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RIDGE-HOTSPOT INTERACTIONS

What Mid-Ocean Ridges Tell Us About Deep Earth Processes

BY JÉRÔME DYMENT, JIAN LIN, AND EDWARD T. BAKER

Earth is a thermal engine that dissipates its internal heat primarily through convection. The buoyant rise of hot material transports heat to the surface from the deep interior while colder material sinks at subduction zones. Mid-ocean ridges and hotspots are major expressions of heat dissipation at Earth's surface, as evidenced by their abundant volcanic activity. Ridges and hotspots, however, could differ significantly in their origins. Ridges are linear features that wind more than 60,000 km around the globe, constituting the major diverging boundaries of Earth's tectonic plates. Hotspots, on the other hand, are localized regions of abnormally robust magmatism and distinctive geochemical anomalies (Figure 1).

The causes of hotspots and their depths of origin are the focus of an intense debate in the scientific community. The "plume" model hypothesizes rising of buoyant mantle plumes as the primary cause of prominent hotspots such as Iceland and Hawaii (Morgan, 1971). In contrast, the "anti-plume" school argues that many of the observed "hotspot" volcanic and geochemical anomalies are simply due to melts leaking through tensional cracks in Earth's lithospheric plates—in other words, hotspots reflect only where the lithospheric plate is cracked, allowing melts to pass through, and not where the underlying mantle is hotter (see www.mantleplumes.org). A hybrid notion is that only a relatively small number of hotspots, especially those of enormous magmatic volumes, have their origin in buoyant thermal plumes rising from the deep mantle (e.g., Courtillot et al., 2003). Regardless of its specific depth of origin, however, when a hotspot is located close enough to a mid-ocean ridge, the two volcanic systems will interact, resulting in unique volcanic, geochemical, and hydrothermal features. In this paper, we discuss major features of hotspot-ridge interactions.

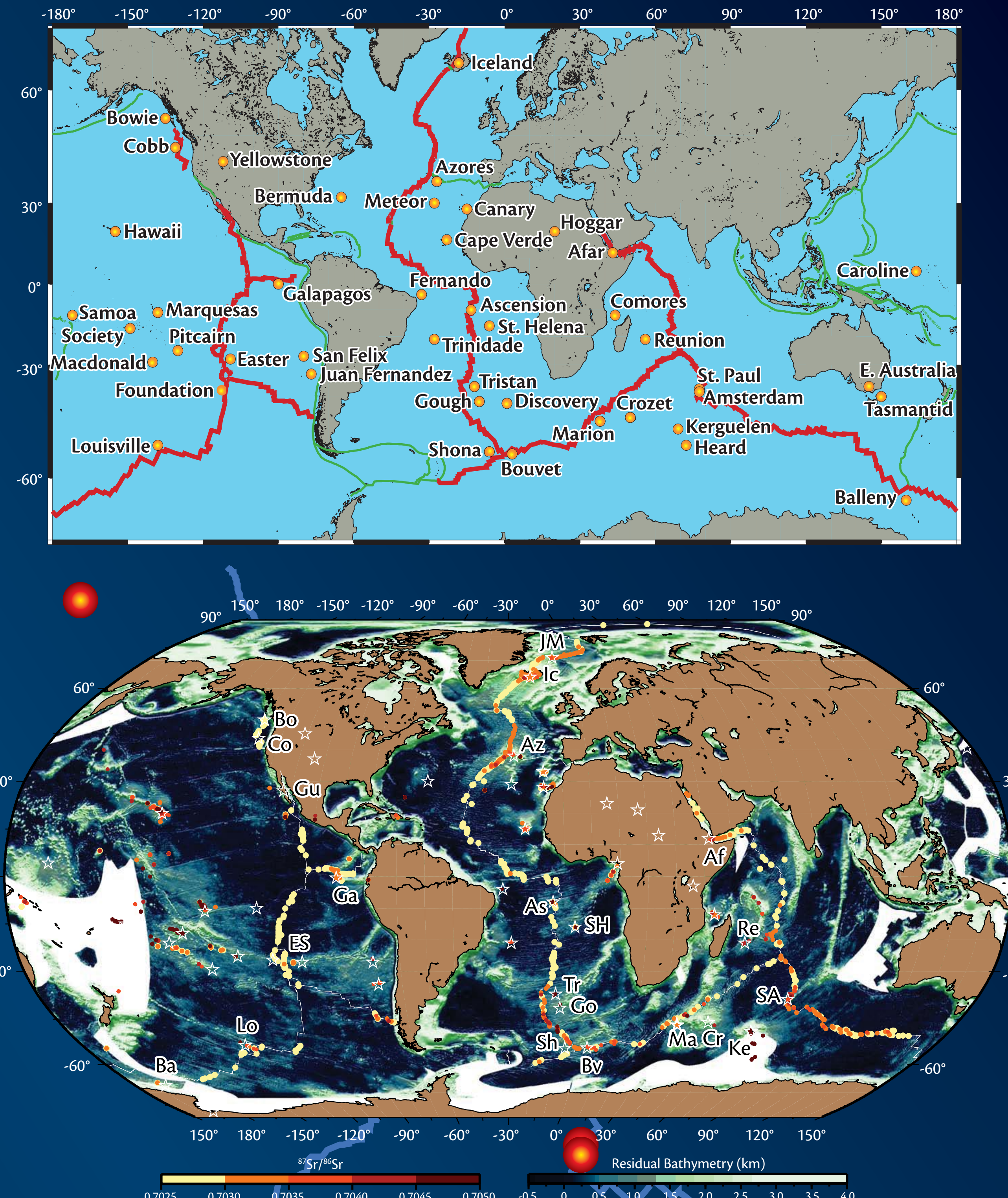


Figure 1. (Top) Map of the world's major hotspots (orange circles) showing that many of them are integrally connected to the global mid-ocean ridge systems (red lines) (Lin, 1998). (Bottom) Map of residual bathymetry of the ocean basins and $^{87}Sr/^{86}Sr$ geochemical anomalies from samples collected along the mid-ocean ridges and ocean islands (Ito et al., 2003). A positive residual bathymetry marks anomalously shallow seafloor relative to the theoretical prediction of Stein and Stein (1992). Circles mark rock sample locations and are colored according to $^{87}Sr/^{86}Sr$ value. Hotspots are shown by stars, and hotspots influencing mid-ocean ridges are labeled: Af = Afar, As = Ascension, Az = Azores, Ba = Balleny, Bo = Bowie, Bv = Bouvet, Co = Cobb, Cr = Crozet, ES = Easter/Sala y Gomez, Ga = Galápagos, Go = Gough, Gu = Guadalupe, Ice = Iceland, JM - Jan Mayen, Ke = Kerguelen, Lo = Louisville, Ma = Marion, Re = Reunion, SA = St. Paul-Amsterdam, Sh = Shona, SH = St. Helena, Tr = Tristan de Cunha.

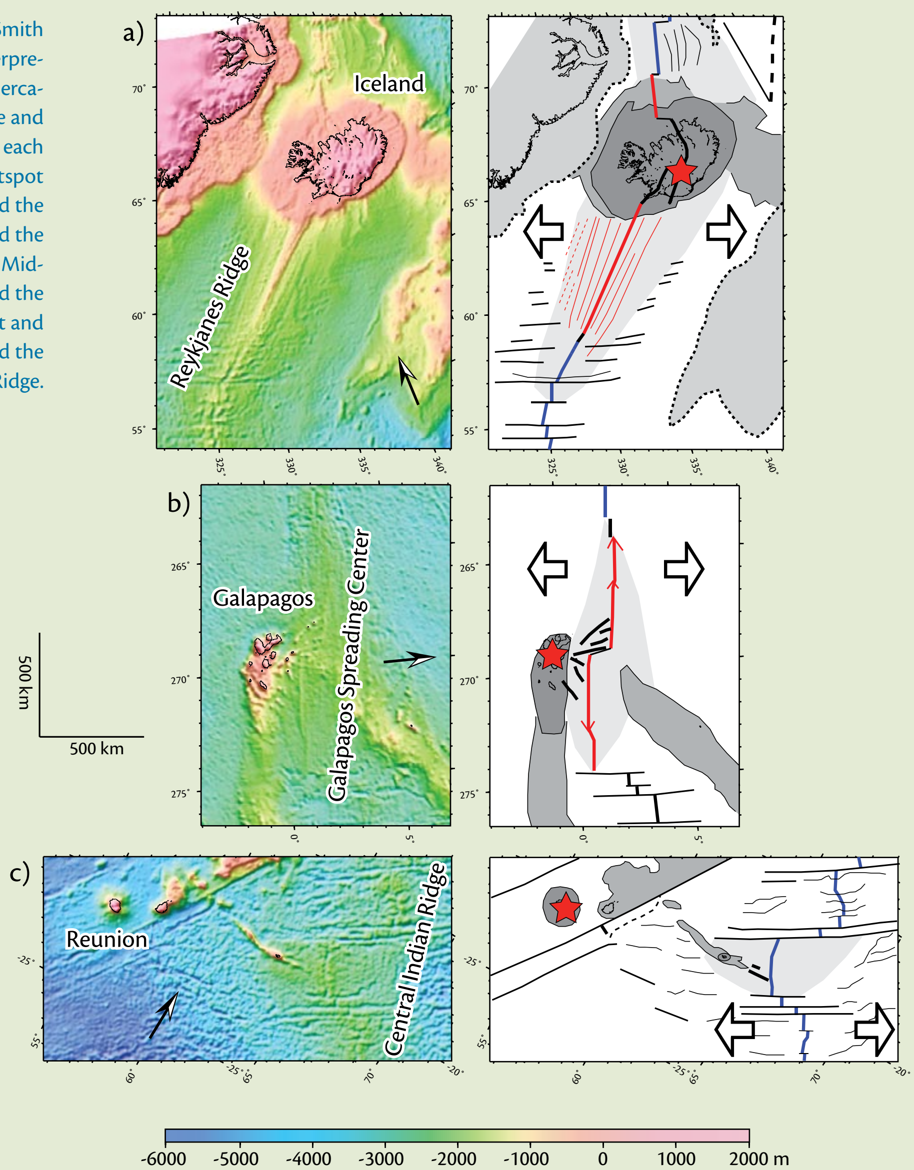
MULTIDISCIPLINARY APPROACHES ARE ESSENTIAL

Ridge-hotspot interactions illustrate important thermal and geological processes and provide unique windows into the chemical composition and heterogeneities of Earth's mantle. To best understand these processes, it is essential to adopt multidisciplinary approaches and to analyze and interpret observational constraints within the framework of conceptual models of ridge-hotspot interactions. Meanwhile, computational modeling and laboratory-based physical experiments play an equally critical role in shaping our thinking on the physical processes of these systems. Here we illustrate how commonly used observational approaches help to advance understanding of ridge-hotspot interaction.

Bathymetry

The influence of hotspots on mid-ocean ridges can be seen most clearly in unusual bathymetry, including shallower-than-normal ridge-axis seafloor depth, underwater plateaus, or volcanic islands rising from the seafloor (Figure 2). The elevated topography near a hotspot is the direct result of thickening of the oceanic crust both by erupting magmas on top of it and intruding magmas near its base. The active upwelling of hotter mantle plumes can also lead to the development of long-wavelength seafloor topographic swells, as observed in some hotspot-ridge systems (e.g., Sleep, 1990; Canales et al., 2002). It has also been observed that ridge segments most influenced by hot-

Figure 2. Maps of predicted seafloor bathymetry (Smith and Sandwell, 1997) and corresponding tectonic interpretations of seven ridge-hotspot systems in oblique Mercator projection so that all maps are at the same scale and the spreading direction is horizontal. A large arrow in each bathymetric map indicates north. (a) Iceland hotspot and the Reykjanes Ridge. (b) Galápagos hotspot and the Galápagos Spreading Center. (c) Reunion hotspot and the Central Indian Ridge. (d) Azores hotspot and the Mid-Atlantic Ridge. (e) Foundation seamount chain and the Pacific-Antarctic Ridge. (f) St. Paul-Amsterdam hotspot and the Southeast Indian Ridge. (g) Marion hotspot and the Southwest Indian Ridge.



spots commonly elongate (“propagate”) at the expense of neighboring segments, resulting in characteristic V-shaped segment discontinuities pointing away from the hotspots (e.g., Phipps Morgan and Sandwell, 1994) (Figure 2).

Mantle Geochemistry

Understanding the size and origin of mantle heterogeneities, and thus the efficiency of convection in homogenizing the mantle, is a primary topic of geochemistry (see also article by Langmuir and Forsyth, this issue). Mid-ocean ridges offer unique access to the diversity of mantle signatures. Rock samples from most ridge segments show “normal” mid-ocean ridge basalt (N-MORB) signatures, while those from hotspots often show “enriched” mid-ocean ridge basalt (E-MORB) signatures with distinctive characteristics in trace elements and isotopic ratios such as La/Sm, K/Ti, Nb/Zr, $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$, $^{206}Pb/^{204}Pb$, and $^{3}He/^{4}He$. Rocks sampled at hotspot-affected ridges exhibit telltale geochemical variations that can generally be ex-

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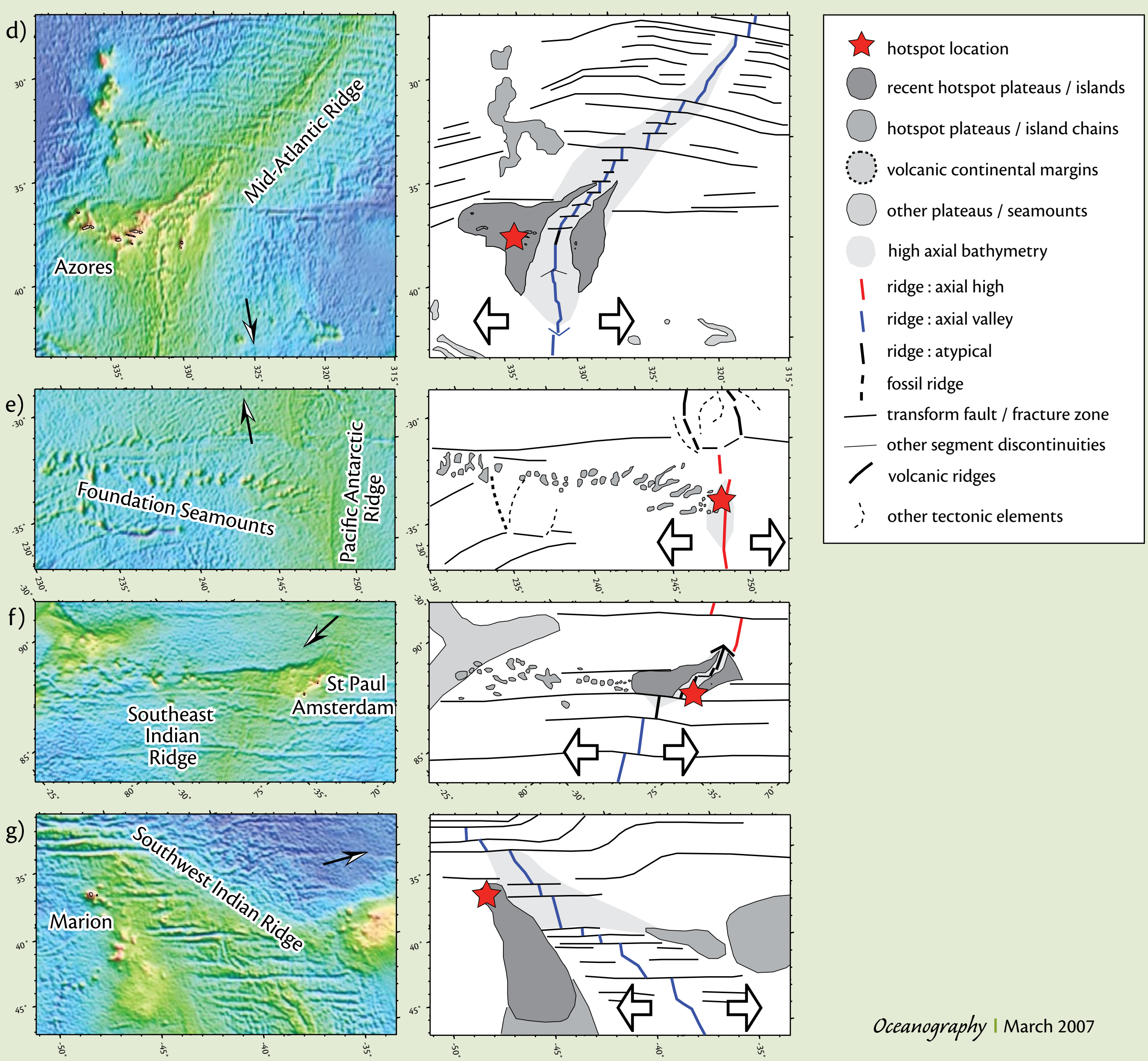


plained by the mixing of "normal" and hotspot mantle materials (e.g., Schilling, 1991). Geochemistry thus provides an invaluable tool to trace how hotspot materials flow and mix with the "normal" upper mantle. The higher abundance of iron in some hotspot regions, such as Iceland, also suggests that mantle melting starts at a greater depth in the mantle beneath hotspots (e.g., Klein and Langmuir, 1987; Shen and Forsyth, 1995), resulting in thicker-than-normal magmatic crust and causing lower-than-normal seismic velocity at depth. Geochemical constraints allow researchers to trace the various geochemical signatures of hotspot material to different mantle components, such as recycled oceanic lithosphere, oceanic crust, or sediments that have been stirred by mantle convection (e.g., Hofmann, 1997).

Ridge-hotspot interactions illustrate important thermal and geological processes and provide unique windows into the chemical composition and heterogeneities of Earth's mantle.

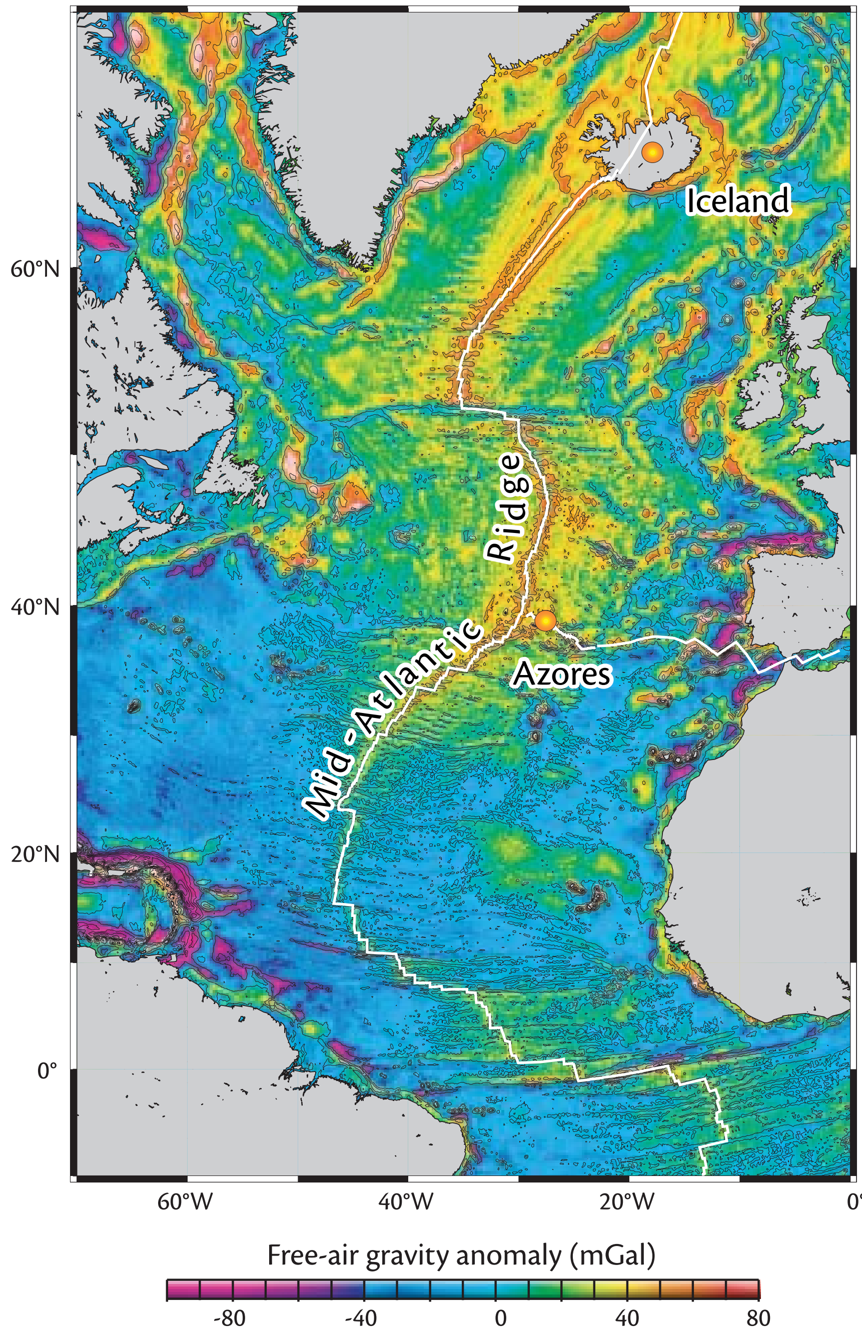
Marine Gravity and Magnetics

Gravity data are commonly used to investigate changes in crustal and mantle density structure caused by ridge-hotspot interactions. Regions influenced by hotspots are systematically associated with more negative residual mantle Bouguer anomalies, reflecting thicker crust and lighter-than-normal materials beneath the seafloor. When combined with independently acquired seismic data, the calculations of residual mantle Bouguer anomalies are especially useful in determining how crustal thickness changes along a specific ridge-hotspot system, enabling researchers to quantify the supply of excess magma and heat to a ridge system due to the influence of a hotspot. Because seismic experiments at sea are intrinsically costly and thus remain scarce, residual mantle Bouguer calculations are instrumental in providing a first-order model of the relative crustal thickness variations for many ridge-hotspot systems (e.g., Ito and Lin, 1995; Ito et al., 2003). Magnetic anomalies and dating of rock-eruption ages, on the other hand, are essential for determining the ages of the oceanic crust and for reconstructing a kinematical history of interacting ridge-hotspot systems (e.g., Dyment, 1998; Müller et al., 1998, 2001).

Seismic Tomography and Reflection/Refraction Experiments

Seismic methods are the only direct way to measure the physical properties of Earth's crust and mantle at relatively good resolutions. Over the last decade, major advances have been made in using state-of-the-art tomographic inversion methods to determine the physical properties of mantle rocks beneath hotspots (e.g., Montelli et al., 2004). The resolution of seismic tomography is significantly improved by installing broadband seismic stations directly on top of ocean islands. For example, seismic tomography revealed that a relatively narrow "root" of low seismic velocity extends to at least 400 km beneath Iceland (Wolfe et al., 1997) (Figure 3). Investigations of P-to-S-wave conversions provided evidence of thinning of the upper-to-lower mantle transition zone between the 410- and 660-km seismic discontinuities, confirming that the "root" of the mantle plume beneath Iceland is relatively narrow (Shen et al., 1998). Similar results from deployments of broadband seismic stations on various islands of the Galápagos Archipelago revealed seismic velocity anomalies within the mantle domain along the direct path between the Galápagos hotspot and the nearby Galápagos Spreading Center (Villagómez et al., submitted).

Seismic reflection/refraction experiments at sea are essential for measuring the thickened oceanic crust due to hotspots. By analyzing seismic signals that are emitted from airguns towed behind a ship but recorded on ocean bottom seismometers, researchers are able to determine the seismic crustal thickness of a ridge system using various seismic refraction and reflection techniques. An experiment along the Galápagos Spreading Center, for example, revealed a gradual increase in crustal thickness approaching the 91°W region, where the ridge axis is closest to the Galápagos hotspot (Detrick et al., 2002; Canales et al., 2002) (Figure 4). Seismic refraction experiments around Iceland similarly revealed that the maximum crustal thickness there is several times that of



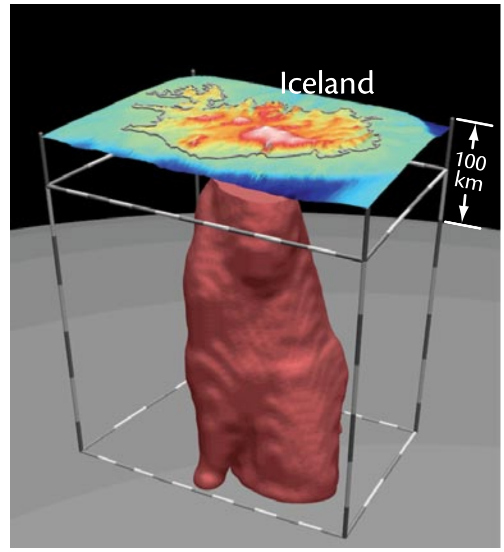
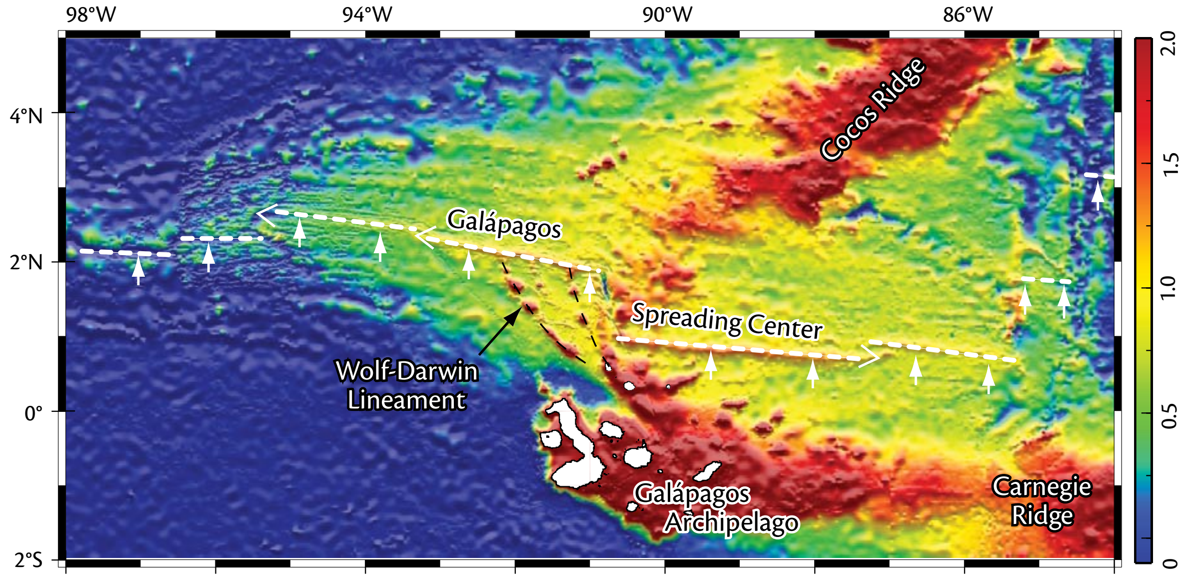


Figure 3. (Left) Map of satellite-derived, free-air gravity data (*Sandwell and Smith, 1997*) revealing that regions of unusually thick and elevated oceanic crust (red and yellow) extend hundreds of kilometers from the Iceland and Azores hotspots along the Mid-Atlantic Ridge. The two hotspots appear to have influenced nearly the entire northern segment of the Mid-Atlantic Ridge (Lin, 1998). (Right) Seismic image of the upper mantle beneath the Iceland hotspot showing a relatively narrow cylindrical "root" of a low-velocity anomaly of approximately 2 percent for P-waves and 4 percent for S-waves, indicating anomalously hot rocks extending to a depth of at least 400 km (Wolfe et al., 1997). *Reprinted with permission from Macmillan Publishers Ltd: Nature, copyright 1997*

the average crustal thickness of normal mid-ocean ridges (e.g., Darbyshire et al., 2000), while the maximum crustal thickness along the Reykjanes Ridge is twice that of the average values for normal ocean ridges (Weir et al., 2001).

STYLES OF RIDGE-HOTSPOT INTERACTIONS

The interaction of a hotspot with a ridge exhibits a variety of styles, depending on the vigor of the hotspot, the geometry and spreading rate of the ridge, the distance separating the ridge and hotspot, the relative motion between the two systems, and the presence of large fracture zones that tend to restrict the along-ridge extent of hotspot influence. Using ridge-hotspot distance as a



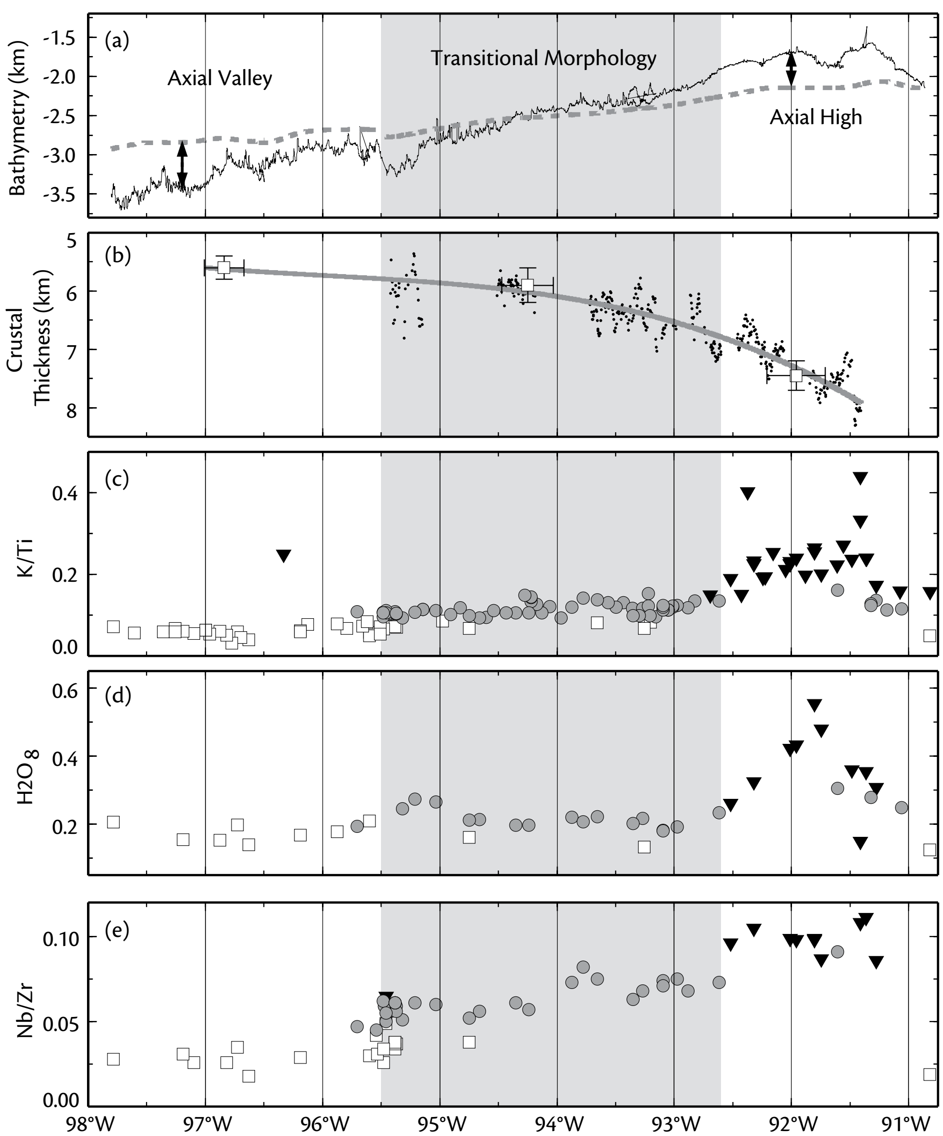


Figure 4. (Top) Map of residual bathymetry showing the interaction between the Galápagos Spreading Center (white dotted lines) and the Galápagos hotspot (*Ito et al., 2003*). Note that the Wolf-Darwin Lineament and other volcanic features (black dashed lines) appear to connect the Galápagos Archipelago to the Galápagos Spreading Center. (Bottom) Correlations between bathymetric, geophysical, and geochemical anomalies along the Galápagos Spreading Center (*Detrick et al., 2002*). (a) Measured ridge-axis seafloor depth (solid lines) and filtered long-wavelength regional depth (dashed lines). (b) Crustal thickness constraints from wide-angle seismic refraction (open squares) and multichannel seismic reflection (dots). (c) Incompatible element ratio K/Ti in basalts sampled along the ridge axis (hotspots have high K/Ti, while normal ridge axes have low K/Ti). (d) Water concentration (corrected for low-pressure crystallization) of basalt samples (see also the discussion of "wet spots" in Langmuir and Forsyth, this issue). (e) Incompatible element ratio Nb/Zr measured in basalt samples. Inverted triangles indicate enriched MORB (defined as K/Ti > 0.15), illustrating the chemical influence of the Galápagos hotspot. Open squares are normal MORB (with K/Ti < 0.15), while shaded circles are transitional MORB (defined as 0.09 < K/Ti < 0.15).

parameter, the ridge-hotspot systems can be categorized into the following three general groups.

Type 1: Ridges over Hotspots

For a ridge located right above a hotspot, the hot mantle material directly feeds the ridge, resulting in a major thermal anomaly, abundant magma production, and sometimes the formation of an oceanic plateau or an island. The geochemical signature of the hotspot material often diminishes gradually along the ridge axis away from the hotspot center.

Iceland is the most prominent present-day example of an on-ridge hotspot (Figure 3). Seismic tomography images show a relatively narrow "root" in the upper mantle beneath Iceland (e.g., Wolfe et al., 1997). The influence of the hotspot is clearly visible from the fact that Iceland rises above sea level and also from the gradual deepening of the ridge-axis depth north and south of Iceland for more than 1000 km (e.g., Searle et al., 1998). The elevated topography is associated with long-wavelength negative residual mantle Bouguer anomalies (e.g., Ito et al., 1996) and crustal-thickness variations (e.g., Darbyshire et al., 2000), suggesting significant along-ridge changes in magma supply. V-shaped seafloor fabrics pointing away from Iceland are particularly prominent along the Reykjanes Ridge (Figure 3). Seismic refraction measurements across the Reykjanes Ridge indicate that the V-shaped ridges are associated with slightly thickened crust (Weir et al., 2002), supporting the hypothesis that the Iceland hotspot has experienced major magmatic-surge episodes on time scales of a few million years (e.g., Ito, 2001). The chemical composition of basalt samples, such as La/Sm, $^{87}Sr/^{86}Sr$, and $^{3}He/^{4}He$ ratios, reveals systematic along-ridge variations, supporting the hypothesis of mixing of "normal" and hotspot mantle materials (e.g., Hart et al, 1973; Schilling, 1991; Chauvel and Hemond, 2000).

Type 2: Ridges in Close Proximity to Hotspots

For a ridge located in close proximity to a hotspot, typically a few hundred kilometers or less, a fraction of the hot mantle material (Schilling, 1991) or melt (Braun and Sohn, 2003) might migrate toward the ridge along the base of the asthenosphere and mix with "normal" mantle or melt to form enriched basalts observed at the ridge axis. Some of this channelled hotspot material may leak through the overlying oceanic lithosphere to generate the volcanic lineaments sometimes observed between ridges and nearby hotspots. There are a large number of present-day examples of near-ridge hotspots, including Galápagos (e.g., Detrick et al., 2002; Sinton et al., 2003), Azores (Cannat et al., 1999; Gente et al., 2003), Easter (Kingsley and Schilling, 1998), Foundation (Maia et al., 2000), St. Paul-Amsterdam (Conder et al., 2000), Marion (Georgen et al., 2001; Georgen and Lin, 2003), and Tristan da Cunha (Schilling et al., 1985).

The Galápagos is a classic example of a near-ridge hotspot (Figure 4). The Galápagos Spreading Center was on top of the hotspot about 10 million years ago. The relative northward motion of the ridge system with respect to the hotspot has resulted in the generation of the complex terrains of the Cocos Ridge, Carnegie Ridge, and other features (Figure 4). The Galápagos Archipelago, which lies about 200 km south of the Galápagos Spreading Center at present, consists of a broad oceanic plateau with a number of oceanic islands. Radial volcanic features, including the Wolf-Darwin Lineament, appear to have connected the Galápagos Archipelago to the ridge axis. Recent detailed morphological study found that several sections of the Galápagos Spreading Center are magmatically "deflated" where these off-axis volcanic lineaments meet the ridge axis, suggesting direct magmatic interactions (Sinton et al., 2003). Seismic modeling using P-to-S-wave conversion techniques revealed an anomalously thin upper-to-lower-mantle transition zone between the temperature-sensitive 410- and 660-km mantle seismic discontinuities, suggesting mantle-plume upwelling from depths greater than 410 km beneath the Galápagos hotspot (Hooft et al., 2003), similar to the results obtained for the Iceland (Shen et al., 1998) and Society (Niu et al., 2002) hotspots.

Along the Galápagos Spreading Center, the seafloor is shallowest immediately north of the Galápagos Archipelago and gradually deepens to the east and west (Figure 4a). Furthermore, the ridge axis changes from an axial-high morphology, where the hotspot influence is the greatest, to an axial valley in distal regions where the magma supply is lower. Seismic studies reveal that the crustal thickness is 5.5 km at 97°W, but gradually increases to 8 km at 91.5°W where the hotspot influence is strong (Detrick et al., 2002; Canales et al., 2002) (Figure 4b). Such changes in seafloor depth and crustal thickness correlate well with variations in residual mantle Bouguer anomalies (Ito and Lin, 1995). Basalt samples collected along the ridge axis and on the Galápagos platform exhibit systematic geochemical anomalies in K/Ti, Nb/Zr (Figure 4), $^{87}Sr/^{86}Sr$, $^{3}He/^{4}He$, and other elements, indicating strong plume-ridge interactions (e.g., Schilling et al., 1982; Graham et al., 1993; Detrick et al., 2002; Cushman et al., 2004).

Type 3: Ridges Farther Away from Hotspots

For a ridge located farther away from a hotspot but still showing evidence of hotspot influence, there may be limited migration of hotspot material toward the ridge through asthenospheric flow, as for the Type 2 case (e.g., Conder, et al., 2002). It is also possible that the asthenospheric mantle that presently lies beneath the ridge has passed near a hotspot at an earlier time and thus has been contaminated by hotspot material—for such contamination to occur, the ridge must have been located previously in the vicinity of a hotspot track. Such an interaction may be observed between the Reunion hotspot and the Central Indian Ridge (Figure 5).

Although presently located 1000 km away from the Central Indian Ridge, the Reunion hotspot may still exert distal or residual influence on the Central Indian Ridge at ~ 19°S (Figure 5). The unusually smooth and elevated bathymetry, the basalt geochemical composition, and the geophysical characteristics of the Central Indian Ridge segment at 19°S all suggest a hotspot influence (e.g., Mahoney et al., 1989). The Rodrigues Ridge is an east-west trending volcanic feature that was formed between 7 and 10 million years ago and that appears to partially connect the Reunion-Mauritius hotspot track to the present-day Central Indian Ridge axis, thus reflecting some type of distal ridge-hotspot interaction (Morgan, 1978). The recent discovery of smaller bathymetric features—the Three Magi and Gasitao Ridges, which extend the Rodrigues Ridge farther east to the near vicinity of the Central Indian Ridge—strongly demonstrates the persistent hotspot influence on the Central Indian Ridge during the last 2 million years (Dyment et al., 1999). However, it is not yet clear whether these

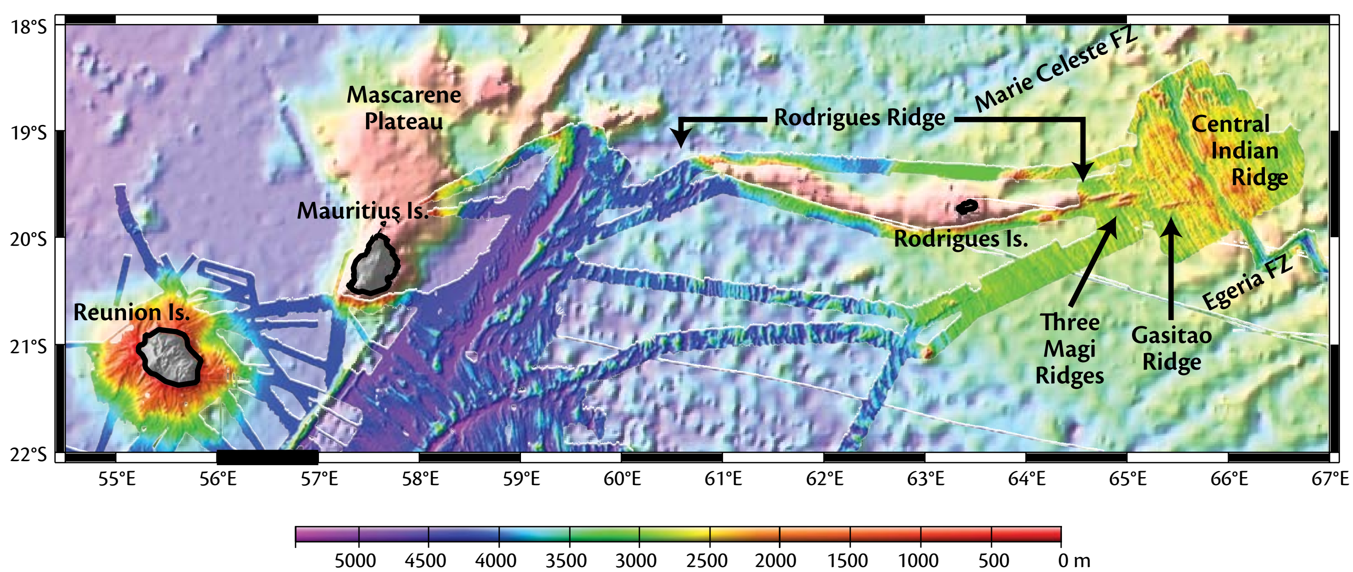


Figure 5. Map of bathymetry showing the relationship between the Reunion-Mauritius hotspot track and the Central Indian Ridge, which is located more than 1000 km away (*Dyment et al., 1999*). Note that a series of east-west trending volcanic ridges are located between the Mauritius Plateau and the Central Indian Ridge, including the relatively large Rodrigues Ridge and the smaller Three Magi and Gasitao Ridges. Full colors show multi-beam bathymetric data, and pale colors the satellite-derived bathymetry (*Smith and Sandwell, 1997*).

east-west trending volcanic lineaments indicate progressively eastward lengthening of a "hotspot conduit" connecting the Reunion-Mauritius hotspot to the eastward-migrating Central Indian Ridge or whether they instead reflect the presence of lithospheric tensional cracks through which melts from the hotspot-contaminated mantle can pierce the lithosphere (e.g., Forsyth et al., 2006).

The three categories above can be viewed as snapshots taken at different stages of the interaction of a ridge with a hotspot (Figure 6): The ridge approaches the hotspot (Stage 1); starts to interact with the hotspot (Stage 2, Type 2); passes over the hotspot and potentially develops an oceanic plateau (Stage 3, Type 1);

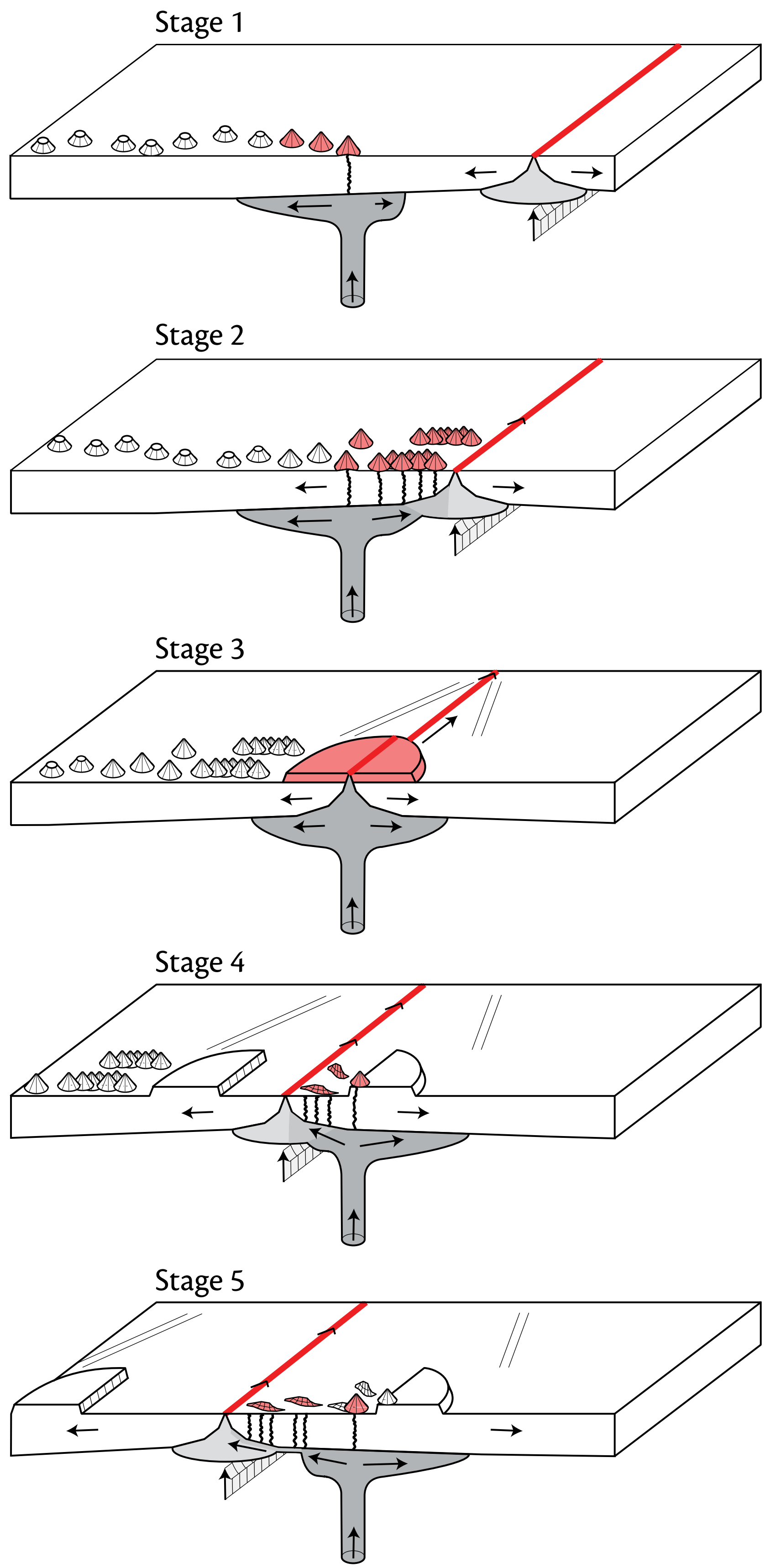


Figure 6. Schematic diagram showing evolution of an interacting ridge-hotspot system. The ridge axis is assumed to migrate to the left relative to the hotspot reference frame. Active volcanic structure is marked by red (ridge) and pale red (hotspot).
Stage 1: The ridge approaches the hotspot.
Stage 2: The ridge starts to interact with the hotspot (e.g., Foundation seamount chain and Pacific-Antarctic Ridge, Figure 2e).
Stage 3: The ridge passes over the hotspot and builds an oceanic plateau (e.g., Iceland hotspot and Reykjanes Ridge, Figures 2a and 3).
Stage 4: The ridge remains in the hotspot vicinity for a while through asymmetric spreading, segment propagation, and ridge jumps (e.g., Galápagos hotspot and Galápagos Spreading Center, Figures 2b and 4; Azores hotspot and Mid-Atlantic Ridge, Figure 2d; St Paul-Amsterdam hotspot and Southeast Indian Ridge, Figure 2f; Marion hotspot and Southwest Indian Ridge, Figure 2g).
Stage 5: The ridge progressively escapes the hotspot influence (e.g., Reunion hotspot and Central Indian Ridge, Figures 2c and 5). Variability in this model depends on the vigor of the hotspot, the ridge spreading rate, the ridge–hotspot relative motion, and the presence of fracture zones that tend to restrict the along-ridge extent of the hotspot influence.

remains in the hotspot vicinity for a while through spreading asymmetry, segment propagation, and ridge jumps (Stage 4, Type 2); and then progressively escapes the hotspot influence (Stage 5, Type 3). Note that in Stages 1 and 2, as the ridge approaches the hotspot, the motion of the oceanic plate opposes the motion of hotspot material toward the ridge axis, making the interaction harder to establish. Conversely, in Stages 4 and 5, as the ridge retreats from the hotspot, the plate motion with respect to the hotspot sharply declines, thereby favoring the transport of hotspot material toward the ridge axis and making the interaction easier to maintain (e.g., Maia et al., 2000).

HYDROTHERMAL EFFECTS OF RIDGE-HOTSPOT INTERACTIONS

Systematic searches for hydrothermal activity along > 7000 km of mid-ocean ridge demonstrate that the spatial density of hydrothermal activity is a robust linear function of spreading rate (Figure 7) (Baker and German, 2004). This trend argues that the availability of mantle heat is the first-order control on the distribution of seafloor vent fields. The universality of this hypothesis remains to be proven, however, especially where magma supply is not a linear function of spreading rate. Ridge sections influenced by a nearby hotspot offer a unique experimental setting for such a test. For example, some crustal thermal models predict that the thicker, hotter crust associated with hotspots substantially impedes the development of convective hydrothermal cooling (e.g., Chen, 2003; Chen and Lin, 2004). Reduced hydrothermal cooling appears to be the simplest explanation for the unusually shallow magma bodies detected along mid-ocean sections overlying the Reykjanes (Sinha et al., 1997) and Galápagos (Detrick et al., 2002) hotspots.

About 10 hotspots lie within 500 km of a mid-ocean ridge, close enough to cause detectable changes in the crustal structure of the ridge. Hydrothermal surveys have been completed along substantial lengths of ridge above four such hotspots: Iceland (Reykjanes Ridge, 57°45′–61°9′N), St. Paul-Amsterdam (Southeast Indian Ridge, 33°–43°S), Galápagos (Galápagos Spreading Center, 89°36′–95°W), and Ascension (Mid-Atlantic Ridge, 7°–11.5°S).

The results of these surveys consistently support the hypothesis of reduced convective cooling along ridge sections influenced by excess magma supply (Figure 7). For each study, the relative spatial density of vent fields was estimated from

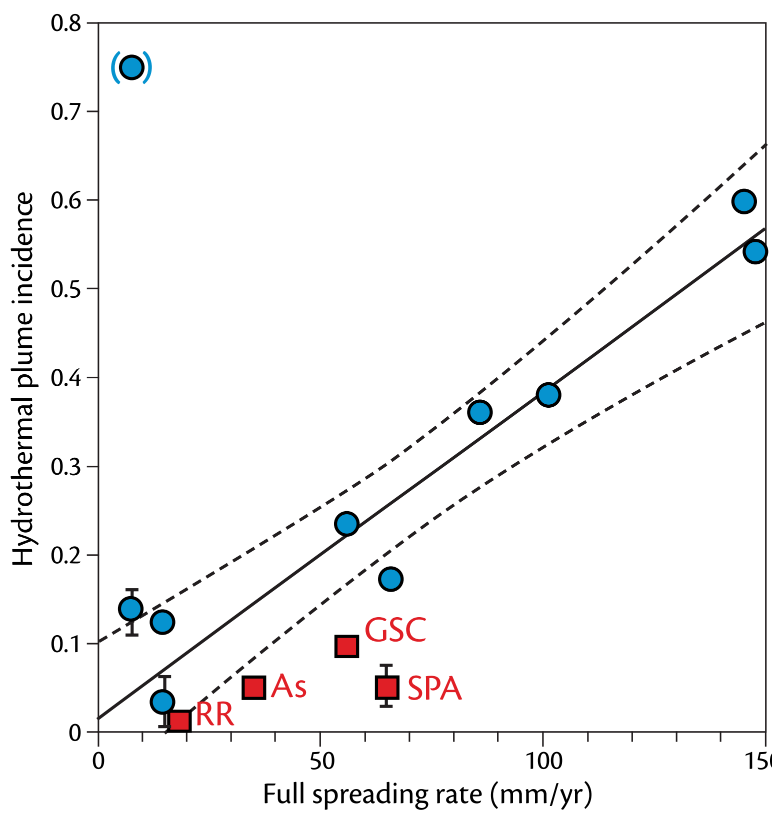


Figure 7. Scatter plot of incidence of hydrothermal plumes versus full spreading rate for 14 ridge sections totalling 7,000 km. Least-squares regression and ±95% confidence limits are shown for ridge sections not near hotspots (blue dots). Red squares show data from four hotspot-affected ridges. Data point for the Gakkel Ridge (in parentheses) is biased by unique hydrography and bathymetry (Baker et al., 2004) and is not included in the least-squares regression. RR = Reykjanes Ridge (Iceland); As = Mid-Atlantic Ridge (Ascension); GSC = Galápagos Spreading Center (Galápagos); SPA = Southeast Indian Ridge (St. Paul-Amsterdam).

the hydrothermal plume incidence, p_h, the fraction of ridge length overlain by hydrothermal plumes (Baker and Hammond, 1992). The first hotspot-affected ridge to be studied was the Reykjanes Ridge. Along 750 km of ridge crest, a suite of 175 vertical profiles found evidence for only a single hydrothermal plume (German et al., 1994), for a remarkably low p_h of 0.012. Shortly thereafter, a crustal magma body only 2–3 km below the seafloor was imaged at the southern end of the survey line (Sinha et al., 1997). These two observations fit the crustal thermal model convincingly, for the shallow magma body could be maintained for long periods only if hydrothermal cooling was diminished by about a factor of 2–4 compared to a "normal" ridge segment (Chen, 2003).

Results were similar along a section of the Southeast Indian Ridge crossing the St. Paul- Amsterdam hotspot. A series of 58 vertical profiles found evidence for two to four hydrothermal plumes, yielding a p_h of 0.034–0.069 (Scheirer et al., 1998). Hydrothermal plumes were more common than along the Reykjanes Ridge, but there were far fewer than expected for a ridge spreading at > 60 mm yr^{-1}. No seismic search for a local magma body has yet been attempted there.

The most detailed survey of hydrothermal activity along a hotspot-affected ridge was only recently completed along the Galápagos Spreading Center (Baker et al., 2006). A continuous, dual-pass deep tow with an array of hydrothermal plume sensors mapped 560 km of ridge crest, centered on the axial high that marks the maximum influence of the Galápagos hotspot. The magma body imaged beneath this high is only 1.4–2.2 km deep (Detrick et al., 2002) (Figure 4). As at the Reykjanes Ridge, the crustal thermal model (Chen, 2003) requires weaker cooling, by perhaps as much as a factor of two, to support a magma body this shallow. Preliminary estimates of the hydrothermal plume data give a p_h value of 0.1 for the Galápagos Spreading Center from 95°–89°36´W, a reduction by at least half compared to other surveyed intermediate-rate spreading ridges.

Further progress is needed in understanding ridge and hotspot styles of hydrothermal heat release and their roles in planetary heat transfer.

The Ascension "hotspot" may not be a mantle plume but simply the expression of a small mantle heterogeneity that supplies excess magma, but without a temperature anomaly (Bruguier et al., 2003). Thus, its effect on hydrothermal activity is not easily predictable. Recent mapping efforts there have found only five vent sites (Devey et al., 2005; German et al., 2005) and a low p_h level of 0.043 from 3°–11°S. This hydrothermal-plume incidence is lower than predicted, but the lack of comparable data for similarly spreading ridges at any "normal" ridge demands a cautious interpretation.

If the distribution of hydrothermal venting is governed by the availability of mantle heat, why should hydrothermal plumes be scarce over hotspot-affected, magma-rich ridges? Two contrasting hypotheses can be tested. First, hotspot-affected ridges may not be cooled primarily by high-temperature vents that billow easy-to-detect hydrothermal plumes, but rather by carpets of weak, low-temperature discharge that leave little trace in the water column. Conventional hydrothermal plume mapping may underestimate this type of convective cooling. The upper 500 m of the Reykjanes Ridge near 58°N, for example, is thought to be heavily fractured and water-saturated (MacGregor et al., 1998). High-temperature hydrothermal fluids may be easily diluted in the shallow crust. Testing this hypothesis will require large-scale, near-bottom hydrothermal plume hunting, an ideal task for the expanding population of autonomous underwater vehicles (AUVs) in the oceanographic research facilities around the world (see Yoerger et al., this issue).

Alternatively, increased magma supply or mantle temperature associated with a hotspot may elevate the crustal temperature above a magma chamber, and this thicker, hotter crust may be more ductile, and thus less susceptible to fracturing than normal oceanic crust (e.g., Chen, 2003). The ratio of convective to conductive cooling would diminish, and the hydrothermal plume distribution results would accurately reflect the degree of hydrothermal cooling. We could test this hypothesis by monitoring the ridge's microseismicity, which should be lower than that of more brittle, non-hotspot ridges.

LOOKING FORWARD

Ridge-hotspot interactions are important earth processes and provide intriguing research directions that will continue to attract the attention of the international research community. This community has accelerated cooperation on ridge and hotspot research in recent years, as reflected in: several major international symposia and workshops, including the 2003 InterRidge Workshop on Ridge-Hotspot Interactions; increased binational and multinational collaborative research expeditions; international exchanges of oceanographic instruments; multinational proposals to drill hotspot-influenced ridges such as the Reykjanes Ridge; and the effort to install an international seafloor observatory on the Mid-Atlantic Ridge south of the Azores hotspot (MOMAR—see article by Juniper et al., this issue). The advances in seismic-imaging techniques and improvements in imaging resolution will provide much needed direct constraints on the physical properties of the mantle beneath interacting ridge and hotspot systems. Further progress is needed in understanding ridge and hotspot styles of hydrothermal heat release and their roles in planetary heat transfer. Multidisciplinary investigations that combine geological, geophysical, geochemical, and geodynamical modeling will continue to guide sampling, monitoring, and data interpretation. Furthermore, future investigations should involve stronger links, not only among the geological subdisciplines, but also between the geological and biological research communities to improve understanding of the roles of hotspot-created shallow-water terrains in fostering seafloor biological communities and defining the biogeography of hydrothermal vent fauna.

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REFERENCES

Baker, E.T., and S.R. Hammond. 1992. Hydrothermal venting and the apparent magmatic budget of the Juan de Fuca Ridge. *Journal of Geophysical Research* 97:3,443–3,456.

Baker, E.T., and C.R. German. 2004. On the global distribution of hydrothermal vent fields. Pp. 245–266 in *Mid-Ocean Ridges: Hydrothermal Interactions Between the Lithosphere and Oceans*. C.R. German, J. Lin, and L.M. Parson, eds, Geophysical Monograph Series, Volume 148, American Geophysical Union, Washington, DC.

Baker, E.T., H.N. Edmonds, P.J. Michael, W. Bach, H.J.B. Dick, J.E. Snow, S.L. Walker, N.R. Banerjee, and C.H. Langmuir. 2004. Hydrothermal venting in magma deserts: The ultraslow-spreading Gakkel and South West Indian Ridges. *Geochemistry, Geophysics, Geosystems* 5(8):Q08002, doi:10.1029/2004GC000712.

Baker, E.T., J.A Resing, S.L Walker, G. Lebon, K. Nakamura, R. Haymon, S. White, and K. Macdonald. 2006. Hydrothermal plume mapping along the hotspot-affected Galapagos Spreading Center finds high-temperature vent sites are anomalously scarce. *Eos, Transactions, American Geophysical Union* 87(52), Fall Meeting Supplement Abstract V14A-06.

Braun, M.G., and R.A. Sohn. 2003. Melt migration in plume-ridge systems. *Earth and Planetary Science Letters* 213:417–430.

Bruguier, N.J., T.A. Minshull, and J.M. Brozena. 2003. Morphology and tectonics of the Mid-Atlantic Ridge, 7°–12°S. *Journal of Geophysical Research* 108(B2):2,093, doi:10.1029/2001JB001172.

Canales, J.P., G. Ito, R.S. Detrick, and J. Sinton. 2002. Crustal thickness along the western Galapagos Spreading Center and the compensation of the Galapagos hotspot swell. *Earth and Planetary Science Letters* 203:311–327.

Cannat, M., A. Briais, C. Deplus, J. Escartin, J. Georgen, J. Lin, S. Mercouriev, C. Meyzen, M. Muller, G. Pouliquen, A. Rabain, and P. da Silva. 1999. Mid-Atlantic Ridge - Azores hotspot interactions: Along-axis migration of a hotspot-derived event of enhanced magmatism 10 to 4 Ma ago. *Earth and Planetary Science Letters* 173:257–269.

Chauvel, C., and C. Hemond. 2000. Melting of a complete section of recycled oceanic crust: Trace element and Pb isotopic evidence from Iceland. *Geochemistry, Geophysics, Geosystems* 1(2): doi:10.1029/1999GC000002.

Chen, Y.J. 2003. Influence of the Iceland mantle plume on crustal accretion at the inflated Reykjanes Ridge: Magma lens and low hydrothermal activity? *Journal of Geophysical Research* 108(B11):2,524, doi:10.1029/2001JB000816.

Chen, Y.J., and J. Lin. 2004. High sensitivity of ocean ridge thermal structure to changes in magma supply: The Galapagos Spreading Center. *Earth and Planetary Science Letters* 221:263–273.

Conder, J.A., D.W. Forsyth, and E.M. Parmentier. 2002. Asthenospheric flow and asymmetry of the East Pacific Rise, MELT area. *Journal of Geophysical Research* 107:2,344, doi:10.1029/2001JB000807.

Conder, J.A., D.S. Scheirer, and D.W. Forsyth. 2000. Seafloor spreading on the Amsterdam-St. Paul hotspot plateau. *Journal of Geophysical Research* 105:8,263–8,277.

Courtillot, V., A. Davaille, J. Besse, and J. Stock. 2003. Three distinct types of hotspots in the Earth's mantle. *Earth and Planetary Science Letters* 205:295–308.

Cushman, B., J. Sinton, G. Ito, and J.E. Dixon. 2004. Glass compositions, plume-ridge interaction, and hydrous melting along the Galapagos Spreading Center, 90.5° to 98°W. *Geochemistry, Geophysics, Geosystems* 5:Q08E17, doi:10.1029/2004GC000709.

Darbyshire, F.A., R.S. White, and K.F. Priestley. 2000. Structure of the crust and uppermost mantle of Iceland from a combined seismic and gravity study. *Earth and Planetary Science Letters* 181:409–428.

Detrick, R.S., J.M. Sinton, G. Ito, J.P. Canales, M. Behn, T. Blacic, B. Cushman, J.E. Dixon, D.W. Graham, and J.J. Mahoney. 2002. Correlated geophysical, geochemical, and volcanological manifestations of plume-ridge interaction along the Galapagos Spreading Center. *Geochemistry, Geophysics, Geosystems* 3: 8,501, doi:10.1029/2002GC-000350.

Devey, C.W., K.S. Lackschewitz, and E.T. Baker. 2005. Hydrothermal and volcanic activity found on the southern Mid-Atlantic Ridge. *Eos, Transactions, American Geophysical Union* 86(22):209, 212.

Dyment, J. 1998. Evolution of the Carlsberg Ridge between 60 and 45 Ma—Ridge propagation, spreading asymmetry, and the Deccan-Reunion hotspot. *Journal of Geophysical Research* 103:24,067–24,084.

Dyment, J., Y. Gallet, and the Magofond 2 Scientific Party. 1999. The Magofond 2 cruise: A surface and deep tow survey on the past and present Central Indian Ridge. *InterRidge News* 8:25–31.

Forsyth, D.W., N. Harmon, D.S. Scheirer, and R.A. Duncan. 2006. Distribution of recent volcanism and the morphology of seamounts and ridges in the GLIMPSE study area: Implications for the lithospheric cracking hypothesis for the origin of intraplate, non–hot spot volcanic chains. *Journal of Geophysical Research* 111:B11407, doi:10.1029/2005JB004075.

Gente, P., J. Dyment, M. Maia, and J. Goslin. 2003. Interaction between the Mid-Atlantic Ridge and the Azores hot spot during the last 85 Myr: Emplacement and rifting of the hot spot-derived plateaus, *Geochemistry, Geophysics, Geosystems* 4 (10):8514, doi:10.1029/2003GC000527.

Georgen, J.E., J. Lin, and H.J.B. Dick. 2001. Evidence from gravity anomalies for interactions of the Marion and Bouvet hotspots with the Southwest Indian Ridge: Effects of transform offsets. *Earth and Planetary Science Letters* 187:283–300.

Georgen, J.E., and J. Lin. 2003. Plume-transform interactions at ultra-slow spreading rates: Implications for the Southwest Indian Ridge. *Geochemistry, Geophysics, Geosystems* 4(9):9,106, doi:10.1029/2003GC000542.

German, C.R., J. Briem, C. Chin, M. Danielsen, S. Holland, R. James, A. Jónsdóttir, E. Ludford, C. Moser, J. Olafsson, M.R. Palmer, and M.D. Rudnick. 1994. Hydrothermal activity on the Reykjanes Ridge: The Steinahóll Vent-field at 63°06´N. *Earth and Planetary Science Letters* 121:647–654.

German, C.R., L.M. Parson, B.J. Murton, S.A. Bennett, D.P. Connelly, A.J. Evans, R.D. Prien, E.Z. Ramirez-Llodra, T.M. Shank, D.R. Yoerger, M. Jakuba, A.M. Bradley, E.T. Baker, and K. Nakamura. 2005. Activity on the southern Mid-Atlantic ridge: tectonically- and volcanically-hosted high temperature venting at 2–7°S, *Eos, Transactions, American Geophysical Union* 86(52), Fall Meeting Supplement, Abstract OS21C-04.

Graham, D.W., D.M. Christine, K.S. Harpp, and J.E. Lupton. 1993. Mantle plume Helium in submarine basalts from the Galapagos platform. *Science* 262:2,023–2,026.

Hart, S.R., J.-G. Schilling, and J.L. Powell. 1973. Basalts from Iceland and along the Reykjanes Ridge: Sr. isotope geochemistry. *Nature Physical Sciences* 246:104–107.

Hofmann, A.W. 1997. Mantle geochemistry: The message from oceanic volcanism. *Nature* 385:219–229.

Hooft, E.E.E., D.R. Toomey, and S.C. Solomon. 2003. Anomalously thin transition zone beneath the Galapagos hotspot. *Earth and Planetary Science Letters* 216:55–64.

Ito, G. 2001. Reykjanes "V"-shaped ridges originating from a pulsing and dehydrating mantle plume. *Nature* 411:681–684.

Ito, G., and J. Lin. 1995. Oceanic spreading center-hotspot interactions: Constraints from along-isochron bathymetric and gravity anomalies. *Geology* 23:657–660.

Ito, G., and J. Lin, 1995. Mantle temperature anomalies along the present and paleo-axes of the Galapagos spreading center as inferred from gravity analyses. *Journal of Geophysical Research* 100:3,733–3,745.

Ito, G., J. Lin, and C.W. Gable. 1996. Dynamics of mantle flow and melting at a ridge-centered hotspot: Iceland and the Mid-Atlantic Ridge. *Earth and Planetary Science Letters* 144:53–74.

Ito, G., J. Lin, and D. Graham. 2003. Observational and theoretical studies of the dynamics of mantle plume-mid-ocean ridge interaction. *Review of Geophysics* 41(4):1,017, doi:10.1029/2002RG000117.

Kingsley, R.H., and J.-G. Schilling. 1998. Plume-ridge interaction in the Easter-Salas y Gomez seamount chain-Easter Microplate system: Pb isotope evidence. *Journal of Geophysical Research* 103:24,150–24,177.

Klein, E.M., and C.H. Langmuir. 1987. Global correlations of ocean ridge basalt chemistry with axial depth and crustal thickness. *Journal of Geophysical Research* 92:8,089–8,115.

Lin, J. 1998. Hitting the hotspots. *Oceanus* 41:34–37.

MacGregor, L.M., S. Constable, and M.C. Sinha. 1998. The RAMESSES experiment. III. Controlled-source electromagnetic sounding of the Reykjanes Ridge at 57°45´N. *Geophysical Journal International* 135:773–789.

Mahoney, J.J., J.H. Natland, W.M. White, R. Poreda, S.H. Bloomer, R.L. Fisher, and A.N. Baxter. 1989. Isotopic and geochemical provinces of the Western Indian Ocean spreading centers. *Journal of Geophysical Research* 94:4,033–4,052.

Maia, M., R. Hékinian, D. Ackermand, A. Dehghani, P. Gente, D. Naar, J. O'Connor, K. Perrot, J. Phipps Morgan, G. Ramillien, S. Révillon, A. Sabetian, D. Sandwell, and P. Stoffers. 2000. The Foundation Seamounts-Pacific Antarctic Ridge interaction: A case study of a ridge approaching a hotspot. *Marine Geology* 167:61–84.

Morgan, W.J. 1971. Convection plumes in the lower mantle. *Nature* 230:42–43.

Morgan, W.J. 1978. Rodriguez, Darwin, Amsterdam … a second type of hotspot island. *Journal of Geophysical Research* 83:5,355–5,360.

Montelli, R., G. Nolet, G. Masters, F.A. Dahlen, and S.-H. Hung. 2004. Finite-frequency tomography reveals a variety of plumes in the mantle. *Science* 303:338–343.

Müller, R.D., W.R. Roest, and J.-Y. Royer. 1998. Asymmetric sea-floor spreading caused by ridge–plume interactions. *Nature* 396:455–459.

Müller, R.D., C. Gaina, W.R. Roest, and D.L. Hansen. 2001. A recipe for microcontinent formation. *Geology* 29:203–206.

Niu, F., S.C. Solomon, P.G. Silver, D. Suetsugu, and H. Inoue. 2002. Mantle transition-zone structure beneath the South Pacific Superswell and evidence for a mantle plume underlying the Society hotspot. *Earth and Planetary Science Letters* 198:371–380.

Phipps Morgan, J., and D.T. Sandwell. 1994. Systematics of ridge propagation south of 30°S. *Earth and Planetary Science Letters* 121:245–258.

Sandwell, D.T., and W.H.F. Smith. 1997. Marine gravity anomaly from Geosat and ERS-1 satellite altimetry. *Journal of Geophysical Research* 102:10,039–10,050.

Scheirer, D.S., E.T. Baker, and K.T.M. Johnson. 1998. Detection of hydrothermal plumes along the Southeast Indian Ridge near the St. Paul-Amsterdam hotspot. *Geophysical Research Letters* 25:97–100.

Schilling, J.-G., R.H. Kingsley, and J.D. Devine. 1982. Galapagos hot spot-spreading center system 1. Spatial petrological and geochemical variations (83°W-101°W). *Journal of Geophysical Research* 87:5,593–5,610.

Schilling, J.-G., G. Thompson, R. Kingsley, and S. Humphris. 1985. Hotspot-migrating ridge interaction in the South Atlantic. *Nature* 313:187–191.

Schilling, J.-G. 1991. Fluxes and excess temperatures of mantle plumes inferred from their interaction with migrating mid-ocean ridges. *Nature* 352:397–403.

Searle, R.C., J.A. Keeton, R.B. Owens, R.S. White, R. Mecklenburgh, B. Parsons, and S.M. Lee. 1998. The Reykjanes Ridge: Structure and tectonics of a hot-spot-influenced, slow-spreading ridge, from multibeam bathymetry, gravity and magnetic investigations. *Earth and Planetary Science Letters* 60:463–478.

Shen, Y., and D.W. Forsyth. 1995. Geochemical constraints on initial and final depths of melting beneath mid-ocean ridges. *Journal of Geophysical Research* 100:2,211–2,237.

Shen, Y., S.C. Solomon, I.T. Bjarnason, and C. Wolfe. 1998. Seismic evidence for a lower mantle origin of the Iceland plume. *Nature* 395:62–65.

Sinha, M.C., D.A. Navin, L.M. MacGregor, S. Constable, C. Peirce, A. White, G. Heinson, and M.A. Inglis. 1997. Evidence for accumulated melt beneath the slow-spreading Mid-Atlantic Ridge. *Philosophical Transactions of the Royal Society of London, A* 355:233–253.

Sinton, J., R. Detrick, J.P. Canales, G. Ito, and M. Behn. 2003. Morphology and segmentation of the western Galapagos Spreading Center, 90.5°–98°W: Plume-ridge interaction at an intermediate spreading ridge. *Geochemistry, Geophysics, Geosystems* 4(12):8,515, doi:10.1029/2003GC000609.

Sleep, N.H. 1990. Hotspots and mantle plumes: Some phenomenology. *Journal of Geophysical Research* 95:6,715–6,736.

Smith, W.H.F., and D.T. Sandwell. 1997. Global seafloor topography from satellite altimetry and ship depth soundings. *Science* 277:1,957–1,962.

Stein, C.A., and S. Stein. 1992. A model for the global variation in oceanic depth and heat flux with lithospheric age. *Nature* 359:123–128.

Villagómez, D.R., D.R. Toomey, E.E.E. Hooft, and S.C. Solomon. Submitted. Imaging the upper mantle beneath the Galápagos Archipelago using surface wave tomography. *Journal of Geophysical Research*.

Weir, N.R.W., R.S. White, B. Brandsdottir, P. Einarsson, H. Shimamura, and H. Shiobara. 2001. Crustal structure of the northern Reykjanes ridge and Reykjanes peninsula, southwest Iceland. *Journal of Geophysical Research* 106:6,347–6,368.

Wolfe, C.J., I.T. Bjarnason, J.C. VanDecar, and S.C. Solomon. 1997. Seismic structure of the Iceland mantle plume. *Nature* 385:245–247.