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Observations of ridge-hotspot interactions in the Southern Ocean

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Abstract. The evolution of ridge-hotspot systems is not well understood. In this investigation, satellite-derived marine gravity data are used in conjunction with underway bathymetric and magnetic anomaly profiles to investigate the nature of ridge-hotspot interaction at four sparsely explored systems in the Southern Ocean. These systems illustrate three different stages of ridge-hotspot interaction in which a migrating spreading center approaches a hotspot (Pacific-Antarctic/Louisville), passes over or is captured by the hotspot (Mid-Atlantic/Shona-Discovery), and ultimately migrates away from the hotspot (Southeast Indian/Kerguelen). All of these systems show some evidence of discrete ridge jumps in the direction of the hotspot as the spreading center attempts to relocate toward the hotspot by asymmetric spreading. Interestingly, these ridge jumps show no evidence of propagating offsets as have been seen on many other ridge-hotspot systems. A simple model predicts that typical plume excess temperatures can weaken the lithosphere sufficiently to promote asymmetric spreading and possibly allow a discrete ridge jump. The presence of previously uncharted, obliquely oriented aseismic ridges and gravity lineations between the ridge and the hotspot supports the notion of asthenospheric flux from the plume to the spreading center both before and after the time when the hotspot is ridge centered. The azimuths of the aseismic ridges cannot be explained by plate kinematics alone; they consistently extend from the ends toward the centers of the adjacent spreading segments suggesting some interaction between plume derived asthenospheric flux and local lithospheric structure. The features discussed here also indicate that the transfer of asthenospheric material from the plume to the spreading center is influenced by the local plate boundary configuration and interaction with transform offsets.

Introduction

Individually, hotspots and mid-ocean ridges are two of the most extensively studied features in the world's ocean basins, yet the nature of their interaction is not well understood. The notion of asthenosperic flow from ridge centered hotspots has been discussed in some detail [e.g., *Vogt*, 1971; *Schilling*, 1973, 1985; *Vogt and Johnson*, 1972, 1975; *Sleep*, 1990], particularly in the case of Iceland. *Morgan* [1978] proposed the possibility of asthenospheric flux between off axis hotspots and nearby ridges to explain seamounts near the Galapagos, Reunion and Amsterdam-St. Paul hotspots. *Schilling* [1985, 1991] has addressed the question of hotspot-migrating ridge interaction in more detail by compiling available geochemical and geophysical data for a number of these systems and investigating mechanisms by which asthenosphere is transferred from the hotspot to the ridge. The majority of hotspot-migrating ridge systems involve a ridge which is migrating away from a nearby hotspot, and it is this type of system that Schilling addresses in his analysis; the less common case of a ridge migrating toward a hotspot has not been studied in as much detail. *Vink* [1984] discusses the formation of the Greenland-Faeroe and Voring Plateaux as a consequence of the interaction between the Iceland hotspot and the nearby spreading center. *Sleep* [1992] also briefly discusses interaction between the New England/Great Meteor hotspot and the Mid-Atlantic Ridge and proposes an entrainment scenario which is expanded upon here. The purpose of this study is to investigate additional ridge-hotspot systems in relatively unexplored regions of the southern ocean and to refine existing scenarios for ridge-hotspot interactions.

The remoteness of the ridges and hotspots in the Southern Ocean has resulted in much less extensive exploration of these features than their counterparts in the northern oceans and therefore hindered our understanding of these systems. The recent availability of medium resolution ($\lambda > 35$ km) gravity maps derived from satellite altimeter measurements has resulted in unprecedented views of the large-scale structure of these remote ocean basins [*Sandwell et al.*, 1995]. The fact that the short-wavelength marine gravity field is dominated by the effects of seafloor topography allows features such as fracture zones, ridges, and seamounts to be charted in areas where no underway data are available. In this study, satellite gravity data are combined with available underway bathymetry and magnetic anomaly data to investigate the nature of ridge-hotspot interactions in relatively unexplored regions of the world's oceans.

This study investigates four poorly understood ridge-hotspot systems in the southern oceans. These systems are characterized by a relative scarcity of underway geophysical data but are clearly depicted in satellite gravity maps. Because these systems have been less thoroughly explored, a detailed analysis, such as that done by *Schilling* [1991] is not yet possible. This study will serve as a preliminary investigation of these systems which will hopefully be supplemented by field programs in the future. The objective here is to document the nature of the interaction given the available data and to

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propose simple mechanisms for the observed features. A more detailed examination of these physical mechanisms will be the subject of a separate study. These systems are of interest because they represent three different stages of ridge-hotspot interaction in which a ridge migrates toward a hotspot, passes over the hotspot, and then migrates away from the hotspot. It is proposed here that these three systems are characterized by discrete ridge jumps and aseismic ridges resulting from asthenospheric flux from the plume to the ridge. There is evidence that the shallow distribution of plume flux is influenced by the dynamics of the spreading center as well as by plate kinematics.

Interaction Between Migrating Ridges and Hotspots

In an absolute sense, most mid-ocean ridges are migrating relative to a "fixed" hotspot reference frame (absolute migration). This becomes apparent when one considers that, in order to remain stationary relative to the mantle, a ridge would have to be bounded by plates which were diverging in the absolute sense and the ridge would be required to spread asymmetrically at a rate exactly equal and opposite to the ridge-orthogonal component of its absolute migration vector. This is clearly not the case over most of the mid-ocean ridge system as may be seen by comparing models of relative and absolute plate motions [*Gripp and Gordon*, 1990; *DeMets et al.*, 1990; *Minster and Jordan*, 1978]. It is assumed that the hotspots discussed here are fixed relative to one another. Although there is evidence that this may not necessarily be the case [e.g., *Molnar and Stock*, 1987], the proposed hotspot motions occur over distances and timescales which do not affect the conclusions of this study. In this study, the migration of a spreading center refers to its "absolute" migration vector relative to the hotspot reference frame and is determined as the average of the absolute motion vectors for its bounding plates as defined by *Stein et al.* [1977]. The relocation of a ridge axis refers to its apparent motion which results from asymmetric spreading.

The first order nature of the interaction between a plume and a migrating mid-ocean ridge depends upon the flux of the plume and the direction and rate of ridge migration relative to the plume. An extremely simplified migrating ridge-plume scenario is illustrated in Figure 1. Initially, the plume is far from the ridge and is manifest by purely intraplate volcanism. During this stage the majority of the plume flux is carried away from the ridge by drag on the base of the lithosphere. As the ridge migrates closer to the plume a fraction of the plume's flux may be entrained by passive upwelling at the ridge. For this to occur there must be some force which opposes the lithospheric drag away from the ridge. It is assumed here that some amount of slope at the base of the lithosphere will direct buoyant plume material ridgeward and this slope should increase nearer ridge as the isotherms steepen near the ridge axis. Buoyancy forces may drive lateral flow along the base of the lithosphere even when no slope is present [*Ribe and Christensen*, 1994], and a dynamic pressure anomaly from the plume flux might also be expected to contribute to the force necessary to overcome lithospheric drag [*Courtney and White*, 1986]. Entrainment in the regional passive flow to the ridge axis could also help draw plume material to the spreading center. The actual dynamics of these interactions will be a complex function of the thermal and mechanical structure of the lithosphere; the flux, buoyancy, and viscosity of the plume material; and the absolute plate velocity [e.g., *Feighner and Richards*, 1993; *Feighner and Kellogg*, 1994; *Kincaid and*

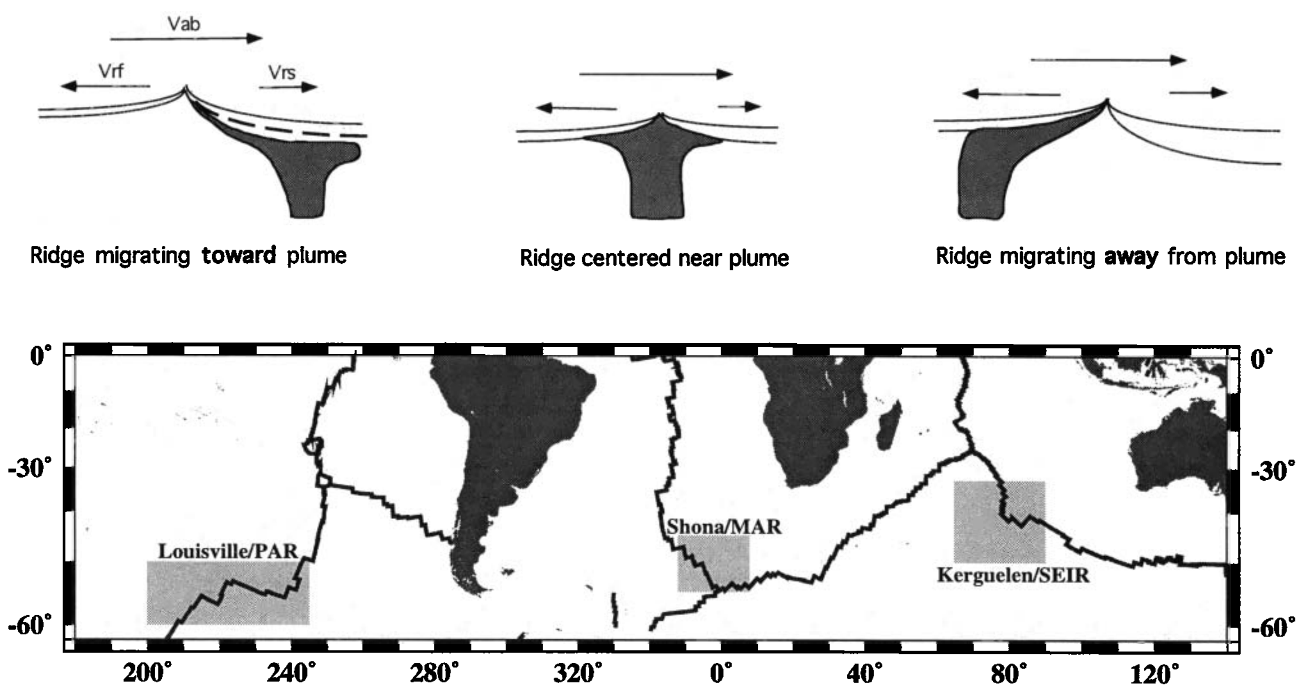

Figure 1. Migrating ridge-hot spot interaction scenario and corresponding location map. Vab, absolute velocity of ridge with respect to the mantle and fixed plume; Vrf, relative velocity of fast spreading ridge flank; Vrs, relative velocity of slow spreading ridge flank. PAR, Pacific-Antarctic Rise; MAR, Mid-Atlantic Ridge; SEIR, Southeast Indian Ridge.

Gable, 1994; *Rowen and Kellogg*, 1994]. As the ridge gets closer, the plume-ridge flux increases and the off-axis volcanism diminishes as more asthenosphere is diverted to the sink at the ridge axis. If the flux of the plume is large enough, seamount production at the ridge axis may increase as the migrating ridge nears the plume and increased melt production may result in crustal thickening and plateau formation when the ridge is centered over the plume [*Vink*, 1984]. As the ridge migration progresses, the ridge will begin to move away from the plume but may continue to entrain some fraction of the plume flux. Eventually, the ridge will be too far from the plume to entrain a significant portion of its flux and intraplate volcanism will resume. This scenario is discussed by *Sleep* [1990], and the details of the later stages of interaction have been discussed by *Schilling* [1985, 1991].

The nature of the plume-ridge interaction will strongly affect the mechanical properties of the lithosphere [e.g., *Davies*, 1994]. The mechanical properties of the lithosphere are controlled primarily by the thermal structure which is dependent on both the degree of asymmetric spreading and the excess temperature and flux of the plume, as well as the rate at which the ridge is migrating with respect to the plume and the nature of the plume's dispersal on the underside of the plate. *Fujita and Sleep* [1978] show that symmetric spreading is stabilized by an unperturbed thermal structure. Plume heating of a ridge flank would however be expected to promote asymmetric spreading. In the systems discussed here the ridge spreads asymmetrically with respect to the absolute migration of the ridge as shown by Figure 1; the opposite case is discussed later.

As the ridge approaches the plume, the effect of the plume's excess temperature will oppose the thermal structure that results from the asymmetric spreading depicted in Figure 1. That is, the plume will impinge upon the colder, stronger flank of the ridge and tend to weaken it. If the thermal effect of the plume is large enough to overcome that of the asymmetric spreading, then the proximal flank of the ridge may become weaker than the distal flank; this may promote increased asymmetric spreading toward the plume. Once the plume is ridge centered, it will supply excess asthenosphere to both flanks of the ridge. If the excess temperature of the plume is large enough it may overcome the effect of the absolute ridge migration and "capture" a section of the ridge, effectively delaying its migration [*Burke et al.*, 1973]. This may be manifest as a series of ridge jumps such as those seen in Iceland [*Saemundsson*, 1974; *Ward*, 1971]. When the ridge eventually begins to migrate away from the plume the thermal perturbation of the plume at the base of the lithosphere now acts in the same sense as the asymmetric spreading to further thin and weaken the lithosphere and retard subsidence on the proximal flank of the ridge relative to the distal flank. This preferential weakening of the proximal flank of the ridge will inhibit the ridge's ability to relocate (whether by asymmetric spreading or discrete ridge jumps) away from the plume. In an extreme case, such as the Galapagos hotspot-Cocos-Nazca Ridge system, the plume effect may resist the absolute ridge migration resulting in spreading center jumps back toward the plume [*Hey and Vogt*, 1977]. The ability of a plume to influence the location of a retreating spreading center was recognized by *Burke et al.*[1973], but the limited data available at the time precluded a detailed study of the phenomenon.

Asymmetric Spreading and Ridge Jumps

While most ridges are migrating relative to a fixed mantle reference, this study considers ridges which are also relocating in the sense that they are spreading asymmetrically. Asymmetric spreading is a poorly understood phenomenon which was once considered exceptional but is now recognized as a fairly common occurrence. Studies such as those of *Carbotte et al.*[1991], *Brozena* [1986], *Rea* [1978], *Hayes* [1976], and *Weissel and Hayes* [1971] indicate that on a local scale asymmetric spreading is very complicated and probably controlled largely by local effects. In the systems discussed here the ridges have attempted to relocate toward the hotspots by spreading asymmetrically. In these cases the asymmetric spreading may result from plume heating.

True asymmetric spreading may be envisioned as a limiting case of ridge jumping in which the jumps are small enough to remain undetected within the 1-2 km neovolcanic zone and yet occur with a consistent polarity such that more lithosphere per unit time is accreted onto one plate than onto the other [*Hey et al.*, 1977]. At the other extreme are very large discrete jumps in the location of the ridge axis such as those discussed by *Mammerickx and Sandwell* [1986]. The cases discussed here involve asymmetric spreading in which there also appear to have been discrete ridge jumps but at a scale intermediate between the two extremes mentioned above.

In the simplest case, the locus of rifting at a spreading center is controlled by the strength of the lithosphere and is therefore dependent primarily on temperature. Asymmetric spreading or an actual ridge jump requires that some location on the ridge flank be weaker than the ridge axis itself. We would generally expect the rift to form at the point where the lithosphere is hottest and therefore weakest. If however, we consider the case of a brittle/ductile two layer lithosphere in which the strength, $S(t)$, is given by the integral of the yield stress envelope, $\sigma(z,t)$

$$S(t) = \int_0^{Z_l} \sigma(z,t)\, dz \qquad (1)$$

where t is age, z is depth, and Z_l is lithosphere thickness, we see that the strengthening is not a simple linear function of the age of the lithosphere (Figure 2; details given in the appendix). In reality, the lithosphere initially strengthens very slowly until the upper mantle has cooled to the point of brittle deformation at which time the lithosphere begins to strengthen much more rapidly. The finite strength of the zero age lithosphere is a result of hydrothermal cooling which cools the upper lithosphere instantly thereby providing some initial strength. More complex models of passive spreading (e.g., advection-diffusion) would predict even stronger lithosphere at the ridge axis relative to the flanks (M. Spiegelman, personal communication, 1994). The point of this illustration is to show that even in the simplest case, there is a finite "window of opportunity" during which the lithosphere at the spreading center is not appreciably weaker than that on the nearby rise flanks. This wider zone of relative weakness provides an opportunity for local variations in thermal and mechanical structure to create a discrete ridge jump. Since the weakest point remains at the axis, some exceptional circumstance would still be required to weaken the flank sufficiently to allow a ridge jump. These variations are evidently rare occurrences since narrow (1-2 km) axial neovolcanic zones are common features of most mid-ocean ridges [*Macdonald*, 1986], while recognizable discrete ridge jumps are relatively uncommon. Variations in the near-ridge stress field resulting from changes in spreading direction and thermal perturbations from off-axis plume material are possible candidates. Episodicity of extension and passive upwelling on slow spreading ridges may also provide an opportunity for the lithosphere at the ridge axis to cool and strengthen beyond the degree shown in this model. While this model may be overly simplified compared to other published models for ridge axis thermal structure and rheology [e.g., *Chen and Morgan*, 1990a,b; *Phipps Morgan and Chen*, 1993], one would expect the basic result to hold true for any ridge axis model in which strength is related to a cooling, two-layer brittle/ductile lithosphere.

The ridge-hotspot systems considered in this study are characterized by asymmetric spreading but also show evidence for discrete ridge jumps in the direction of the hotspot. In all cases the ridge axis appears to have relocated plumeward onto the slower spreading, presumably stronger plate; the most likely cause for this would seem to be a thermal weakening of that plate by sublithospheric plume material. In the case of the ridge migrating toward a plume and spreading asymmetrically in the same sense (Figure 1), the plume-induced heating of the proximal flank acts to oppose the strength differences caused by the asymmetric spreading. If the excess temperature of the plume is high enough to offset the effect of the asymmetric spreading, then a critical point is reached where the proximal flank becomes generally weaker than the distal flank. Now the strength difference of the asymmetric spreading has been eliminated, and the locus of rifting may more easily accelerate in the direction of the plume by discrete ridge jumps if sufficient local conditions occur on the proximal flank. In the opposite case, where the ridge migrates away from the plume, the proximal flank of the ridge is always hotter and weaker than the distal flank (unless asymmetric spreading occurs in the opposite sense to the ridge migration). This would promote rifting on the proximal flank, contrary to whatever forces we assume to be responsible for ridge migration away from the plume. If the excess temperature of the plume is large enough, the proximal flank will be weakened sufficiently to allow the ridge axis to jump back toward the plume. This is seen in the Cocos-Nazca-Galapagos system [*Hey and Vogt*, 1977] and apparently in the Southeast Indian Ridge-Kerguelen system discussed below.

The following sections of this paper investigate four ridge-hotspot systems in detail using both satellite gravity data from the Geosat-Geodetic Mission and ERS 1 missions [*Sandwell et al.*, 1995] and all underway geophysical data

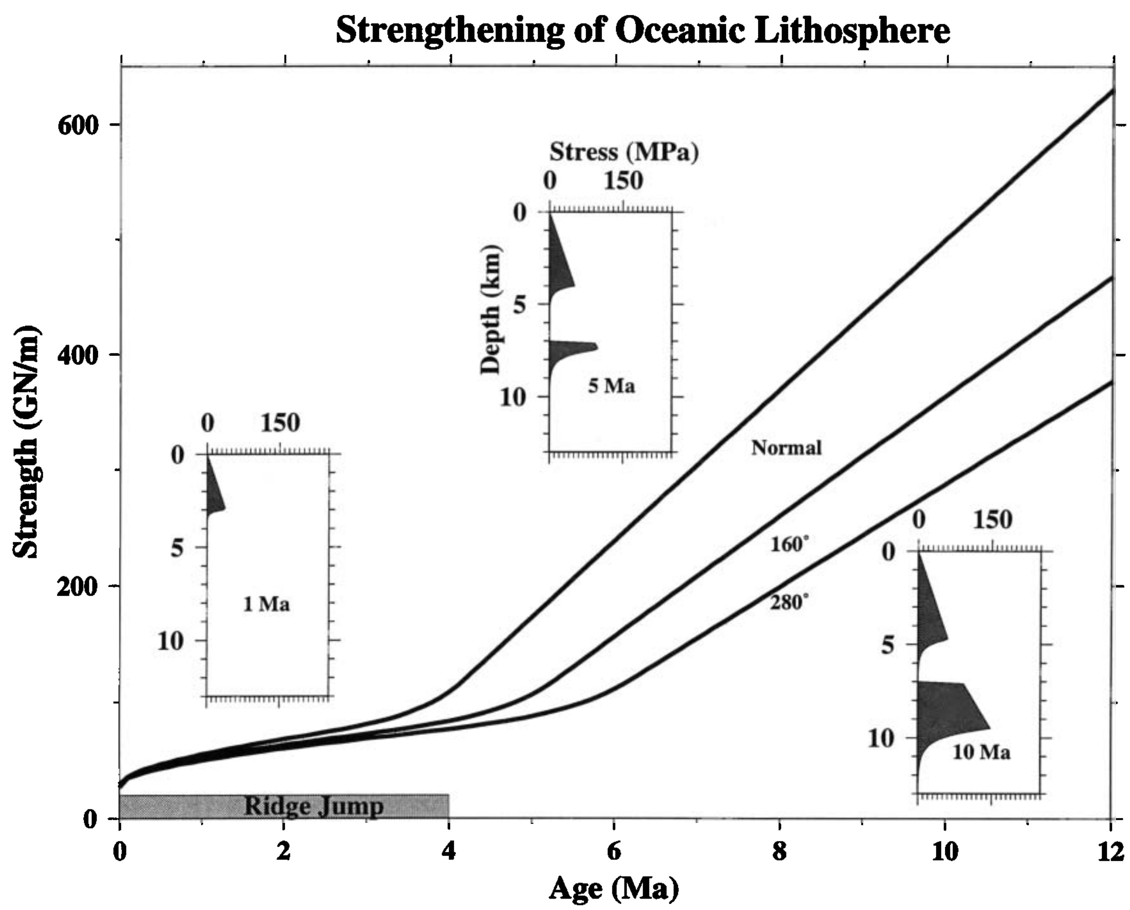

Figure 2. Strengthening of oceanic lithosphere for a brittle/ductile cooling plate model as in equation (1). The case of normal oceanic lithosphere is shown along with that of plume affected lithosphere with elevated basal temperatures of 160° and 280°K. The details are given in the appendix. Note the rapid strengthening at ~4-6 Ma as the mantle cools sufficiently to undergo brittle deformation. The shaded region indicates the time during which the flanks are most susceptible to local perturbations which may cause a ridge jump.

(bathymetry and magnetic anomaly) currently available from the National Geophysical Data Center and Lamont-Doherty Earth Observatory databases. Although the spreading histories of the ridge segments were determined from underway magnetic anomaly profiles, the isochrons from the grid of *Muller et al.*[1993] help to illustrate the spreading history of the ridge as determined by plate reconstructions. Absolute ridge migration vectors are determined for each area using the HS2-Nuvel1 absolute plate motion model of *Gripp and Gordon* [1990] and are given in polar coordinates (**r**, θ) with azimuths given in degrees clockwise from North (Figure 4). Asymmetric spreading is described by the ratio of half spreading rates (V_S/V_f is slow rate/fast rate).

Pacific-Antarctic Rise-Louisville Hotspot System

Background and Plate Kinematics

The interaction between the Louisville hotspot and the Pacific-Antarctic Rise (PAR) is quite poorly understood. This is a consequence of its remote location and the lack of available geophysical and geochemical data in the vicinity. Studies by *Lonsdale* [1988] and *Watts et al.*[1988] summarize the structure and evolution of the ridge but do not provide conclusive evidence for the current location of the hotspot. *Lonsdale* [1988] infers the location of the hotspot to be north of the Eltanin Fracture Zone (FZ) system near 50.5°S, 139.2°W on the basis of a depth anomaly and a very large seamount from which Pleistocene lavas were dredged or possibly on a smaller seamount to the southeast (P. Lonsdale, personal communication, 1994). *Vogt* [1976] inferred the present location of the hotspot to be at the ridge axis, between the Eltanin and Udintsev FZs, on the basis of shallowing seen in bathymetric profiles. *Epp* [1978] inferred a similar location on the basis of the orientation of the Louisville Seamounts and the Hawaiian hotspot trend.

At the point on the PAR nearest the Louisville hotspot (55°S, 222°E) the migration of the PAR is dominated by the motion of the Pacific plate (-64°, 93 mm/yr) as the Antarctic plate is nearly stationary (-66°, 12 mm/yr). The resultant ridge migration vector (-65°, 52 mm/yr) is northwestward and nearly parallel (~3°) to the direction of relative plate motion in the area. The half spreading rates on the Antarctic and Pacific plates are 53 and 33 mm/yr, respectively.

Observations From Satellite Gravity and Underway Data

The satellite gravity map in Plate 1 shows a number of ridge parallel gravity lineations on both the western flank of the PAR south of the Udintsev FZ and on the eastern flank of the rise north of the fracture zone. These lineations are near the resolution limit of the satellite data and the sparse distribution of underway data in this area provides only one useful example of bathymetry and magnetic anomaly profiles crossing these lineations. The profile, collected by the USNS *Eltanin* in 1966, crosses the lineations on the Antarctic plate between the Eltanin and Udintsev FZs and shows that the more distal linear gravity high corresponds to a small bathymetric high while the lineation nearer the ridge corresponds to a bathymetric deep with uplifted flanks. The lineations on the western ridge flank south of the Udintsev FZ are more pronounced in the gravity map but not clearly depicted by the available underway data. Figure 4 also illustrates a potential pitfall of working with archival underway data. The ~60-km offset between the features in the bathymetry profile and those in the satellite gravity profile is indicative of a navigation error in the 1966 ship data. The misnavigation of the underway magnetic anomaly profile has resulted in mislocation of anomaly picks and has thereby corrupted the gridded age model of *Muller et al.*[1993]. This is apparent from the displaced isochrons between the Udintsev and Eltanin FZs shown in Figure 3.

Fortunately, a high-quality magnetic anomaly profile is available for *Eltanin* leg 23 and provides a detailed spreading history of the ridge segment between the Udintsev and Eltanin FZs. In addition to showing the Antarctic plate spreading faster by asymmetric spreading (V_S/V_f = 32/52 = 0.6), this profile clearly shows an extended anomaly 2a which coincides with the lineation nearer the ridge as shown in Figure 4. This extended anomaly may be more easily seen when compared with a model profile as shown in Figure 5. If the ridge jump were larger then part of anomaly 2a would be missing on the opposite flank; evidently, it was small enough not to disrupt the sequence on the Pacific plate. The possibility that this anomaly represents a ridge jump was also raised by *Molnar et al.*[1975]. The more distal lineation shows no indication of a large ridge jump in the magnetic anomaly profile although interpretation of the profile is complicated by a course change in the critical area.

These lineations occur on the fast spreading flanks of asymmetrically spreading ridge segments. The magnetic anomaly profile shown in Figure 4 shows the northwestward relocation of the rise axis by asymmetric spreading. Such a detailed spreading history of the segment to the south of the Udintsev FZ is not available; however, tectonic reconstructions and isochron charts of both *Mayes et al.*[1990] and *Muller et al.*[1993] indicate that this ridge segment was spreading asymmetrically such that the ridge axis has relocated to the southeast, in the opposite sense of the segment to the north of the Udintsev FZ. Both sets of lineations therefore appear to be created in the wake of asymmetrically spreading ridge axes. If the present location of the Louisville hotspot is near the axis of the ridge segment between the Eltanin and Udintsev FZ, then both of the ridge segments would have relocated closer to the hotspot at the time the lineations were created.

Also shown on the gravity map in Plate 1 is a linear gravity high extending diagonally from the Eltanin FZ system near 216° E to the rise axis near 55°S. This high corresponds to a very large (>3000-m relief) aseismic ridge or closely spaced chain of seamounts. This aseismic ridge bears some resemblance to the aseismic ridges seen on other systems discussed in this study and may be related to sublithospheric flux from the Louisville hotspot or a migration of the plume material along the spreading axis. The gravity map in Plate 1 also shows an interesting change in the character of the regional gravity in the corridor bounded by the Udintsev and Eltanin FZs. The region of this corridor between the ridge axis and the nearest lineation to the east is marked by higher regional gravity than the area to the east of the lineation or the area on the opposite ridge flank. Bathymetry profiles seem to indicate that this area is shallower than the area to the east of the lineation and possibly subsiding more slowly (Figure 4), although it is difficult to obtain meaningful estimates of subsidence rates for such a small area.

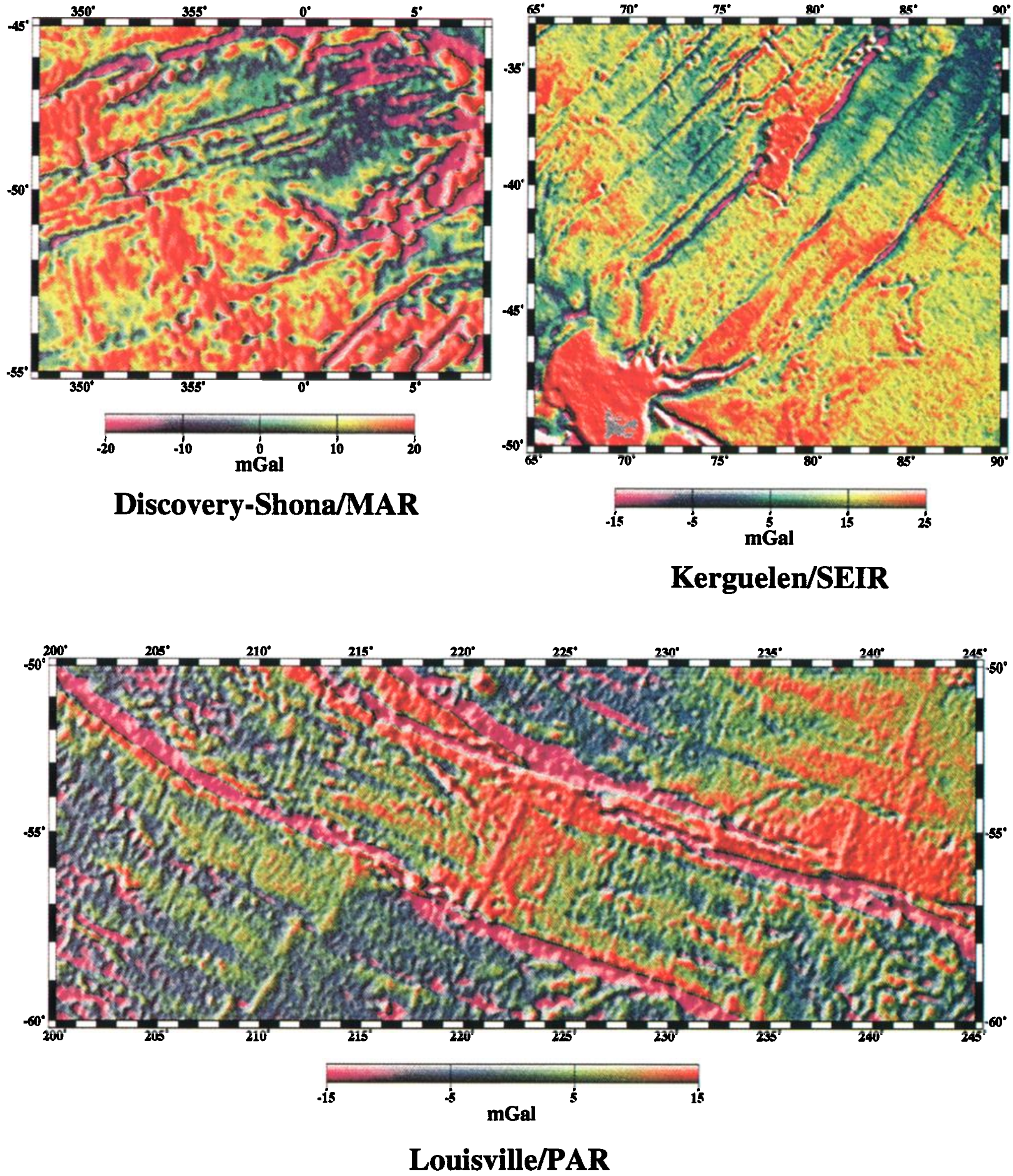

Plate 1. Satellite gravity maps of the three ridge-hotspot systems discussed in this study. Index maps shown in Figure 3. Location map shown in Figure 1.

Mid-Atlantic Ridge-Shona/Discovery Hotspot Systems

Background and Plate Kinematics

The systems considered here are the southernmost Mid-Atlantic Ridge (MAR) and Shona and Discovery hotspots. The existence of a Shona hotspot, distinct from the Bouvet hotspot, was originally proposed by *Hartnady and le Roex* [1985] on the basis of geochemically anomalous lavas, apparently different from those of Bouvet, which were dredged from the southern MAR near 52°S. They postulate that the hotspot is currently located near the Shona seamount at (54.5°S, 354°E). Preliminary results of a recent isotopic and rare earth element (REE) analysis by *Douglass et al.* [1994,

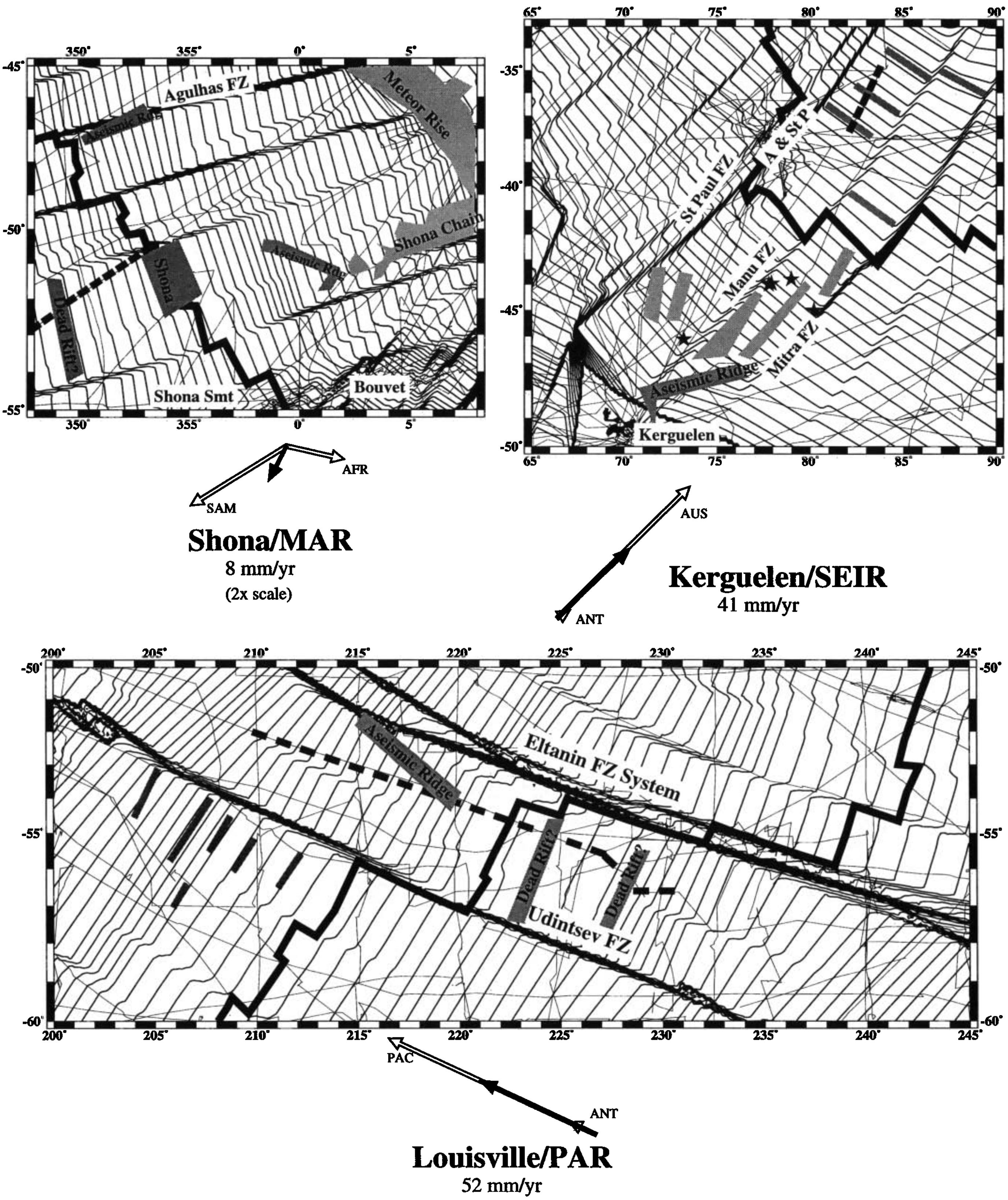

Figure 3. Index maps for ridge-hotspot systems discussed in this study. Light lines show available underway profile data. Dashed lines show locations of profiles in Figures 4-7. Heavy line indicates ridge axis from *Small and Sandwell* [1994]. Isochrons based on global age map of *Muller et al.* [1993]. Stars indicate off-axis earthquake epicenters. Shaded regions indicate features discussed in text. Vectors show absolute motion of bounding plates (open) and ridge migration (solid); rates correspond to absolute ridge migration. Global location map shown in Figure 1.

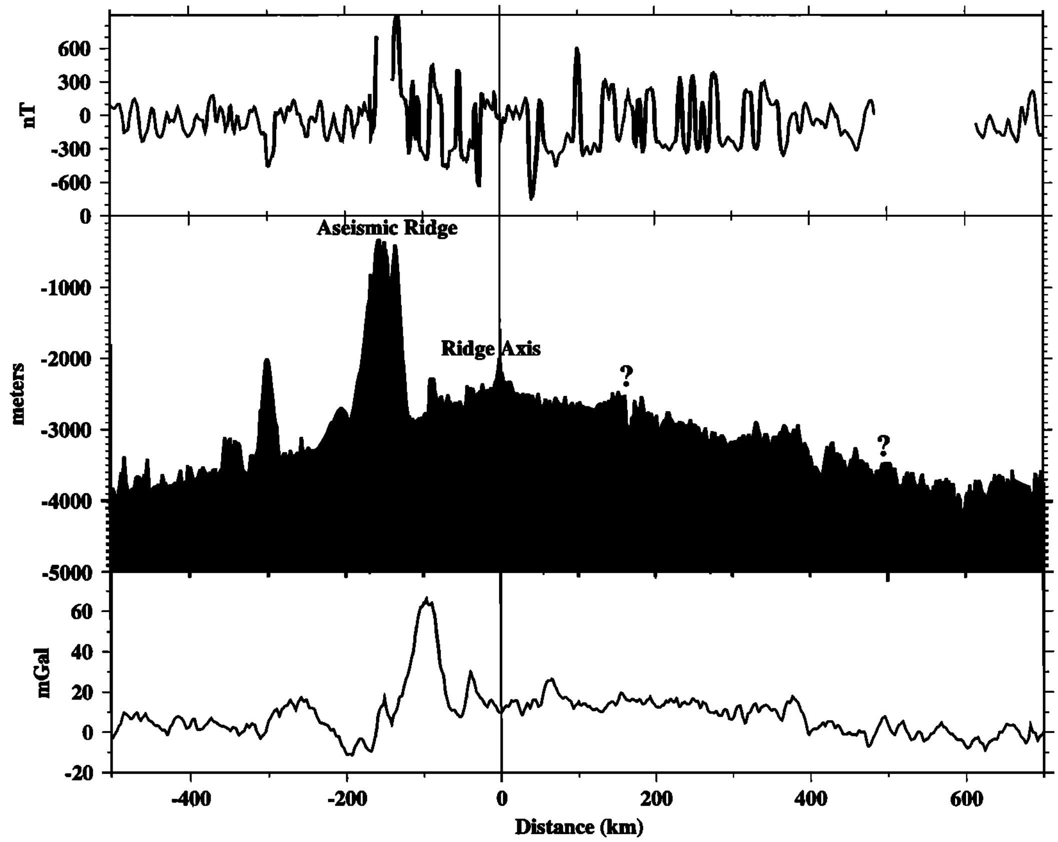

Figure 4. Underway bathymetry, magnetic anomaly and coincident satellite gravity profiles from Pacific-Antarctic Rise flank. Locations shown in Figure 3. Basement deep and ridge corresponding to gravity lineations are indicated by question mark. Note ~60-km offset between satellite and bathymetry profiles; this is a result of a navigation error in the underway data.

also Influence of the Discovery and Shona mantle plumes on the Southen Mid-Atlantic Ridge: Rare earth evidence, submitted to *Geophysical Research Letters*, 1995] indicate that the Shona hotspot may actually be located closer to the ridge axis or possibly at the axis itself near (51.5°S, 354.2°E). The ridge axis in this area is marked by very shallow depths (1500 m) and a disappearance of the axial valley near the midsection of the segment [*Small et al.*, 1994].

It was proposed by *Kempe and Schilling* [1974], on the basis of light rare earth element enrichment (i.e., high La/Sm ratios), that the Discovery Tablemount may also have been created by a small mantle plume. The orientation of the Discovery seamount chain supports this hypothesis. Although the current location of the plume is not known, plate reconstructions place it near (44.45°S, 6.45°W) (J. Douglass et al., submitted manuscript, 1995).

The absolute plate motion model of *Gripp and Gordon* [1990] shows divergent motions of the African (103°, 12 mm/yr) and South American (-122°, 23 mm/yr) plates resulting in a net southward absolute migration (-153°, 8 mm/yr) of the ridge axis on the Shona segment (51.5°S, 354.25°E). This produces a small westward component of ridge perpendicular migration (115°, 6 mm/yr). This segment is currently spreading symmetrically at 32 mm/yr [*Small et al.*, 1994]. The kinematics of the Discovery segment to the north are almost identical to those of the Shona segment.

Observations From Satellite Gravity and Underway Data

The satellite gravity map in Plate 1 shows the change in character of the ridge axis in the area described above. One of the more prominent features seen in this gravity map is the ridge parallel lineation near 350°E which runs the length of the ridge segment and has a gravity anomaly similar to that characteristic of slow spreading ridge axes. There is one underway bathymetric profile crossing this feature (Figure 3), and its morphology is very similar to that of a slow to intermediate spreading ridge axis with an axial valley and slightly uplifted flanks (Figure 6). Unfortunately, magnetic anomaly data are not available along this profile, but isochrons and tectonic reconstructions of *Muller et al.*[1993] indicate that this ridge segment was spreading asymmetrically with the ridge axis relocating rapidly to the east at the time this feature was formed. The reconstruction of *Muller et al.*[1993] is constrained in this area by magnetic anomaly picks of *Cande et al.*[1988]; although they have no picks near the axis of the Shona segment, the adjacent segments to the north and south suggest consistent eastward relocation with asymmetries (V_s/V_f) between 0.6 and 0.8 based on distances to anomaly 3.

The migrating hotspot model for the formation of the Meteor Rise and Shona Ridge proposed by *Hartnady and le*

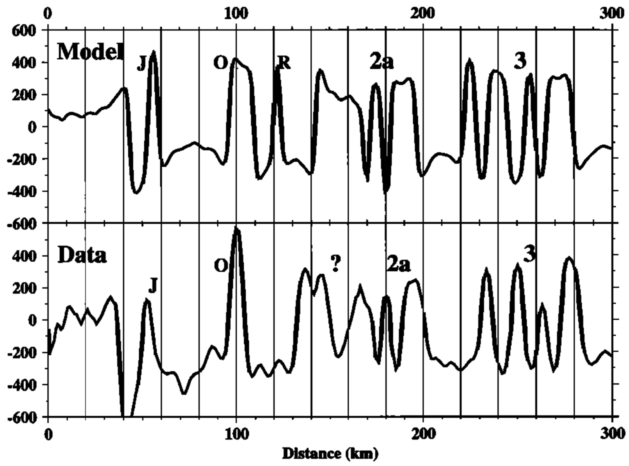

Figure 5. Comparison between magnetic anomaly profile shown in Figure 4 and a model profile. Note the extra peak in the anomaly 2 sequence. This anomaly coincides with the basement deep seen in Figure 4.

Roex [1985] provides a clever explanation for the zig-zag pattern of these seamount chains but it is now apparent that there are additional complexities in this ridge hotspot system. Plate 1 indicates that the feature interpreted as the Shona Ridge is actually part of a large, discontinuous cluster of seamounts extending toward the MAR. At the western terminus of this cluster of seamounts is a linear, W-NW trending gravity high which appears more continuous than the cluster of seamounts to the east. This gravity high almost certainly results from an aseismic ridge similar to the gravity highs in the other regions discussed in this study. The area to the west of this ridge is characterized by a regional free air gravity high which extends to the MAR axis and further onto the western flank of the ridge as far as the ridge axis parallel linear feature discussed above. To the north, the segment of the MAR immediately south of the Falkland-Agulhas transform is also anomalously shallow (~1900 m) but appears to maintain an axial valley structure throughout the segment. The ridge axis here appears to be offset to the east where it too ajoins an E-NE trending aseismic ridge on its eastern flank. The MAR to the north of the transform shows typical slow spreading anomaly character but the presence of several oblique linear features on both ridge flanks suggest northward propagation of ridge axis discontinuities at some time in the past.

Southeast Indian Ridge-Kerguelen Hotspot System

Background and Plate Kinematics

The nature of interaction between the Southeast Indian Ridge (SEIR) and the Kerguelen and St. Paul hotspots is not well understood. *Morgan* [1978] originally proposed the possibility of asthenospheric flux from the Kerguelen to the Amsterdam-St. Paul hotspot. Lavas dredged from the Amsterdam-St. Paul massif are geochemically distinct from those of Kerguelen, although one sample from the massif shows a Kerguelen isotopic signature [*Dosso and Murphy,* 1980; *Michard et al.,* 1986]. While the tracks of the Kerguelen and St. Paul hotspots are nearly coincident on the Indian plate prior to ~17 Ma [*Luyendyk and Rennick,* 1977], it is not known to what extent they are related today. Although the SEIR has been surveyed and sampled between the Rodriguez Triple Junction and the Amsterdam-St.Paul massif [e.g., *Royer and Schlich,* 1988; *Sauter et al.,* 1991; *Munschy and Schlich,* 1989, *Dosso and Murphy,* 1980; *Michard et al.,* 1986], geochemical and underway geophysical data are very sparse on the SEIR to the southeast of the massif (Figure 3).

At the point on the SEIR nearest the Kerguelen hotspot (43°S, 83°E) the migration of the SEIR is dominated by the motion of the Australian plate (45°, 76 mm/yr) as the Antarctic plate is nearly stationary (58°, 6 mm/yr). The resultant ridge migration vector (46°, 41 mm/yr) is northeastward and nearly parallel (~8°) to the direction of relative plate motion. The full spreading rate is currently symmetric at 70 mm/yr.

Observations From Satellite Gravity and Underway Data

Satellite gravity data provide a much clearer view of this region than was previously available from the rather sparse underway data (Plate 1 and Figure 3). In the northeast corner of the region shown in Plate 1 are a series of E-SE striking, ridge parallel lineations in the two corridors to the east of the St. Paul FZ. These features are near the resolution limit of the satellite gravity data and there are very few bathymetric data available in this area (Figure 3), but one profile, collected by the R/V *Galieni* in 1968, indicates that at least two of these lineated anomalies are caused by steep sided troughs (Figure 7). Magnetic anomaly profiles, published by *Royer and Schlich* [1988], indicate that the SEIR was spreading asymmetrically (V_s/V_f = 25/31 = 0.81) at the time that these features were formed. The sense of the asymmetry was such that lithosphere was accreting preferentially to the Australian plate counteracting the northeastward ridge migration by

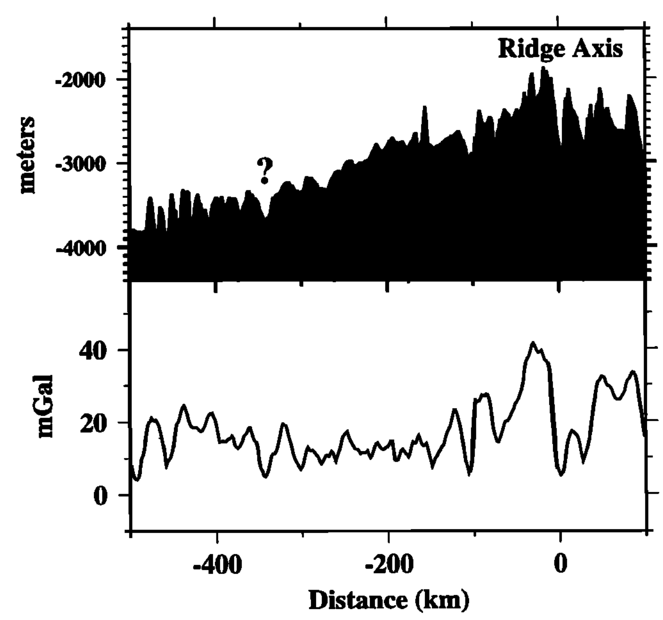

Figure 6. Underway bathymetry and coincident satellite gravity anomaly profiles from Mid-Atlantic Ridge flank. Location shown in Figure 3. Basement deep corresponding to gravity lineation on western ridge flank is indicated by question mark. No magnetic anomaly data were collected along this track.

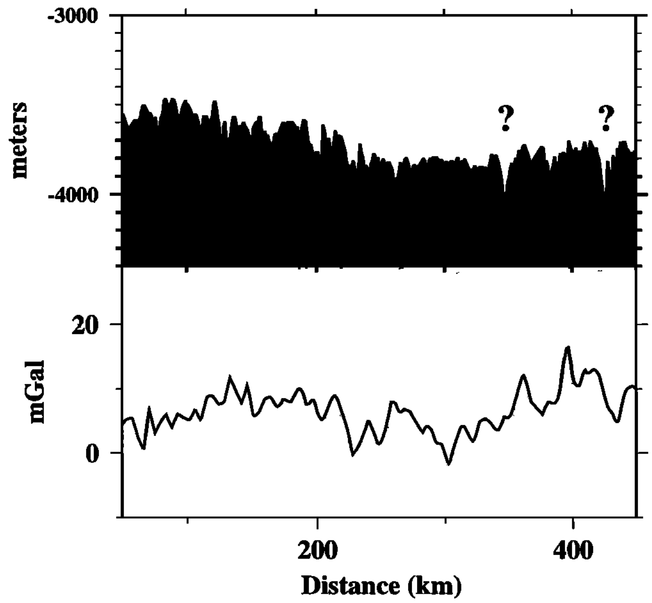

Figure 7. Underway bathymetry and coincident satellite gravity anomaly profiles from Southeast Indian Ridge flank. Location shown in Figure 3. Basement deeps corresponding to gravity lineations are indicated by question mark. Note also the flattening of the seafloor at distances greater than 200 km. Distances are in kilometers along track from 37.8°S 80.0°E.

relocating the ridge to the southwest in the direction of the Kerguelen hotspot and reducing its northeastward migration rate by ~6 mm/yr. Interestingly, the plate reconstruction of *Royer and Schlich* [1988] shows the other segments of the SEIR spreading asymmetrically in the opposite sense, relocating northward away from Kerguelen in accordance with the predictions of the model of *Stein et al.*[1977]. The lineations persist until ~3 Ma at which time the asymmetric spreading ceased and these two ridge segments resumed symmetric spreading [*Royer and Schlich,* 1988]. These lineations may be the result of small scale ridge jumps in the direction of the Kerguelen hotspot. Although there is no indication of missing/doubled magnetic anomalies on the profile shown by Royer and Schlich [1988], the jumps may have been too small (< 1 m.y.) to be resolved in the reversal record. A stretched anomaly is seen nearer to the rise axis (~17 Ma) on their profile, but there is not a pronounced bathymetric trough associated with it.

A number of features seen in Plate 1 suggest a connection between the Kerguelen hotspot and the SEIR. The most prominent feature is the linear gravity high extending from the northeastern corner of the Kerguelen Plateau to the Mitra FZ. This gravity high corresponds to a very large (3000-m relief) aseismic ridge that rises to within 700 m of the sea surface on underway bathymetric profiles. In addition, there are a number of more subtle gravity highs in the corridor extending from the northern flank of this aseismic ridge to the ridge segment bounded by the Mitra and Manu FZs. In the adjacent corridor to the northeast there are three less prominent linear gravity highs trending toward the ridge as well as a broad chain of seamounts connecting the northern flank of the Kerguelen Plateau to the segment of the ridge axis just south of the Amsterdam-St. Paul massif. These seamounts intersect the ridge axis at the abrupt termination of the axial valley on the southern flank of the massif and may also be a result of a connection between the Kerguelen hotspot and the SEIR. It is possible that the broad, low-amplitude highs extending from the flank of the aseismic ridge to the spreading center may result from crustal thickness variations related to plume-ridge flux. *Small and Sandwell* [1994] have proposed that the sharp increase in the ridge axis anomaly amplitude eastward of the Mitra transform is a result of Kerguelen plume flux being channeled to the ridge axis along the lithospheric thickness change on the Mitra FZ.

Discussion

The systems discussed above illustrate three different types of interaction between hotspots and migrating ridges. In each case there is some evidence for discrete ridge jumps in the direction of the hotspot as well as for asthenospheric flux from the plume to the spreading center both before and after the spreading center has migrated over the plume. These systems support the plume source-ridge sink model of *Schilling* [1985, 1991] and the time evolution outlined by *Sleep* [1990], but they also indicate additional complications in plume-ridge interaction.

Initiation of Plume-Ridge Interaction

The Louisville-PAR system illustrates a primary stage of plume-ridge interaction. In this system the ridge is migrating very rapidly (52 mm/yr) toward the plume in the absolute sense as well as relocating plumeward by asymmetric spreading. The aseismic ridge extending diagonally from the Eltanin FZ system toward the rise axis suggests some physical connection between an off-axis hotspot and the spreading center. The termination of this aseismic ridge occurs at the same age (~3 Ma) as the ridge jump on the opposite flank. It is not known whether this aseismic ridge was formed at the rise axis or on the rise flank; the flanking gravity lows suggest the presence of a flexural moat which would imply that it was formed on lithosphere with a low elastic thickness. The azimuth of this aseismic ridge (-47°) is significantly different from the current direction of absolute motion of the Pacific plate (-64°), which suggests that the eruptive location of the aseismic ridge has moved relative to the hot spot chains upon which current estimates of Pacific absolute motion are based. If the aseismic ridge is a manifestation of asthenospheric flux from the plume to the spreading center, then it would seem to imply that its source has migrated from the end of the spreading segment toward its center. If the current location of the hotspot is to the north of the Eltanin FZ system, then the aseismic ridge discussed here may be the trace of a smaller, separate limb of the plume or perhaps material which has diverted subsequent to its interaction with the base of the lithosphere. The presence of regional gravity highs and depth anomalies on the spreading segments immediately adjacent to the Eltanin FZ system are also consistent with the notion of a complex redistribution of plume material as it is entrained by the spreading center. Further support for a ridge-plume connection is given by *Castillo et al.*[1994], who find preliminary evidence for Louisville trace element and isotopic signatures in recently obtained dredge samples from the segment of the ridge axis nearest the aseismic ridge.

The second stage of ridge-plume interaction, in which the plume and spreading center are coincident, may be illustrated by the Shona-MAR system. The trail of the Shona hotspot was previously interpreted as consisting of a single, W-SW trending ridge (the Shona Ridge) but, as shown in Plate 1, it is actually a cluster of individual seamounts which terminates abruptly with an elongate NW trending aseismic ridge that was previously uncharted. Although the spreading history of this mid-ocean ridge segment is not known, the termination of the aseismic ridge appears to coincide with the inferred eastward ridge jump which may mark the final stage of the plume's capture of the spreading center. The character of the MAR axis from 50°S southward to the triple junction and the abrupt termination of the Shona hotspot trail at the edge of the regional gravity high in this area suggest a complex redistribution of plume flux from the Shona hotspot. The axial morphology appears to have been profoundly influenced by the plume; axial valleys are present only directly adjacent to the ridge axis offsets [*Small et al.*, 1994]. Individual segments seem to persist, but the offsets between 52°S and the triple junction do not appear to leave prominent traces off axis. The presence of axial valleys at segment ends and nodal deeps in the transforms suggests a partitioning of plume flux at depth rather than a shallow along-axis flow.

A situation similar to those described above may also be seen farther to the north on the MAR. The elongate gravity high on the eastern flank of the ridge immediately south of the Falkland-Agulhas FZ (Plate 1) marks an aseismic ridge which bears a resemblance to those discussed above. A recent study by *Douglass et al.*[1994, also submitted manuscript, 1995] indicates that basalt samples recovered from the MAR immediately south of the Falkland-Agulhas FZ show Pb isotopic composition suggesting a plume influence distinct from that of the Shona hotspot. The current configuration of the spreading center in this area suggests that the ridge may be in the process of jumping eastward toward the Discovery hotspot but underway data in the area are too sparse to confirm or refute this proposition. The current location of the Discovery hotspot is not known but the results of Douglass et al.(submitted manuscript, 1995) and the regional bathymetric (~1900 m) and gravity highs at the ridge axis suggest that some fraction of its flux may currently be entrained by the spreading center. If the plume is located to the north of the Agulhas FZ, then some plume material may have crossed the Agulhas FZ and been channeled southwestward along the fracture zone to produce the isotopic anomaly at the ridge axis (J.G. Schilling, personal communication, 1994). The relative decrease in lithospheric thickness southward across the Agulhas FZ would promote migration of buoyant plume material across the fracture zone. This would explain the small north striking gravity high connecting the eastern end of the aseismic ridge with the regional gravity high to the north of the fracture zone. The Discovery-MAR system may represent a stage of ridge-plume interaction in which the plume is now establishing a connection to the ridge. *Douglass et al.*[1994, also submitted manuscript, 1995] suggest that the connection between the spreading center and the Discovery hotspot may still be rather distant on the basis of the character of the along-axis REE enrichment pattern. Although both the Discovery and Shona systems represent cases where the ridge is actually migrating slowly away from the presumed location of the hotspot, the evidence presented here and by J. Douglass et al.(submitted manuscript, 1995) suggest that the plumes have established some connection with the spreading center and impeded their westward migration. The relatively low velocity of the African plate may allow a more radial dispersion of the plume material at the base of the lithosphere rather than entraining it and carrying it away from the ridge. An analogous situation may be seen to the north where the Ascension/Circe and St. Helena hotspots seem to have established some connection to the MAR and are inhibiting its westward migration by ridge jumps and propagations [*Hanan et al.*, 1986; *Schilling et al.*, 1985; *Brozena and White*, 1990].

In the cases described above, there appears to be some physical connection between off-axis hotspots and spreading centers which have never been ridge centered. Preliminary geochemical evidence from the PAR [*Castillo et al.*, 1994] and Southern MAR [*Douglass et al.*, 1994, also submitted manuscript, 1995] support this idea. In both laboratory and numerical simulations of plume-ridge interaction, *Kincaid and Gable* [1994] have also found that such a connection can be established. This is also suggested by the transition from intraplate volcanism to the more focused formation of a continuous aseismic ridge which may terminate with a discrete ridge jump. A possible scenario is illustrated by Figure 8. In stage A there is no connection between the spreading center and the plume, which is manifest as discrete intraplate volcanoes. In stage B the plume material impinges on lithosphere weak enough to allow the production of a more continuous volcanic edifice and begins to migrate toward the center of the ridge segment as a result of increasing slope on the base of the lithosphere. The slope on the base of the lithosphere results from cooling and thickening with age perpendicular to the rise axis but also with distance along axis from the cold boundaries at the ends of the ridge segment. In stage C a fraction of the plume's flux becomes entrained by the spreading center and migration of the plume material continues toward the center of the ridge segment. As the flux from the plume to the spreading center increases, it is distributed along the axis of the spreading segment which acts as a line sink. In stage D the lithosphere between the plume and the spreading segment is sufficiently heated and weakened to allow a ridge jump as the locus of accretion moves abruptly toward the plume. At this point a much larger portion of the plume flux is absorbed by the spreading center and production of the linear volcanic chain on the rise flank ceases. In stage E the plume is ridge centered and the abandoned ridge axis and off axis volcanic edifices are rafted away on opposite flanks of the ridge. Complications such as the effect of melting of the asthenosphere, the mechanism by which the ridge jumps, and the dynamics of local migration of plume material toward the center of the spreading segment must be examined in greater detail and are beyond the scope of this paper. The migration proposed above would not be a migration of the entire plume but rather the plume derived asthenospheric material at the base of the lithosphere. A strong argument for an off-axis plume source in the past is the narrow aseismic ridge itself; if the plume source were ridge centered and migrating along the axis, it might be expected to distribute excess material more evenly along the length of the ridge axis rather than localizing it into a narrow constructional feature.

Termination of Plume-Ridge Interaction

The Kerguelen-SEIR system illustrates the late stage plume-ridge interaction as the ridge axis has crossed the plume and is carried away on the trailing edge of the Australian plate but continues to be influenced by the plume. It was proposed by *Small and Sandwell* [1994] that asthenospheric flux from the Kerguelen hotspot along the Mitra FZ may be responsible for

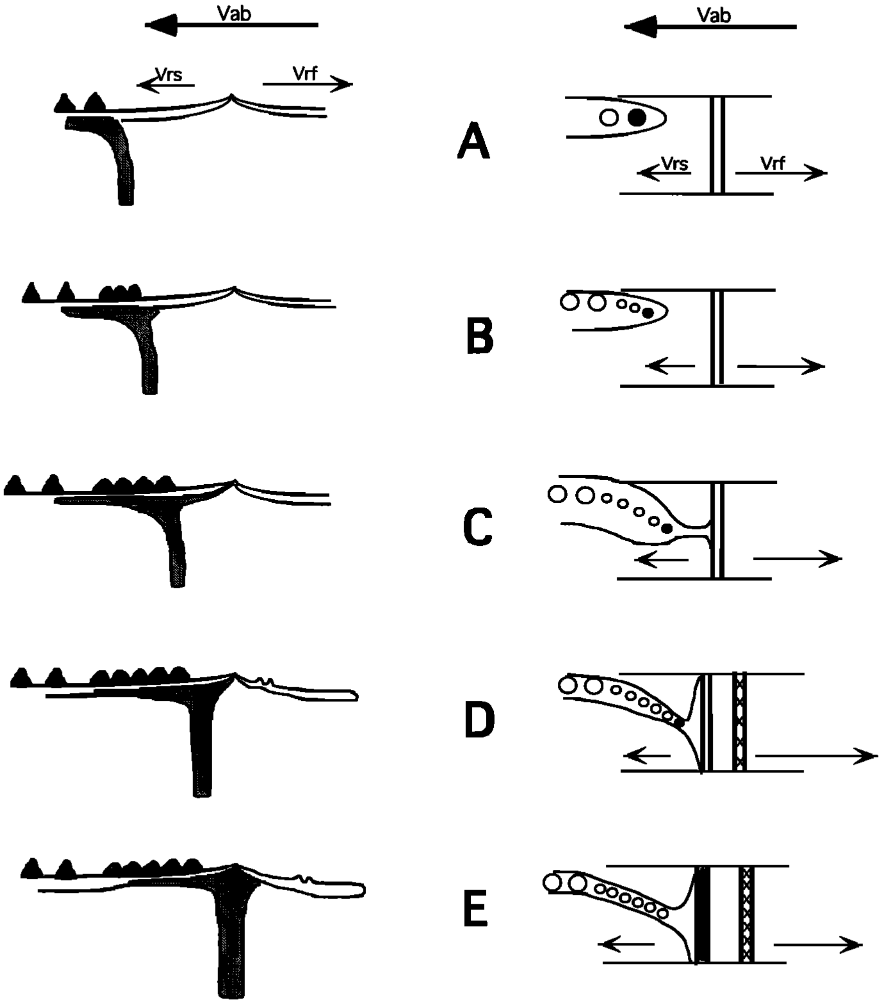

Figure 8. Cartoon depicting possible ridge-hotspot interaction scenario as spreading centers migrate toward hotspots. Sequences progress from Figure 8a to Figure 8e with side view depicted on left and plan view on right. Plate motion arrows are labeled as in Figure 1. Solid circle indicates current location of the hotspot. Open circles represent volcanic edifices indicating past locations. The sequence of events is explained in the text.

changes in the nature of the ridge axis morphology on the SEIR between 75°E and 90° and this question is addressed in greater detail by *Ma et al.* [1994] and Y. Ma and J. Cochran (Transitions in axial mophology along the Southeast Indian Ridge, submitted to *Journal of Geophysical Research*, 1995). The presence of axial valley structures on the ridge axis on both sides of the Amsterdam and St. Paul massif seems to indicate that the influence of the Amsterdam-St. Paul hotspot on the Southeast Indian Ridge is local and is less than that of the Kerguelen hotspot.

The difference in the character of the gravity anomalies in the St. Paul-Manu corridor and the Manu-Mitra corridor suggests fundamental differences in relationship between the plume and the ridge in each of these corridors. In the St. Paul-Manu corridor the plume's influence seems to have been limited to the sporadic production of seamounts. The Manu-Mitra corridor shows a greater plume influence with the production of a large aseismic ridge which eventually waned and may now be manifest as variations in crustal thickness resulting from underplating of plume derived material. *Royer and Schlich* [1988] show that the majority of the ridge segments on the northern SEIR have relocated to the northeast behind the fast moving Australian plate; these two segments relocated in the opposite direction toward the receding Kerguelen hotspot. The present-day ridge axis of these two segments may no longer be influenced by the plume if the remaining flux is being channeled to the ridge along the Mitra FZ. This may account for the apparent disappearance of the fracture zone signature on the Antarctic plate if material has been erupted along the fracture zone by a mechanism similar to that proposed by *Epp* [1984]. The eventual localization and decrease in the plume-ridge flux may also be reflected in this segment's recent (~3 Ma) return to symmetric spreading [*Royer and Schlich,* 1988]. An analogous example of plume channeling along a fracture zone might be seen on the Central Indian Ridge where isotopic data from *Mahoney et al.* [1989] suggest that flux from the Reunion hot spot may have channeled along the Marie Celeste FZ to the ridge axis after the termination of the Rodriguez ridge.

The character of the broad, elongate, ridge perpendicular gravity highs between the SEIR and the Kerguelen hotspot may be related to the nature of any plume-ridge flux which may have occurred in the past. There appear to be three distinct highs extending from the aseismic ridge to the spreading center. The westernmost high may be the result of a diminishing flux to the spreading center from the flank of a primary conduit beneath the aseismic ridge. The central gravity high may be the manifestation of flux from the end of a conduit beneath the aseismic ridge to the spreading center. The termination of the aseismic ridge would result from the inability of the plume flux to break through the thickening lithosphere at some point in the systems evolution. The continuation of the broad gravity high from the end of the aseismic ridge suggests that some connection to the spreading center was maintained until ~8 Ma. The easternmost gravity high terminates at ~3.5 Ma the time at which spreading on this segment became symmetric [*Royer and Schlich,* 1988]. Although there is no direct evidence for a conduit of the type discussed by *Schilling* [1985, 1991], the restricted, elongate shape of these gravity highs could be the result of some sort of channelized flow pattern between the plume and the spreading center. The presence of three distinct features may be a result of the time evolution of the flow field resulting from the slight obliquity (~11°) of the spreading direction to the absolute motion of the ridge axis.

Further evidence for some form of large-scale plume-ridge flux is provided by the regional seismicity. Regional teleseismic events in the area between Kerguelen and the SEIR (Figure 3) with T axes parallel to the SEIR have been interpreted by *Bergman et al.*[1984] as resulting from the release of thermal and bending stresses, related to asthenospheric flux from Kerguelen to Amsterdam-St. Paul hotspot proposed by *Morgan* [1978]. The seismicity would however appear to support the assertion that the flux from Kerguelen is not to Amsterdam and St. Paul but rather to the SEIR near 87°E [*Small and Sandwell,* 1994].

The model of *Morgan* [1978] proposes that plume material which is channeled to the nearest point on the spreading center will create a "second type" of hotspot chain with an azimuth predicted by the vector sum of the ridge-perpendicular component of the ridge migration vector and the apparent motion vector of the plume with respect to the overriding plate. The azimuths of the aseismic ridges discussed above do not agree with those predicted by Morgan's model. On the Louisville/PAR system the predicted azimuth is 114°, and the azimuth of the aseismic ridge on the Pacific plate is 133°. On the Shona/MAR system the predicted azimuth is -90° and the azimuth of the aseismic ridge varies between -52° and -70°. Farther north, adjacent to the Falkland-Agulhas Transform, the aseismic ridge has an azimuth of -120° as compared to a predicted azimuth of -79°. The large (~60°) difference in the azimuths of these two aseismic ridges also seems to preclude any explanation based solely on absolute plate motions. The best agreement with Morgan's model is found with the broad gravity highs on the southern flank of the SEIR; the gravity lineations have a mean azimuth of 33° and the predicted azimuth is 44°. These gravity highs may reflect the effect of shallower, thicker crust resulting from underplating of plume material rather than extrusives which have reached the spreading center itself. One complicating factor is that Morgan's model discusses only the manifestation at the spreading ridge axis of the plume material but does not address the nature of the plume-ridge flow when the ridge is migrating obliquely to the direction of spreading. In this case it is not clear whether a connecting conduit will maintain a curvature through time or whether a new conduit will be established periodically (J.G. Schilling, personal communication, 1994). The three parallel gravity highs between the Kerguelen hotspot and the SEIR may therefore represent three different phases of plume-ridge connection.

Discrete Ridge Jumps Versus Offset Propagation

It is interesting that the gravity maps show ridge parallel lineations suggestive of abrupt, discrete ridge jumps rather than V-shaped lineations expected of propagating offsets. In more well-studied systems, such as the Galapagos hotspot [*Hey and Vogt,* 1977] and Ascension/Circe and St. Helena hotspots [*Brozena and White,* 1990], ridge migration away from hotspots is delayed by ridge jumps, but they are associated with propagating offsets. If the features discussed in this study are indeed the traces of ridge jumps then the question arises as to why the spreading center moves abruptly rather than gradually by propagation as is seen in many other locations. *Phipps Morgan and Sandwell* [1994] find evidence for a number of such propagating offsets in the satellite gravity data set used here so the ability to resolve these features is not likely to explain their absence. Examples are shown in Plate 1 north of the Eltanin FZ and to the NW of the Amsterdam-St. Paul massif. The latter features diverge from a point at the center of the segment, possibly indicating nucleation of a bidirectional rift propagating toward both segment ends simultaneously. The obvious source of a segment wide weakening for the ridge jumps would be the excess temperature of plume flux entrained by the spreading center. In order for this to occur, the plume flux must disperse along a ridge segment in a manner sufficient to weaken the entire segment flank simultaneously thereby allowing the locus of spreading to jump instantly. The simple model shown in Figure 2 is intended merely to demonstrate that a finite zone of relative weakness surrounds the ridge axis. This model actually represents an upper bound on the difficulty a ridge relocation must overcome; melting of upwelling plume material, diking of melt, dynamic uplift resulting in ridge push, and thermomechanical lithospheric erosion by plume-ridge flux all offer viable mechanisms for weakening the lithosphere and encouraging ridge jumps in the direction of the plume. Simple models for ridge jumps indicate that buoyancy forces resulting from lower density material at the base of the lithosphere may be sufficient to overcome ridge push forces and induce tensional stresses on the near axis flank of a fast spreading ridge (N. Sleep, personal communcation, 1995). Thermal weakening coupled with these buoyancy forces may be sufficient to bring about a discrete jump in the location of the ridge axis. One puzzling aspect of the apparent ridge jumps described here is the short distance which they seem to jump, generally less than 20 km. Although it is easier for a ridge to jump a short distance (N. Sleep, personal communication, 1995), it is not clear what energetic advantage could be gained by such a small relocation.

If the plume material were dispersing along an entire segment of the spreading center, then it should be reflected by decreased subsidence on the proximal flank between the plume and the spreading center. Bathymetric coverage in the South Atlantic and Southeast Indian areas is not sufficient to test this prediction but the profile shown in Figure 4 verifies that this is indeed the case at the South Pacific area. Subsidence is nearly symmetric about the ridge axis between the aseismic ridge and the abandoned rise axis in the past 3 M.y.. Since the Pacific flank is spreading at ~60% the rate of the Antarctic flank, it is therefore anomalously shallow. On the older portions of the rise flanks the Pacific plate is consistently at least 500 m deeper than the Antarctic plate at any given distance from the rise axis as would be expected.

The most direct way to test the initiation scenario would involve surveying and sampling the aseismic ridges at either the South Atlantic or South Pacific systems. Age information on both the aseismic ridge and adjacent seafloor would constrain the timing of the ridge's formation. Isotopic and trace element signatures may confirm or refute a plume origin for the ridges and age dating would allow for determination of an age progression approaching the spreading center. Rock samples collected at the Shona spreading segment suggest plume enrichment but it is not yet possible to pinpoint the location of the hotspot (J. Douglass et al., submitted manuscript, 1995]; a more detailed survey of the region to the south will be necessary. Samples from the Discovery segment also show plume enrichment but again off axis surveying and sampling are not adequate to determine the current location of the plume. Sampling of the PAR axis also appears to confirm a plume influence [*Castillo et al.*, 1994], but the relationship to the aseismic ridge is not known. If the plume is still off axis then the primary melt might be expected to be erupted at the aseismic ridge with the more refractory residual components being transported to the spreading center and possibly being underplated rather than erupted (R. Buck, personal communication, 1994). Sampling the ridge axis and the seamounts in the corridor between the SEIR and the Kerguelen Plateau could establish not only the extent of plume influence on the present-day ridge axis but also the time evolution of the plume-ridge interaction. Ultimately, combined geophysical and geochemical programs would allow the more detailed interdisciplinary approaches of *Schilling* [1991] and *Ito and Lin* [1995] to be employed.

Conclusions

The majority of well-studied ridge-hotspot systems involve a ridge migrating away from a hotspot; the cases discussed here involve ridges migrating toward hotspots, hotspot dominated ridges and a ridge migrating away from a hotspot. Although each of these systems is characterized by a paucity of underway geophysical data, they are clearly depicted in satellite gravity maps which provide medium resolution ($\lambda >$ ~35 km) view of the interaction between hotspots and migrating ridges.

The Louisville-PAR and Discovery-MAR systems illustrate primary stages of ridge-hotspot interaction in which a migrating spreading center begins to entrain some amount of the plume's flux. The Shona-MAR system is an example of a migrating ridge which appears to have been "captured" by a plume and now entrains the majority of the plume's flux over a longer length of spreading center. The Kerguelen-SEIR system illustrates a much later stage in which the spreading center has migrated away from a formerly ridge centered hotspot and is now experiencing a diminishing plume influence. All three systems are marked by what appears to be a complex redistribution of plume material which influences several distinct spreading center segments rather than manifesting itself as a single eruptive center as in the case of intraplate hotspots.

Satellite-derived gravity maps suggest the occurrance of discrete ridge jumps toward the hotpot in all of the systems discussed here. The jumps are manifest by ridge-parallel lineations that coincide with basement deeps which resemble slow to intermediate spreading rate ridge axes. On the Louisville/PAR system magnetic anomaly data are available and show an extra anomaly coinciding with the lineation. In three of the cases discussed here the jumps occur prior to the spreading center crossing the hotspot; in the Kerguelen/SEIR case the jumps occur in the opposite direction as the spreading center migrates away from the hotspot. The Discovery-MAR system may currently be in the process of ridge jumping.

A simple model of migrating ridge-hotspot interaction illustrates the presence of a broad, relatively weak region near the ridge axis which may allow ridge jumps to occur with a minimum of extenuating circumstances. This model also predicts that a spreading center migrating toward a hotspot will experience increasing plume influence with time which may allow the plate boundary to accelerate toward the plume and even promote discrete jumps in the location of the spreading center. The presence of segment long, ridge-parallel lineations and the absence of propagating rift traces in these systems suggests that any relocation of the spreading center must be essentially instantaneous. In the cases of spreading centers migrating toward hotspots or being captured, these discrete jumps on the distal rise flank coincide with the termination of oblique aseismic ridges on the proximal flank. It is proposed here that these aseismic ridges are the result of plume flux entrained by the spreading center and that the ridge jumps may, in some cases, be related the capture of the spreading center by the plume. This mechanism also explains the obliquity of the aseismic ridges as the surface manifestation of the buoyant plume flux which migrates updip along the base of the lithosphere away from the cool end of the spreading segment toward the center of the segment. If it can be verified that these aseismic ridges are actually the manifestation of plume flux to the spreading center, then the proposed mechanism would suggest that the presence of a line sink at the spreading center can influence the dynamics of the plume flux as it begins to interact with the lithosphere and would extend *Schilling*'s [1985] plume source-ridge sink model to the case of ridges which have not yet crossed a hotspot.

Appendix: Strengthening of Oceanic Lithosphere

In this simple example, oceanic lithosphere is assumed to strengthen as it cools and thickens. A two-layer, brittle/ductile rheology is assumed where the strength is given by the integral of the yield stress envelope over the thickness of the lithosphere (equation (1)). The yield stress envelope is the smaller of either the brittle or ductile failure relation at a given depth z [*Brace and Kohlstedt*, 1980]. In the case of a cooling lithosphere, the brittle strength increases with depth, while the ductile strength decreases with depth. The brittle deformation in tension is described by the empirical relation of *Byerlee* [1978] as reported by *Wessel* [1992]

$$\Delta\sigma(z) = 0.786\, \rho g z, \qquad \sigma < 200 \text{ MPa} \qquad \text{(A1)}$$

where $\rho = 2670\ kg/m^3$ for the crust and $3000\ kg/m^3$ for the mantle with the Moho set at 7 km depth.

The ductile deformation [*Goetze*, 1978; *Evans and Goetze*, 1979; *McNutt and Menard*, 1982] is approximated by the relationship

$$\Delta\sigma(z) = \left[\frac{\dot{\varepsilon}}{B_1} \exp\left(\frac{Q_1}{RT(z)}\right)\right]^{\frac{1}{n}} \quad \Delta\sigma < 200\ \text{MPa} \qquad \text{(A2)}$$

where $\varepsilon = 10^{-15}\ s^{-1}$, $B_1 = 6.12 \times 10^{-2}\ MPa^{-n}\ s^{-1}$, $Q_1 = 2.76x10^5$ J/mol, $R = 8.3144$ J $Mol^{-1}\ K^{-1}$, $n = 3.05$ for a diabase crust [*Caristan*, 1982] and $B_1 = 5.28x10^5\ MPa^{-n}\ s^{-1}$, $Q_1 = 5.28x10^5$ J/mol , n = 3.5 for an olivine mantle [*Kirby and Kronenberg*, 1987].

The geothermal gradient, T(t,z), is approximated by a cooling half space model [*Turcotte and Oxburgh*, 1967] as

$$T(t,z) = T_m\ \text{erf}\left(\frac{z}{2\sqrt{\kappa t}}\right) \qquad \text{(A3)}$$

where $T_m = 1600°K$ and $\kappa = 10^{-6}\ m^2\ s^{-1}$. In the case of plume heated lithosphere T_m is increased by the excess temperature of the plume ($T = T_M + T_E$). The effect of hydrothermal cooling is included by assuming that the lithosphere is cooled to 273°K to a depth of 2 km. The time dependence of the thermal model implies a time dependence of the ductile deformation relation (A2) which results in strengthening of the lithosphere with age shown in Figure 2.

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