Plate-kinematic explanation for mid-oceanic-ridge depth discontinuities

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ABSTRACT

The global mid-ocean-ridge system is characterized by several regional-scale depth and geochemical anomalies. A prominent depth discontinuity between the East Pacific Rise and the Pacific-Antarctic Rise also coincides with a geochemical discontinuity that has been suggested by previous workers to indicate a boundary between distinct mantle-upwelling domains with separate convective histories. We propose a plate-kinematic origin for this discontinuity in which different rates of asthenospheric sequestration and spreading-center migration result in different equilibrium depths for different spreading centers. Absolute plate motions determine both the rate at which asthenosphere is converted to lithosphere (i.e., the sequestration rate) and the rate at which the spreading center moves relative to hotspots (i.e., the migration rate). If limits on the consumption (i.e., the sequestration/migration ratio) of asthenosphere by spreading centers are determined by the thickness and flux of asthenosphere, then the fast-spreading, slowly migrating East Pacific Rise should have a deeper equilibrium depth than the slower-spreading, rapidly migrating Pacific-Antarctic Rise. Sustained, localized asthenospheric consumption by the East Pacific Rise contrasts with the lower consumption and abundance of asthenospheric flux from hotspots near the Pacific-Antarctic Rise. A similar mechanism could explain the discontinuity between the localized depth anomaly on the Southwest Indian Ridge near the Bouvet hotspot and the much broader, but deeper, anomaly on the adjacent Mid-Atlantic Ridge, where asthenosphere is being transformed to lithosphere at more than three times the rate of the Southwest Indian or American-Antarctic Ridge. Geochemical evidence is consistent with the notion of deeper, more extensive melting under both of the spreading centers with anomalously high sequestration/migration ratios.

Keywords: mid-oceanic ridge, bathymetry, asthenosphere, hotspot.

INTRODUCTION

Coinciding sharp changes in the isotopic composition of mid-oceanic-ridge basalts (MORBs) and spreading-center depths between the East Pacific Rise and Pacific-Antarctic Rise present a paradox in which the sharp nature of this transition suggests a superficial origin, whereas the nearby abundance of hotspots in the superswell region and Darwin Rise suggests a deep origin for the geochemical and thermal division of the Pacific mantle (Vlastelic et al., 1999). To resolve this paradox, Vlastelic et al. (1999) inferred that the depth and isotopic discontinuities reflect a large-scale change of temperature and composition of the Pacific mantle. They suggested that lower-mantle upwelling at 25°S on the East Pacific Rise separates two deep-mantle domains with separate convective histories that have produced different chemical and thermal structures of the MORB mantle source. Here we propose a simple kinematic explanation for this paradox and discuss the relationship between plate kinematics and asthenospheric consumption at mid-ocean ridges. We suggest that the depth and geochemical discontinuities between the East Pacific Rise and Pacific-Antarctic Rise may have a plate-kinematic origin related to differences in migration and spreading rates of the two spreading centers. We also present evidence that a similar process may explain prominent depth and geochemical discontinuities at spreading centers in the South Atlantic.

The rate of plate divergence (spreading rate) controls the conversion of asthenosphere into lithospheric plates by melt extraction and accretion to the plates. Absolute plate motions that result in spreading also cause the spreading center to move relative to the ‘‘fixed’’ hotspot frame of reference. If the absolute velocity vectors of the diverging plates are not exactly equal and opposite, then the spreading center must migrate with a rate and direction determined by the average of the bounding plate-motion vectors (Stein et al., 1977). Spreading centers can therefore be considered migrating sinks that sequester asthenosphere by converting it to lithosphere. A slowly migrating, fast-spreading ridge sequesters a large volume of asthenosphere relative to the size of the source region from which the asthenosphere is removed. The effect of such a ridge on a region of the underlying mantle must be different from what would be expected when a spreading center sequesters less asthenosphere (spreads more slowly) or migrates more rapidly. The velocity (rate and direction) of spreading-center migration and the rate of asthenospheric extraction (spreading rate) should therefore influence the effect of the spreading center on the underlying mantle.

In a migrating-sink hypothesis, kinematically modulated upwelling should influence the flow of asthenosphere as well as the location and extent of melting beneath the spreading center. Plate-kinematic effects on melting were considered by Davis and Karsten (1986) to explain seamount distributions, and by Schouten et al. (1987) to explain propagating offsets at spreading centers. Predicted consequences include deeper and more extensive melting at slowly migrating spreading centers (Schouten et al., 1987) and differential fractionation and high seamount abundance on leading plates of rapidly migrating ridges (Davis and Karsten, 1986).

We propose that kinematic differences in the rate of asthenospheric consumption (sequestration rate/migration rate) could influence the equilibrium depth of mid-ocean ridges if asthenosphere cannot be supplied to the spreading center at the rate at which it is being consumed to make plates. If the dynamics of asthenospheric flow in the vicinity of hotspots (e.g., Morgan, 1971; Vogt, 1976; Schilling, 1991; Phipps Morgan et al., 1995) can be extended to a wider range of spreading centers, then the notion of restricted asthenospheric flow implies that the consumption rate must be balanced by the supply rate. The association of hotspots with excess asthenospheric flux from plumes is believed to influence both the depth of the surrounding spreading centers and the composition of the lavas erupted there (e.g., Schilling, 1985). Here we consider the complementary idea of limited flux of a finite-thickness asthenosphere.

PLATE KINEMATICS

Current plate kinematics result in nearly proportional rates of lithospheric formation and spreading-center migration for most of the global mid-ocean-ridge system (Fig. 1). The consequences of plate kinematics on mantle dynamics should be most apparent at triple junctions with kinematic discontinuities. Of the four ridge-dominated triple junctions on

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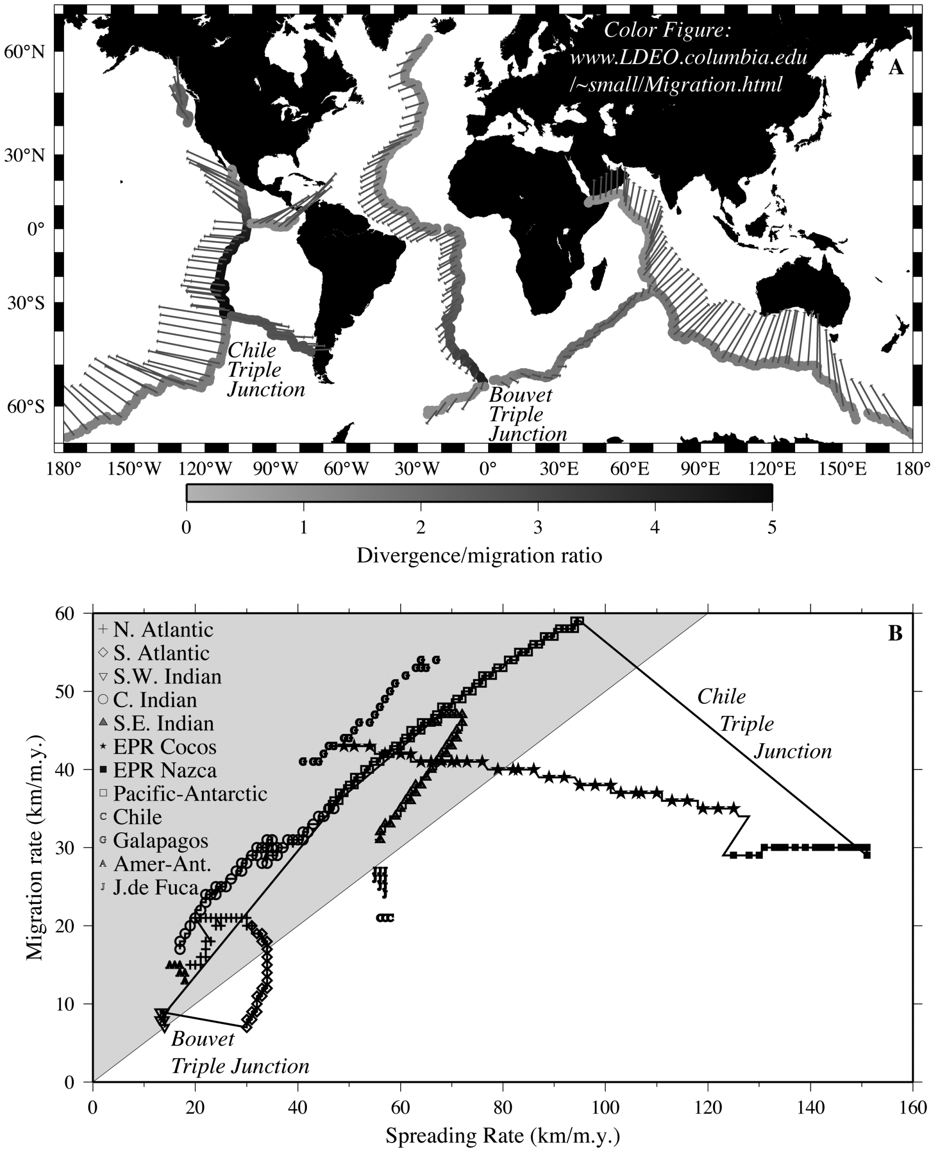

Figure 1. Spreading-center migration and asthenospheric sequestration rates resulting from current plate motions. A: Migration vectors are derived from divergent absolute-plate-velocity vectors (from HS2-Nuvel 1, Gripp and Gordon, 1990) as described by Stein et al. (1977). Consumption ratio of spreading (i.e., divergence) rate (from Nuvel 1A, DeMets et al., 1994) to migration rate is indicated by shade of plate boundary. Note prevalence of low ratios and prominent discontinuities at triple junctions. B: Kinematic configuration of primary mid-ocean-ridge system. Lines connecting different symbols show kinematic discontinuities at triple junctions. Note that most spreading centers migrate slightly faster than they accrete lithosphere to bounding plates (gray). Prominent exceptions are southern East Pacific Rise (EPR) and southern Mid-Atlantic Ridge. These spreading centers are also sites of geochemical and depth discontinuities.

the primary ridge system, the largest kinematic discontinuities occur at the Bouvet and Chile triple junctions (Fig. 1), sites of prominent bathymetric and geochemical discontinuities. On the basis of plate kinematics, we expect the southern Mid-Atlantic Ridge and southern East Pacific Rise to be consuming more asthenosphere from their source regions than the adjacent spreading centers with lower divergence/migration ratios.

The kinematic discontinuity between the southern East Pacific Rise and Pacific-Antarctic Rise at the Chile triple junction coincides closely with a prominent depth discontinuity (Small and Danyushevsky, 1997) and a geochemical and isotopic discontinuity (Vlastelic et al., 1999). The southern East Pacific Rise creates lithosphere at a rate of 151 km/m.y. while migrating at 29 km/m.y., and the Pacific-Antarctic Rise creates lithosphere at 95 km/m.y. while migrating at 59 km/m.y. The southern East Pacific Rise is therefore consuming asthenosphere from its mantle source region at more than three times (151/29 vs. 95/59) the rate of the Pacific-Antarctic Rise. Figure 2 shows that the southern East Pacific Rise is consistently ~400 m deeper than the Pacific-Antarctic Rise. The depth discontinuity does not occur precisely at the triple junction, but near the Easter hotspot, 700 km to the north. The shallow depth of the southern East Pacific Rise near the Easter hotspot suggests that the hotspot is supplying the excess asthenosphere necessary to compensate for the high kinematic consumption. This is also suggested by geochemical evidence (Kingsley and Schilling, 1998). In the scenario we propose, the excess plume flux from the Easter hotspot is responsible for the shallower ridge depths between the Easter hotspot and the Chile triple junction.

The existence of a regional depth discontinuity on the southern East Pacific Rise suggests that there are either large-scale temperature differences in the underlying mantle (and thus different crustal thicknesses) or that there is a difference in the dynamic forces controlling the equilibrium depth of the ridge. If the abrupt depth discontinuity were the consequence of a sharp thermal gradient, we would expect to see corresponding differences in the chemistry of lavas from the southern East Pacific Rise and Pacific-Antarctic Rise caused by lower degrees of melting under the deeper southern East Pacific Rise. Work on the southern East Pacific Rise (MELT Seismic Team, 1998), in addition to Figure 2C, suggests that this is not the case.

We propose that the depth discontinuity along the eastern Pacific plate boundary may be a consequence of differences in the balance between asthenospheric consumption and supply. The high sequestration rate of the slowly migrating southern East Pacific Rise must require greater flow of asthenosphere to the spreading center than the lower sequestration rate of the more rapidly migrating Pacific-Antarctic Rise. If the rate at which a finite thickness of asthenosphere can flow to the ridge is either limited by mantle viscosity or supplemented by the proximity of plume sources, then kinematic differences in consumption rate should be reflected in different equilibrium depths for the spreading centers. The volume of asthenosphere consumed also depends on asthenospheric rheology and melt extraction. Thermal accretion of asthenosphere is not spreading-rate dependent, but the instantaneous accretion processes at the ridge crest are proportional to spreading rate. The volume of melt extracted to form crust provides a minimum estimate of asthenospheric sequestration. Rheological hardening from melt-induced dehydration (Hirth and Kohlstedt, 1996) may result in much greater instantaneous (<2 m.y.) accretion of asthenosphere at spreading centers. Viscous drag on the base of the plate could also advect as-

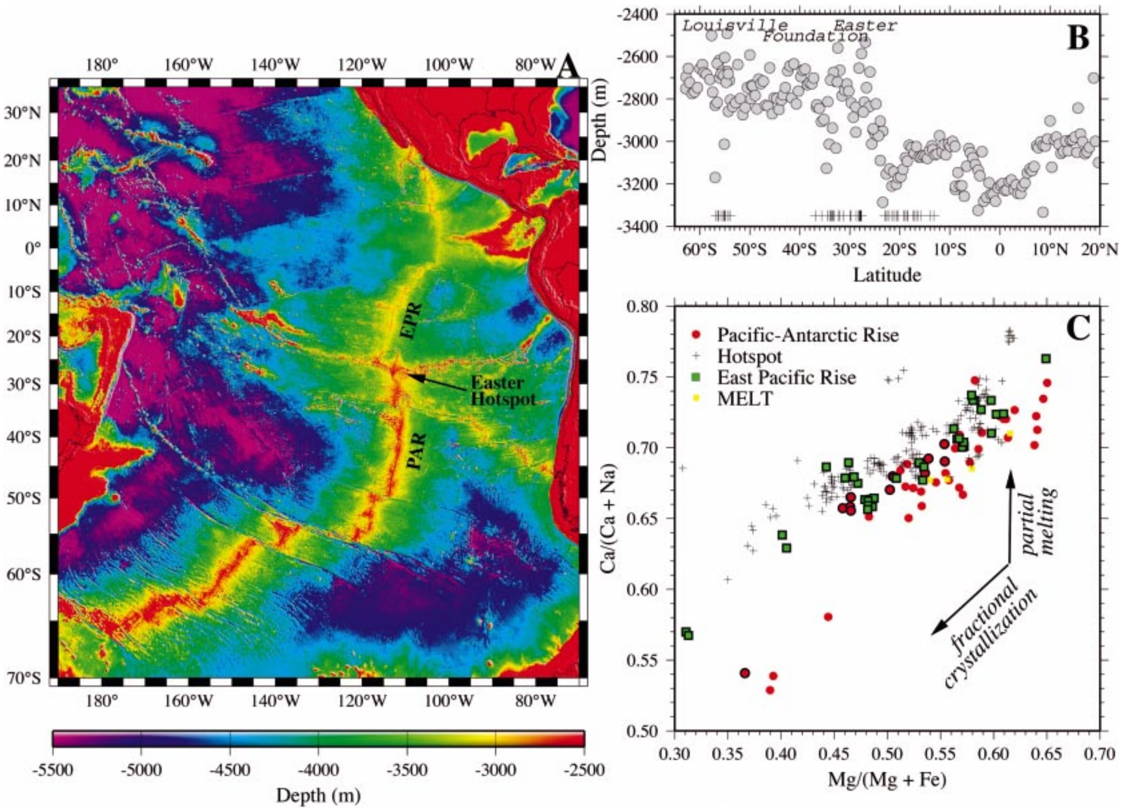

Figure 2. Depth and geochemical discontinuities on eastern Pacific spreading centers. (A) Bathymetry and (B) median depth within 50 km of spreading center clearly show that southern East Pacific Rise (EPR) is consistently ~400 m deeper than Pacific-Antarctic Rise (PAR). Crosses in B show locations of lava samples in C. C: Higher Ca/Na ratios of ridge-crest southern East Pacific Rise pillow-rim glasses compared to glasses from Pacific-Antarctic Rise suggest higher degrees of melting and deeper-mantle upwelling beneath southern East Pacific Rise. Note that Ca/(Ca + Na) vs. Mg/(Mg + Fe) systematics of glass compositions proposed by Dick et al. (1984) and Schouten et al. (1987) are analogous to using Na8 (Na_2O content normalized to 8 wt% MgO) as indicator of extent of mantle melting (Langmuir et al., 1992). Compositions of pillow-rim glasses are from Smithsonian catalogue of mid-oceanic-ridge basalt glasses (Bach et al., 1994; Vlastelic et al., 2000; Hekinian et al., 1997; Macdougall and Lugmair, 1986).

thenosphere away from the plate boundary in proportion to spreading rate.

A further implication of the observed kinematic effects is that mantle under the southern East Pacific Rise should be ascending from greater depths, resulting in higher average degrees of melting compared to the Pacific-Antarctic Rise. The alternative, i.e., asthenosphere supplied only by shallow flow to the spreading center from a broad region surrounding the ridge, is dynamically problematic because it would maximize viscous shear at the base of the plates moving away from the spreading center (Stein et al., 1977). Geochemical evidence is consistent with the notion of deeper, more extensive melting under the southern East Pacific Rise compared to the Pacific-Antarctic Rise. The compositions of pillow-rim glasses from the southern East Pacific Rise show consistently higher Ca/Na ratios compared with Pacific-Antarctic Rise glasses at a given Mg/Fe ratio (Fig. 2). As discussed by Schouten et al. (1987), higher Ca/Na ratios are a likely indicator of higher degrees of mantle melting under the ridge. An exception to this pattern is seen in some samples obtained from the MELT study area at 19.2°–18.4°S that plot in the field of the Pacific-Antarctic Rise. The observed differences in glass compositions between the southern East Pacific Rise and Pacific-Antarctic Rise are generally consistent with deeper-mantle upwelling beneath the southern East Pacific Rise and do not support the hypothesis that the southern East Pacific Rise is deeper because the underlying mantle is cooler.

SLOW SPREADING RIDGES

The spreading centers surrounding the Bouvet triple junction are also characterized by kinematic discontinuities, depth anomalies, and geochemical transitions (Fig. 3). Kinematic differences in asthenospheric consumption were originally proposed by Schouten et al. (1987) to explain geochemical patterns observed here. If asthenospheric supply rate is considered, the kinematic discontinuities may also explain the disparity between the prominent depth anomaly observed on the southern Mid-Atlantic Ridge, the much smaller depth anomaly on the Southwest Indian Ridge, and absence of any depth anomaly on the American-Antarctic Ridge (Small, 1995). Both the southern Mid-Atlantic Ridge and Southwest Indian Ridge are influenced by hotspots, but the greater divergence/migration ratio of the southern Mid-Atlantic Ridge (30/7 = 4.3) may result in deeper, more extensive mantle tapping than the lower ratios on the Southwest Indian Ridge (13/9 = 1.4) and American-Antarctic Ridge (18/14 = 1.3). The higher spreading rate on the southern Mid-Atlantic Ridge may consume excess plume flux from the Shona hotspot and produce regionally thicker crust, whereas the lower consumption on the Southwest Indian Ridge may result in a prominent but more localized depth anomaly.

The Bouvet triple junction is also the site of the geochemical discontinuity discussed by Schouten et al. (1987). Similar to what is observed at the Chile triple junction, lavas from the southern Mid-Atlantic Ridge are characterized by higher Ca/Na ratios, indicating higher degrees of mantle melting and likely upwelling from deeper levels (Roex, 1987; Schouten et al., 1987). Extending the idea originally proposed by Schouten et al. (1987),

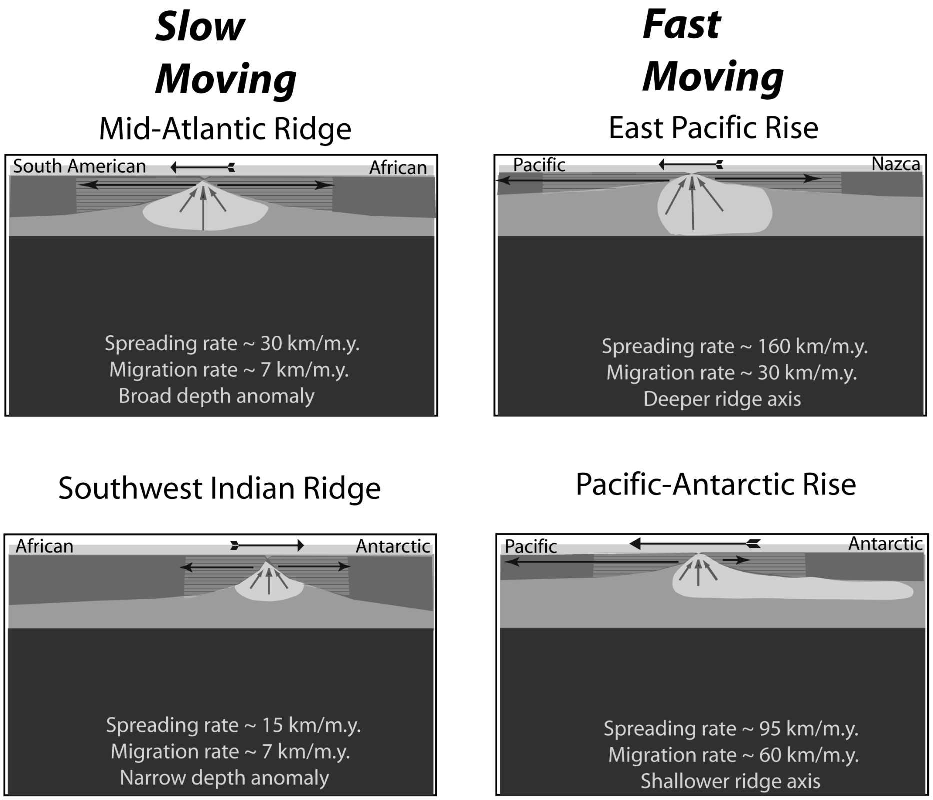

Figure 3. Differences in kinematic consumption for eastern Pacific and southern Atlantic spreading centers. Lighter gray regions of asthenosphere indicate region tapped to make new lithosphere (hachured). Spatial and temporal scales are increased on slow moving ridges for clarity. Southern East Pacific Rise has very high divergence/migration ratio, so it sequesters larger volume of asthenosphere from narrower lateral region than Pacific-Antarctic Rise. Southern East Pacific Rise is deeper because it sequesters more material from smaller lateral region faster than can be replenished by asthenospheric return flow. Both southern Mid-Atlantic Ridge and Southwest Indian Ridge are supplemented by plumes, but southern Mid-Atlantic Ridge is consuming asthenosphere at twice rate of Southwest Indian Ridge. Crustal thickening on southern Mid-Atlantic Ridge would influence twice lithospheric area it would on Southwest Indian Ridge, resulting in broad, distributed depth anomaly compared to slower-spreading ridge.

to incorporate kinematic dispersal of plume flux would explain the contrast between the areally extensive depth anomaly surrounding the Shona segment and the localized depth anomaly on the Bouvet segment.

If the idea of restricted asthenospheric flow proposed herein is correct, the Shona hotspot should provide an abundance of asthenosphere for the slow-spreading southern Mid-Atlantic Ridge despite its slow migration. The Easter hotspot similarly feeds the southernmost East Pacific Rise, but the high consumption of the East Pacific Rise north of the Easter hotspot may exceed the northward supply of asthenosphere, thus drawing down the equilibrium depth of the southern East Pacific Rise relative to the Pacific-Antarctic Rise.

The mechanisms proposed here assume the existence of a finite-thickness asthenosphere (e.g., Morgan, 1971). Current models of ridge-hotspot interaction also implicitly assume constraints on the supply of asthenosphere to spreading centers to explain the influence of plume flux on seafloor depth. The notion of different equilibrium depths and thermal structures could be tested with seismic measurements of crustal thickness and mantle velocity structure spanning the discontinuities.

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Notes
