Lithospheric Stress State Responsible for Hotspots at Ridge-Transform-Intersections?

Erin K Beutel

College of Charleston

Contrary to our current understanding of ridge-hotspot interactions, several papers have noted small seamounts with hotspot geochemical signatures located at or near ridge-transform-intersections (RTIs) rather than at the center of ridge segments (Graham et al, 1996; Hekinian et al 1999; Johnson et al, 2000; Klingelhoger et al, 2001). I propose that these ridge-transform-intersection seamounts are the result of lithospheric stress concentrations that propagate into the mantle. This implies some seamount locations are influenced by lithospheric stress concentrations, which suggests a new mechanism by which all "hotspot" locations may be affected.

The existence of seamounts with hotspot geochemical signatures, (hereafter simply called hotspots with no implied inference to their origin), in the center of ridges is relatively well understood. In the case of a plume origin for hotspots, ridges are believed to focus plumes: a) because hotspots are entrained in the mantle upwelling that feeds the ridges, b) because they are weak areas within the crust, and c) because there exists a physical and thermal gradient that effectively funnels the material to the ridge like a sink to a drain (Figure 1) (Kincaid et al, 1996; Kincaid et al. 1995; Sleep, 1990). Once at the ridge, hotspots add magma to the central area of upwelling, i.e. the center of the ridge segment. In the case of a heterogeneous mantle origin for hotspots, ridges are believed to intersect areas of fertile mantle, which results in rapid decompression melting and seamount formation (Anderson, 1992). Neither theory offers a clear explanation for the presence of hotpots at ridge-transform-intersections.

Any hypothesis presented regarding the presence of hotspots at ridge-transform-intersections must not only explain why hotspots exist at RTIs, but also why they would only exist there on occasion. I propose that seamounts form at RTIs because stress is concentrated at crack-tips, but that this stress is only large enough to influence the mantle and produce seamounts under certain conditions. Hotspots at ridge-transform-intersections may occur when ridge-tip propagation is not feasible or during the build-up of stress prior to propagation.

Three-dimensional finite element models of a series of ridge segments were constructed to determine if the stress field at the ridge-transform intersections changes when slip along the transforms is inhibited. The elastic finite element program Felt by Gobat and Atkinson (1996) was used to construct a box model of 3 ridge segments 1200-1400 km long separated by transforms 600-800 km long. The ridges are modeled as weak areas in a relatively strong 100 km thick lithosphere that is underlain by a 100 km weak low-velocity zone and then 400 km of mantle. Ridge-push forces were applied to the ridges and slab-pull forces were applied to the edges of the model. A variety of scenarios involving different transform strengths (i.e. ease of slip) and force ratios were run to determine what effect changing transform strength had on the stress field at the ridge-transform intersection. In all cases, increasing the resistance to slip along the transform resulted in increased extensional stress at the RTI not only in the lithosphere, but also in the mantle (Figure 2).

Increased extensional stress at the ridge-transform intersection can result in ridge propagation, however, multiple criteria may need to be met for the ridge to propagate. Phipps Morgan and Parmentier (1985) proposed that ridge propagation could only occur when the stress at the ridge tip is: a) greater than the strength of the plate; b) greater than the energy to create a new transform (also Lachenbruch and Thompson, 1972); and c) greater than the energy dissipation from the opposing ridge (also Pollard and Aydin, 1984). Other factors affecting ridge propagation include the degree of asthenospheric flow to the ridge tip and the topographic gradient between the ridge center and ridge tip (Phipps Morgan and Parmentier, 1985; Parmentier and Forsyth, 1985; Spence and Turcotte, 1985; Wilson and Hey, 1995; West et al., 1999). If the stress at the ridge tip (RTI) is not great enough to overcome most of the above criteria, then we must assume that the ridge will not propagate and high levels of extensional stress will be concentrated at the ridge tip (RTI).

It is under this condition that I propose hotspots form at the ridge-transform-intersection (RTI). High levels of extensional stress in the lithosphere and asthenosphere (Figure 3) will likely result in localized normal faulting events and crustal thinning. Crustal thinning and extensional stress in the asthenosphere would result in decompression of the mantle.

Decompression of the mantle can produce a seamount with a hotspot geochemical signature via two very different means. In the case of a heterogeneous mantle, decompression melting of fertile mantle would result in an excess of melt with a hotspot signature. Decompression of the mantle and the formation of a melt would also a change the thermal and physical gradient at the ridge. Crust at the transforms tends to be thinner than at the center of the ridge and the presence of melt would increase the positive buoyancy of the crust. This change in the physical and possibly thermal gradient could draw plumes from the center of the ridge to the ridge-transform-intersection (Figure 3).

To conclude, the presence of seamounts with hotspot geochemical signatures at ridge-transform-intersections are potentially the result of concentrations of extensional stress at the RTI due to inhibited slip along the adjacent transform. These hotspots may be the result of either plumes or a heterogeneous mantle as both would be affected by the attendant lithospheric decompression.

REFERENCES

Anderson, D. L; Tanimoto, Toshiro; Zhang, Yu-shen, 1992, Plate tectonics and hotspots; the third dimension: Science, vol.256, no.5064, pp.1645-1651.

Graham, D W; Castillo, P R; Lupton, J E; Batiza, R, 1996, Correlated He and Sr isotope ratios in South Atlantic near-ridge seamounts and implications for mantle dynamics: Earth and Planetary Science Letters, vol.144, no.3-4, pp.491-503.

Hekinian, R.; Stoffers, P.; Ackermand, D.; Revillon, S.; Maia, M.; Bohn, 1999, Marcel Ridge-hotspot interaction; the Pacific-Antarctic Ridge and the foundation seamounts: Marine Geology, vol.160, no.3-4, pp.199-223.

Johnson, K T M; Graham, D W; Rubin, K H; Nicolaysen, K; Scheirer, D S; Forsyth, D W; Baker, E T; Douglas-Priebe, L M, 2000, Boomerang Seamount; the active expression of the Amsterdam-St. Paul Hotspot, Southeast Indian Ridge: Earth and Planetary Science Letters, vol.183, no.1-2, pp.245-259.

Kincaid, C; Schilling, J G; Gable, C, 1996, The dynamics of off-axis plume-ridge interaction in the uppermost mantle: Earth and Planetary Science Letters, vol.137, no.1-4, pp.29-43.

Kincaid, C; Ito; G; Gable, C., 1995, Laboratory investigation of the interaction of off-axis mantle plumes and spreading centres: Nature (London), vol.376, no.6543, pp.758-761.

Klingelhofer, F.; Minshull, T.A.; Blackman, D.K.; Harben, P.; Childers V., 2001, Crustal structure of Ascension Island from wide-angle seismic data: implications for the formation of near-ridge volcanic islands: Earth and Planetary Science Letters, vol.190, pp41-56.

Lachenbruch, A. H. ; Thompson, G. A., 1972, Oceanic ridges and transform faults; their intersection angles and resistance to plate motion: Earth and Planetary Science Letters, v. 15, p. 116-122.

Morgan, J. P.; Parmentier, E. M., 1985, Causes and rate-limiting mechanisms of ridge propagation; a fracture mechanics model: JGR, Journal of Geophysical Research B, v. 90, p. 8603-8612.

Parmentier, E. M.; Forsyth, D. W., 1985, Three-dimensional flow beneath a slow spreading ridge axis; a dynamic contribution to the deepening of the median valley toward fracture zones: JGR, Journal of Geophysical Research B, v. 90, p. 678-684.

Pollard, David D.; Aydin, Atilla, 1984, Propagation and linkage of oceanic ridge segments: JGR. Journal of Geophysical Research. B, vol.89, no.12, pp.10,017-10,028.

Sleep, Norman H., 1990, Hotspots and mantle plumes; some phenomenology: JGR, Journal of Geophysical Research, B, vol.95, no.5, pp.6715-6736.

Spence, D A.; Turcotte, D L, 1985, Magma-driven propagation of cracks: JGR, Journal of Geophysical Research. B, vol.90, no.1, pp.575-580.

West, B. P.; Lin, J.; Christie, D. M., 1999, Forces driving ridge propagation: JGR, Journal of Geophysical Research, B, v. 104, p. 22,845-22,858.

Wilson, Douglas S; Hey, Richard N, 1995, History of rift propagation and magnetization intensity for the Cocos-Nazca spreading center: JGR, Journal of Geophysical Research, B, vol.100, no.6, pp.10,041-10,056.

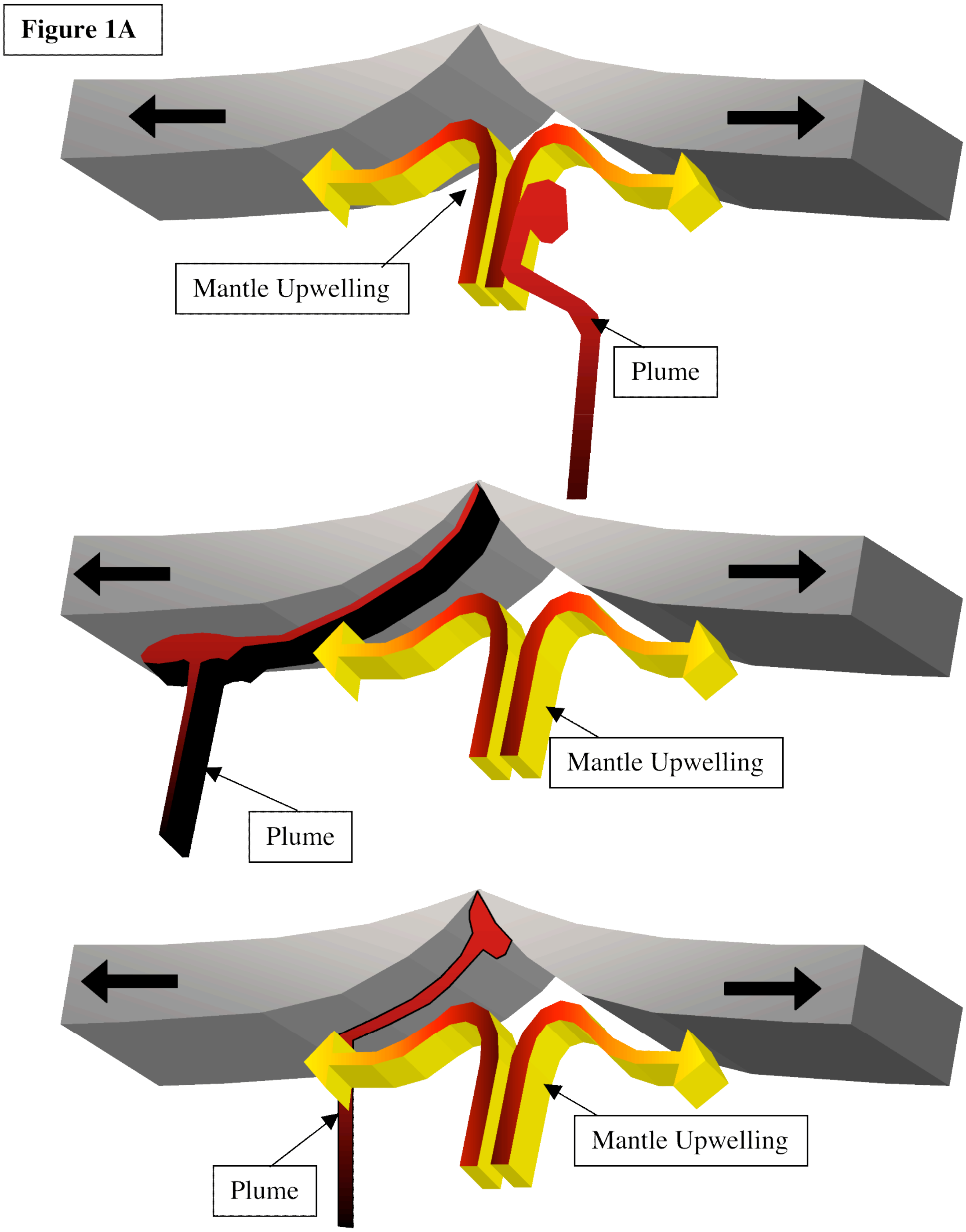
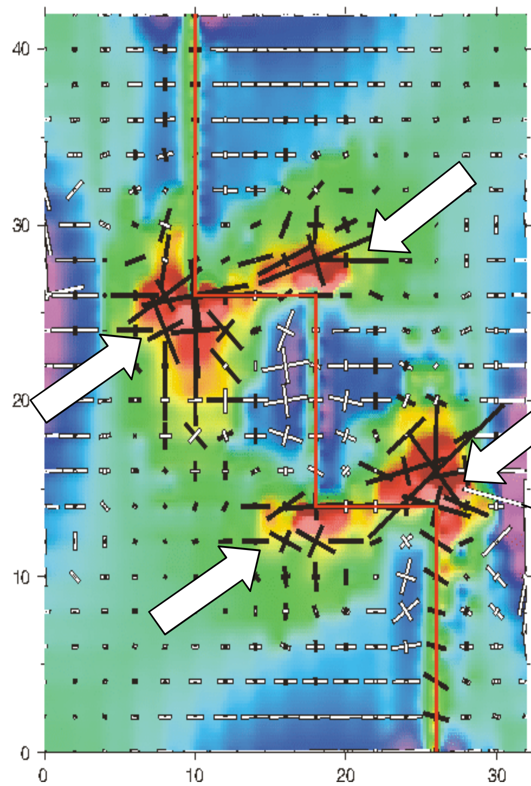


Figure 1: Possible Ridge-Hotspot Interactions (e.g. Kincaid et al., 1996; Kincaid et al., 1995; Sleep, 1990)
A: Plume is entrained in shallow upwelling beneath ridge.
B: Cartoon of a hotspot supplying material to a ridge via a conduit flowing up the topography of the ridge and overcoming the mantle flow away from the ridge.
C: Cartoon of a hotspot entrained to a ridge by flowing along the base of the lithosphere, also overcoming the mantle flow away from the ridge.

Figure 2A: Mapview Results, 33 Km, Strong Transform



Maximum Stress Intensity Scale

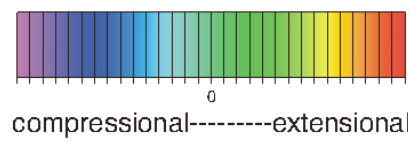


Figure 2B: Cross-Section of Results: Strong Transform

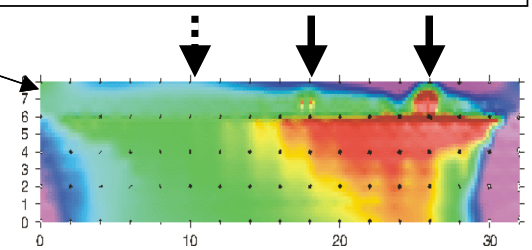


Figure 2A: Mapview Results, 33 km Depth, Strong Transform: Results of ridge-push forces exerted on a 3-D box with 3 ridges and 2 strong transforms. The model is fixed at the base of the box, 8 units (~800 km) below the surface. The background colors indicate the type and intensity of the maximum stress, blue being compressional and red being extensional. The bars are maximum and minimum stress vectors, white indicates compression and black indicates extension. White arrows indicate zones of extension at ridge-transform-intersections.

Figure 2B: Cross-Section of Results, Strong Transform: Cross-section of model described above. As indicated by the arrow, the cross-section location is parallel to the first transform (at Y=14) on the mapview results. Color scheme and bars are as described above. Solid black arrows indicate location of ridge-transform intersections, and dotted arrows indicate the where the ridge segment would exist if it were extended in length. Note that the extensional stress propegates through the lithosphere, asthenosphere and into the mantle.

Figure 3A: Along Ridge Cross-Section

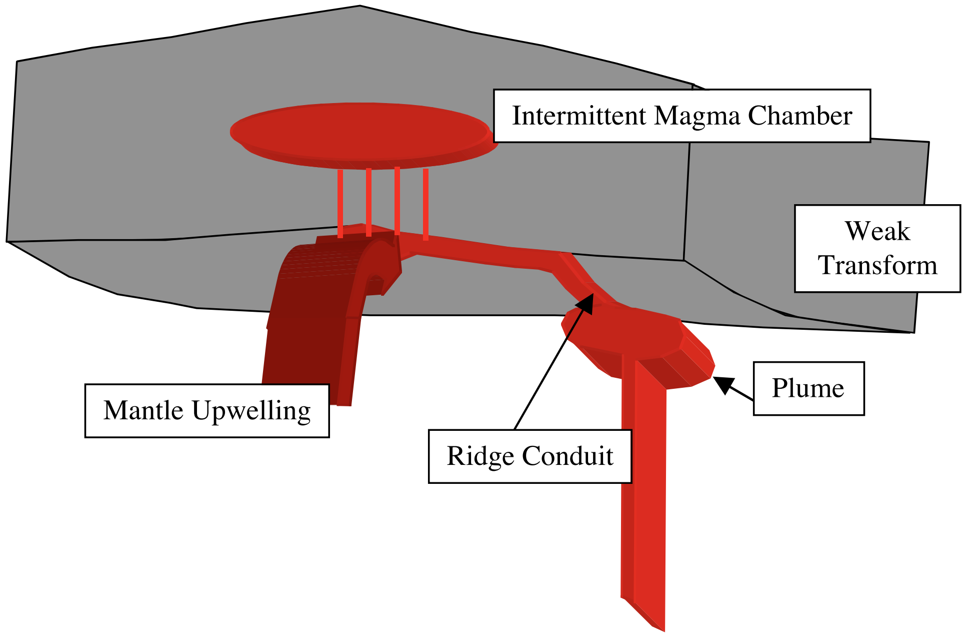


Figure 3B:Along Ridge Cross-Section

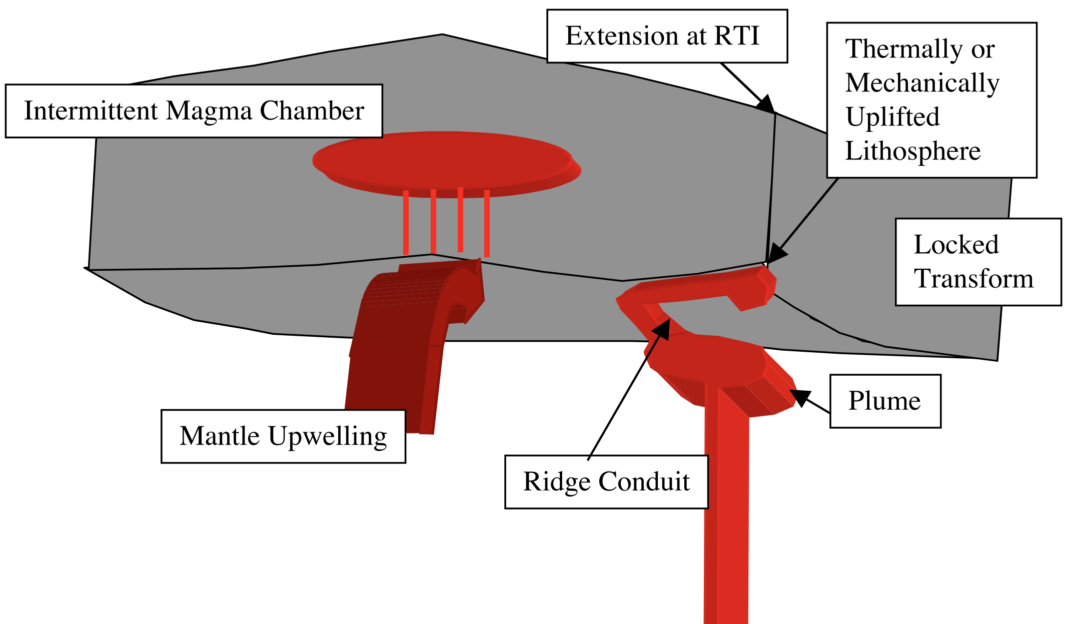


Figure 3: A Cartoon of plume with conduit to ridge when slip along transform is unimpeded. **B**: Cartoon of plume conduit to ridge diverted by extension at the ridge-transform-intersection. Note that both cartoons are along ridge cross-sections and show a schematic of the ridge from one transform to the next.