away from rise axis showing analytical solution for bending stresses (σ_{xx}) in uniform lithosphere. Negative stresses (blue) represent differential tension, positive stresses (red) represent differential compression. B: Same cross section as in A but with stress field recalculated to estimate effect of introducing two complementary mode I opening cracks (heavy black lines centered about 10 km off-axis). Calculation follows Scholz (1990, p. 9) and assumes perfectly sharp, planar cracks with no cohesion between crack walls.

Lavier et al., 2000). Incorporation of these effects requires implementation of numerical schemes that are beyond the scope of this paper. However, while the critical stress level for failure is unknown and variable, the space (or time) interval required to achieve critical levels in between faulting events is directly related to the strain rate, which can be estimated analytically by taking the derivative of equation 2 with respect to off-axis distance, and then multiplying by the nominal half-spreading rate, *U*,

$$\dot{\varepsilon} = \frac{\partial}{\partial x}\varepsilon_{xx}(x, z)U = \Delta w'''(x)h(z)U = \frac{4Uw_0}{\alpha^3}e^{-x/\alpha}\sin\left(\frac{x}{\alpha}\right)h(z). \quad (4)$$

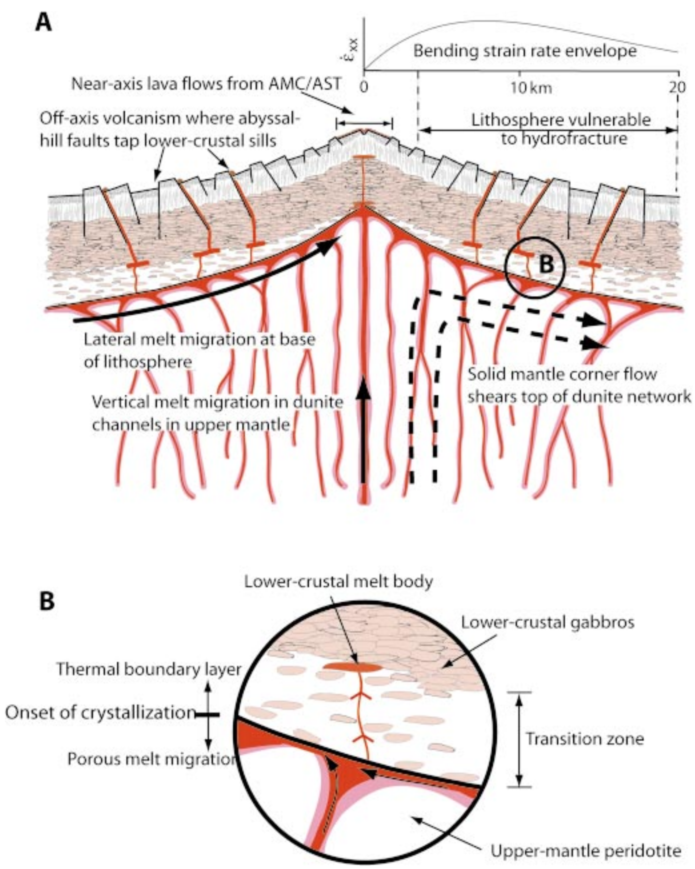

Figure 4. A: Conceptual illustration of upper mantle and lithospheric processes related to melt delivery and crustal accretion at fast-spreading mid-ocean ridge. B: Close-up view of crystallization front interface, where melts accumulate and decompact to form sublithospheric channel that enables lateral melt migration toward rise axis. Permeability barrier is leaky; some melts are able to continue migrating upward, and then either crystallize within thermal boundary layer or erupt as seamounts if they encounter favorable conditions for hydrofracture (Kelemen and Aharonov, 1998). AMC—axial magma chamber; AST—axial summit trough.

The bending strain rate is zero at the rise axis and in the far field (~35–40 km off axis), and achieves maximum values of $\sim 3 \times 10^{-15}$ s^{-1} at a distance of ~10 km from the rise axis (Fig. 2). The strain rate envelope suggests that bending faults will be active within a discrete interval starting a few kilometers from the rise axis (once critical stress levels are achieved) and extending out ~20 km, with negligible activity directly on the rise axis and in the far field. This is the same off-axis interval over which abyssal hill fault throws are observed to increase (e.g., Bohnenstiehl and Carbotte, 2001; Macdonald, 1998).

Bending is a fundamentally different mechanical process than tectonic stretching in that, to first order, bending generates mode I opening cracks while stretching generates mode II shear failure. Mode I cracks propagating downward into the crust provide an efficient means to reduce differential stresses in the lithosphere, but crack-tip stress intensities remain high during opening (e.g., Scholz, 1990). The effect of mode I cracks on the off-axis differential stress field is illustrated in Figure 3. A single pair of complementary mode I cracks penetrating to a depth of 3 km at a distance of ~10 km from the rise axis effectively reduces differential stresses throughout the lithosphere except for a small region immediately beneath the crack tips. The relatively high differential stresses that bending produces on the upper surface of the lithosphere effectively propagate downward with the opening cracks, such that conditions remain at or near failure until the cracks reach the neutral depth of bending.

The stress field shown in Figure 3B is an oversimplification in that downward-propagating mode I cracks will probably incorporate a component of mode II sliding as the overburden increases with depth, and in that other factors such as thermal contraction and plasticity must be considered in a complete treatment (e.g., Shah and Buck, 2003). The point we wish to make, however, is that bending and mode I fracturing are particularly effective mechanisms for triggering off-axis volcanism because stresses remain high at the propagating crack tips, and because lower crustal compression from bending will increase melt pressures in lower crustal sills or lenses, thereby moving these liquid or partially molten features closer to a critical state for hydrofracture. This implies that abyssal hill faulting may trigger off-axis volcanic eruptions in a region extending out to ~25 km from the rise axis, where bending stresses are likely to open downward-propagating fractures. A one-to-one correlation between the seafloor position of seamounts and abyssal hill faults is not always observed, nor is it necessary in our model since melts ascending along a fault plane may abandon the fault when they encounter fractured and permeable rock near the top of the lithosphere.

GEOLOGICAL MODEL FOR CRUSTAL ACCRETION AT FAST-SPREADING RIDGES

We present a conceptual model for melt migration and crustal accretion processes at fast-spreading ridges that is consistent with a wide range of theoretical and observational constraints (Fig. 4). Our model incorporates melt migration in the upper mantle via porous reactive flow channels (i.e., dunites). The intrinsic melt buoyancy results in near-vertical melt flow lines in the upper mantle, although the dunites are continuously deforming via corner flow under the ridge, which will tend to shear the tops of dunite channels beneath the ridge flanks. Vertical melt migration is eventually impeded by the effects of crystallization as melts pass through the ~1250 °C isotherm and enter a thermal boundary layer. Crystallization reduces permeability, generating a barrier (i.e., crystallization front) at the base of the lithosphere (Kelemen and Aharonov, 1998; Korenaga and Kelemen, 1997; Spiegelman, 1993b). Melts accumulate beneath the permeability barrier, where melt buoyancy drives lateral migration in response to the basal topography of the interface, which slopes up toward the rise axis.

Melts accumulating in the sublithospheric channel have three possible fates: (1) they may migrate all the way to the rise axis and become emplaced as sills or eruptions through the central magmatic system, (2) they may erupt on the rise flanks if they experience conditions for lithospheric penetration on their way to the rise axis, or (3) they may crystallize in the sublithospheric channel and underplate the crust. The observation of anomalously young lavas and seamounts on the ridge flanks demonstrates that the permeability barrier at the base of the lithosphere is leaky and that some melts are able to penetrate through the lower lithosphere and erupt onto the seafloor. The mechanisms that enable vertical melt migration through the crystallization front and through a region of presumed differential compression are not well understood (Fig. 4B), but they must reflect the combined effects of the melt ascent rate, crystallization rate, decompaction, and the rheology of the thermal boundary layer.

We note that our model only applies to fast-spreading ridges with axial high morphologies. The bending stress model we invoke is specific to fast-spreading, axial high environments, and cannot be used to describe stress patterns at slow-spreading ridges with axial valley morphologies where other factors such as lithospheric stretching (Buck and Poliakov, 1998) and long-term magmatic cycles (e.g., Kappel and Ryan, 1986; Klitgord and Mudie, 1974) are likely important.

REFERENCES CITED

Behn, M.D., Lin, J., and Zuber, M.T., 2002, A continuum mechanics model for normal faulting using a strain-rate softening rheology: Implications for thermal and rheological controls on continental and oceanic rifting: Earth and Planetary Science Letters, v. 202, p. 725–740.

Bohnenstiehl, D.R., and Carbotte, S.M., 2001, Faulting patterns near 19 degrees 30′S on the East Pacific Rise; fault formation and growth at a superfast spreading center: Geochemistry, Geophysics, Geosystems–G^3, v. 2, p. 31, doi: 10.1029/2001GC000156.

Buck, W.R., 2001, Accretional curvature of lithosphere at magmatic spreading centers and the flexural support of axial highs: Journal of Geophysical Research, ser. B, Solid Earth and Planets, v. 106, p. 3953–3960.

Buck, W.R., and Poliakov, A.N.B., 1998, Abyssal hills formed by stretching oceanic lithosphere: Nature (London), v. 392, p. 272–275.

Carbotte, S., and Macdonald, K.C., 1992, East Pacific Rise 8 degrees–10 degrees 30′N; evolution of ridge segments and discontinuities from SeaMarc II and three-dimensional magnetic studies: Journal of Geophysical Research, ser. B, Solid Earth and Planets, v. 97, p. 6959–6982.

Crawford, W.C., and Webb, S.C., 2002, Variations in the distribution of magma in the lower crust and at the Moho beneath the East Pacific Rise at 9°–10°N: Earth and Planetary Science Letters, v. 203, p. 117–130.

Garmany, J., 1989, Accumulations of melt at the base of young oceanic crust: Nature (London), v. 340, p. 628–632.

Ghods, A., and Arkani-Hamed, J., 2000, Melt migration beneath mid-ocean ridges: Geophysical Journal International, v. 140, p. 687–697.

Goldstein, S.J., Perfit, M.R., Batiza, R., Fornari, D.J., and Murrell, M.T., 1994, Off-axis volcanism at the East Pacific Rise detected by uranium-series dating of basalts: Nature (London), v. 367, p. 157–159.

Hieronymus, C.F., and Bercovici, D., 2000, Non-hotspot formation of volcanic chains: Control of tectonic and flexural stress on magma transport: Earth and Planetary Science Letters, v. 181, p. 539–554.

Hirth, G.J., Escartin, J., and Lin, J., 1998, The rheology of the lower oceanic crust: Implications for lithospheric deformation at mid-ocean ridges, *in* Buck, W.R., et al., eds., Faulting and magmatism at mid-ocean ridges: American Geophysical Union Geophysical Monograph 106, p. 291–303.

Kappel, E.S., and Ryan, W.B.F., 1986, Volcanic episodicity and a non-steady state rift valley along Northeast Pacific spreading centers; evidence from Sea MARC I: Journal of Geophysical Research, ser. B, Solid Earth and Planets, v. 91, p. 13,925–13,940.

Kelemen, P.B., and Aharonov, E., 1998, Periodic formation of magma fractures and generation of layered gabbros in the lower crust beneath oceanic spreading ridges, *in* Buck, W.R., et al., eds., Faulting and magmatism at mid-ocean ridges: American Geophysical Union Geophysical Monograph 106, p. 267–289.

Klitgord, K.D., and Mudie, J.D., 1974, The Galapagos spreading center: A near-bottom geophysical survey: Royal Astronomical Society Geophysical Journal, v. 38, p. 563–586.

Korenaga, J., and Kelemen, P., 1997, The origin of gabbro sills in the Moho transition zone of the Oman ophiolite: Implications for magma transport in the lower crust: Journal of Geophysical Research, v. 102, p. 27,729–27,749.

Lavier, L.L., Buck, W.R., and Poliakov, A.N.B., 2000, Factors controlling normal fault offset in an ideal brittle layer: Journal of Geophysical Research, v. 105, p. 23,431–23,442.

Macdonald, K.C., 1998, Linkages between faulting, volcanism, hydrothermal activity and segmentation on fast spreading centers, *in* Buck, W.R., et al., eds., Faulting and magmatism at mid-ocean ridges: American Geophysical Union Geophysical Monograph 106, p. 27–58.

Phipps Morgan, J., 1987, Melt migration beneath mid-ocean spreading centers: Geophysical Research Letters, v. 14, p. 1238–1241.

Scholz, C.H., 1990, The mechanics of earthquakes and faulting: New York, Cambridge University Press, 439 p.

Shah, A.K., and Buck, W.R., 2003, Plate bending stresses at axial highs, and implications for faulting behavior: Earth and Planetary Science Letters, v. 211, p. 343–356.

Shaw, H.R., 1980, The fracture mechanisms of magma transport from the mantle to the surface, *in* Hargraves, R.B., ed., Physics of magmatic processes: Princeton, New Jersey, Princeton University Press, p. 201–264.

Sims, K.W.W., Goldstein, S.J., Blichert-Toft, J., Perfit, M.R., Kelemen, P., Fornari, D., Michael, P.J., Murrell, M.T., Hart, S.R., DePaolo, D.J., Layne, G.D., Ball, L.A., Jull, M., and Bender, J.F., 2002, Chemical and isotopic constraints on the generation and transport of magma beneath the East Pacific Rise: Geochimica et Cosmochimica Acta, v. 66, p. 3481–3504.

Sims, K.W.W., Blichert-Toft, J., Fornari, D.J., Perfit, M.R., Goldstein, S.J., Johnson, P., DePaolo, D.J., Hart, S.R., Murrell, M.T., Michael, P.J., Layne, G.D., and Ball, L.A., 2003, Aberrant youth: Chemical and isotopic constraints on the origin of off-axis lavas from the East Pacific Rise, 9°–10°N: Geochemistry, Geophysics, Geosystems–G^3, v. 4, doi: 10.1029/2003GC000443.

Sparks, D.W., and Parmentier, E.M., 1991, Melt extraction from the mantle beneath spreading centers: Earth and Planetary Science Letters, v. 105, p. 368–377.

Spiegelman, M., 1993a, Flow in deformable porous media, Part 1—Simple analysis: Journal of Fluid Mechanics, v. 247, p. 17–38.

Spiegelman, M., 1993b, Physics of melt extraction: Theory, implications, and applications: Royal Society of London Philosophical Transactions, v. 342, p. 23–41.

Spiegelman, M., and McKenzie, D., 1987, Simple 2-D models for melt extraction at mid-ocean ridges and island arcs: Earth and Planetary Science Letters, v. 83, p. 137–152.

Toomey, D.R., Wilcock, W.S.D., Solomon, S.C., Hammond, W.C., and Orcutt, J.A., 1998, Mantle seismic structure beneath the MELT region of the East Pacific Rise from P and S wave tomography: Science, v. 280, p. 1224–1227.

Vogt, P.R., 1974, Volcano spacing, fractures, and thickness of the lithosphere: Earth and Planetary Science Letters, v. 21, p. 235–252.

Webb, S.C., and Forsyth, D.W., 1998, Structure of the upper mantle under the EPR from waveform inversion of regional events: Science, v. 280, p. 1227–1229.

White, S.M., MacDonald, K.C., Scheirer, D.S., and Cormier, M.-H., 1998, Distribution of isolated volcanoes on the flanks of the East Pacific Rise, 15.3°S–20°S: Journal of Geophysical Research, v. 103, p. 30,371–30,384.

Zou, H., Zindler, A., and Niu, Y., 2002, Constraints on melt movement beneath the East Pacific Rise from ^{230}Th-^{238}U disequilibrium: Science, v. 295, p. 107–110.

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