"Plume-Ridge Interactions" as a Consequence of Ridge Suction

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Geological processes are consequences of Earth's thermal evolution. Plate tectonics, which is driven by the cooling lithospheric plates atop the mantle, explains geological phenomena along plate boundaries such as volcanisms and earthquakes at ocean ridges and within subduction zones. Mantle plumes, which are considered to result from cooling of the earth's deep interior, explain geological phenomena taking place away from plate boundaries such as intra-plate volcanisms, seamount chains etc. In this context, we may say that mantle plumes and plate tectonics are genetically independent of each other. However, when the ascending plumes approach lithospheric plates, interactions between the two inevitably result. Such interactions are most prominent near ocean ridges where the lithosphere is thin and the effect of plumes is best revealed. "Plume-ridge interaction" has been a hot topic in recent years, and much effort has been expended in this area [1-22]. While all these existing models differ in detail, they have several common assumptions: (1) mantle plumes are deep-sourced and necessarily hot, hotter than MORB mantle; (2) plume materials, relatively to MORB source, are enriched in volatiles and incompatible elements; (3) plumes dynamically "invade" MORB mantle; and (4) dispersion of plume materials in MORB mantle or mixing between the two distinct singular materials prior to or during melting gives rise to the "geochemical mixing" in erupted lavas.

Here we offer some new perspectives on plume-ridge interactions: (1) plumes and MORB source share a common two-component mantle [19,23-25]: *E*asy-to-melt or *E*nriched dikes/veins (*E*) dispersed in the *D*ifficult-to-melt or *D*epleted peridotitic matrix (*D*). (2) Plumes are likely to have variably greater *E/D* than MORB source whose *E/D* varies as well [19,24-28]. (3) Not all plumes necessarily come from excessively hot deep interiors although plume materials could well be intrinsically hotter because of greater abundances of heat producing elements (e.g., Th, U, K), depending on both the history and size of the "plume material domains". (4) While ocean ridges are mostly passive features in terms of plate tectonics, they play an active, *NOT passive*, role in the context of plume-ridge interactions. This active role is simply a ridge suction force that drives asthenospheric mantle flow towards ridges because of material needs to form the ocean crust at ridges and lithospheric mantle in the vicinity of ridges: > 99.9% ocean crust is formed at ridges, and ~ 50% total thickness of oceanic lithosphere is created in the first ~ 17.5 m.y. (i.e., $t_{1/2} = [0.5*70^{1/2}]^2$, assuming an oceanic plate reaches its full thickness, say, ~ 95 km, after ~ 70 Ma [29]). This ridge suction force *must* increase with increasing plate separation rate because of increased material demand per unit time [19]. For example, in the first one m.y., the mass flux towards the ridge to form the crust (assuming 5 km thick for simplicity) and lithospheric mantle due to heat loss per unit along-ridge length (km) is Φ (km^{-3}/Ma) = $25R_{1/2}$ (where the proportionality 25 has the unit of km^2, and $R_{1/2}$ is half-spreading rate, km/Ma). As the seismic low-velocity zone atop the asthenosphere has the lowest viscosity that increases rapidly with depth [30,31], the ridge-ward asthenospheric flow is largely horizontal beneath the lithosphere in the direction against the motion of the overlying plate. It follows that the asthenospheric flow is necessarily decoupled from its overlaying oceanic lithospheric plate, and the degree of the decoupling increases with increasing spreading rate (Figure 1).

The above concept is fully supported by observations. (1) The systematic lava compositional variations along the Foundation hotline towards the Pacific-Antarctic Ridge result from progressive decompression melting of ridge-ward flowing plume materials (Figure 2). (2) The similar geochemical observations in lavas along Easter Seamount lavas from Salas-y-Gomez Islands to the Easter Microplate result from the same process. (3) The increasing ridge suction force with increasing spreading rate explains why the Iceland plume has asymmetric effects on its neighboring ridges: both topographic and geochemical anomalies extend < 400 km along the slower (20 to 13 mm/yr northward) spreading South Kolbeinsey Ridge, but > 1500 km along the faster (20 to 25 mm/yr southward) spreading Reykjanes Ridge. (4) The spreading-rate dependent ridge suction force also explains the first-order differences between the fast-spreading East Pacific Rise

(EPR) and the slow-spreading Mid-Atlantic Ridge (MAR). Identified mantle plumes/hotspots are abundant near the MAR (e.g., Iceland, Azores, Ascension, Tristan, Gough, Shona and Bouvet), but rare along the entire EPR (notably, the Easter hotspot at ~ 27°S on the Nazca plate). Such apparent unequal hotspot distribution would allow a prediction of more enriched MORB at the MAR than at the EPR. However, the mean compositions between MAR-MORB and EPR-MORB are similar in terms of incompatible element abundances, and are identical in terms of Sr-Nd-Pb isotopic ratios (Figure 3). This suggests similar extents of mantle plume contributions to EPR and MAR MORB. We consider that the apparent rarity of near-EPR plumes/hotspots results from fast spreading. The fast spreading creates large ridge suction forces that do not allow the development of surface expressions of mantle plumes as such, but draw plume materials to a broad zone of sub-ridge upwelling, giving rise to random distribution of abundant enriched MORB and elevated and smooth axial topography along the EPR (vs. MAR).

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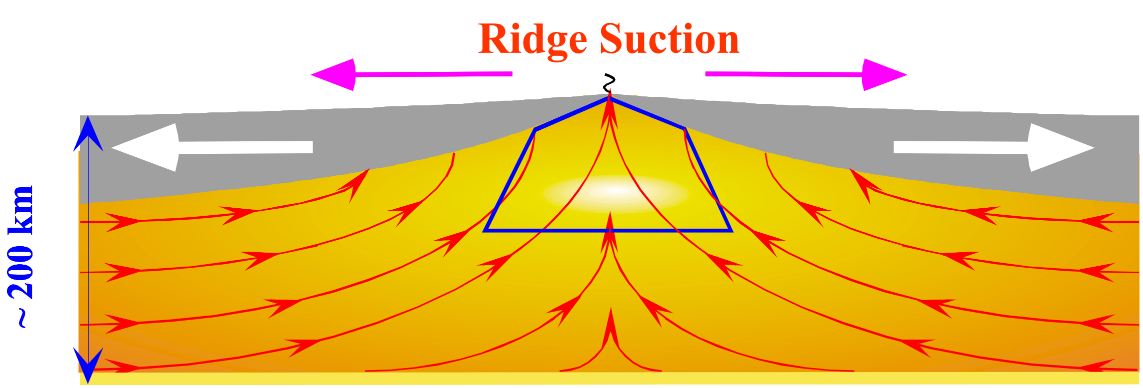

Figure 1. The regions of asthenosphere beneath ocean ridges have the lowest pressure in the entire asthenospheric mantle that drive asthenospheric flows (i.e., ridge suction). This suggests that the spreading lithospheric plates are necessarily decoupled from the sublithospheric flow. This is an important concept needed to understand mantle flows in the context of plate tectonics. The actually "affected" depth or depth range is unconstrained, but probably coincides with the seismic low-velocity zone, say, down to 200-250 km. The outline in blue represents region of decompression melting for MORB.

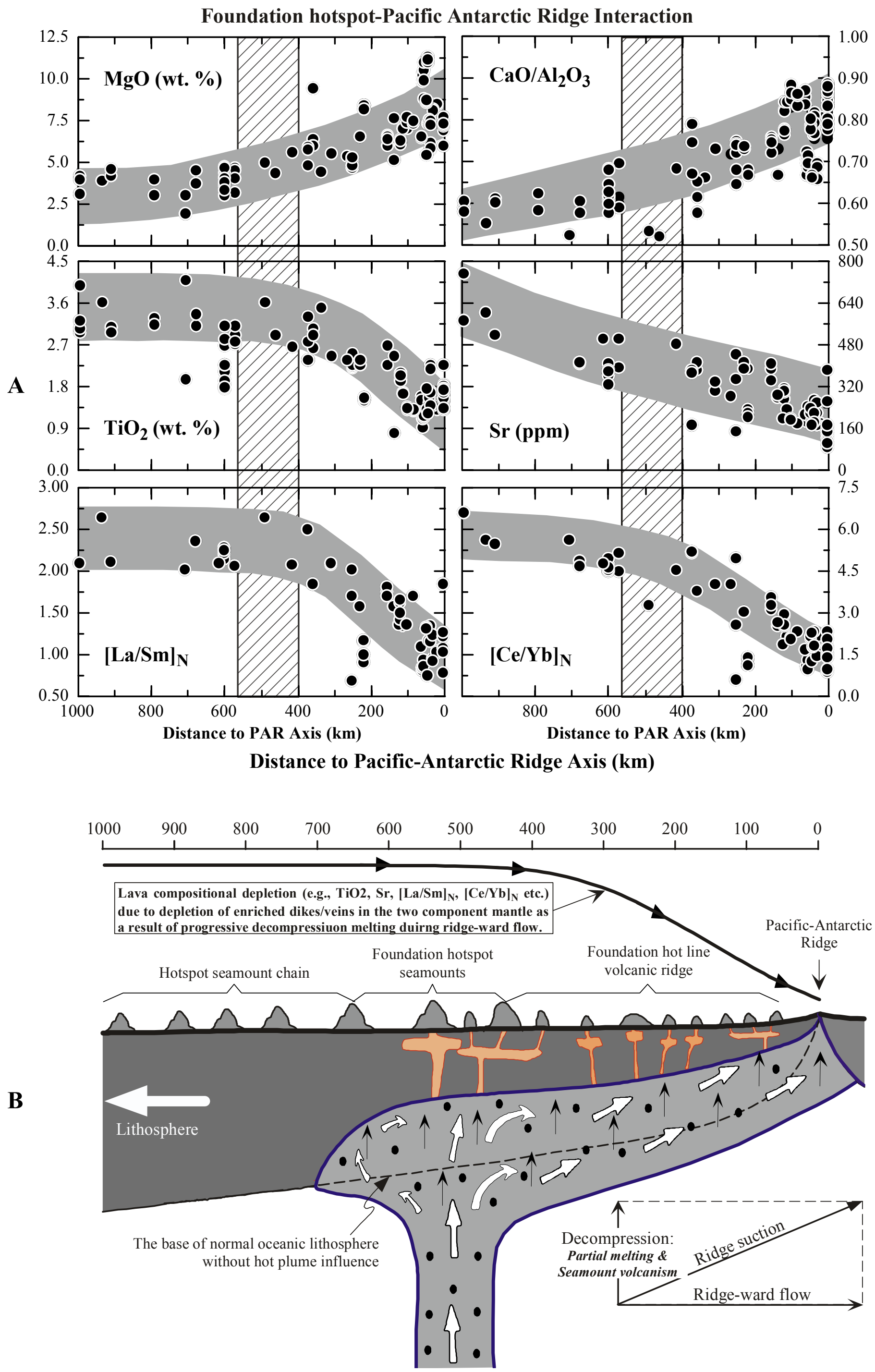

Figure 2. ***A***. Lava geochemical systematics along the Foundation hotline volcanic ridges (~ 37°S) as a function of distance to the Pacific Antarctic Ridge. While scattered, the most data define systematic trends as highlighted by the shaded bands. ***B***. Cartoon illustrating that the observed lava geochemical variation is the consequence of progressively melting a two-component plume material. Ridge suction requires the "hot" and "wet" plume material to flow towards the ridge with an upwelling component that causes decompression melting of the flowing plume material. The enriched dikes/veins (*E*) with low solidus temperatures are progressively depleted during the ridge-ward flow, thus leading to progressive melting of the more depleted matrix (*D*), and producing more depleted lavas towards the ridge. The geochemical data are from [16,17] with highly evolved samples (andesites, dacites and rhyolites having SiO_2 > 55 wt. %) excluded.

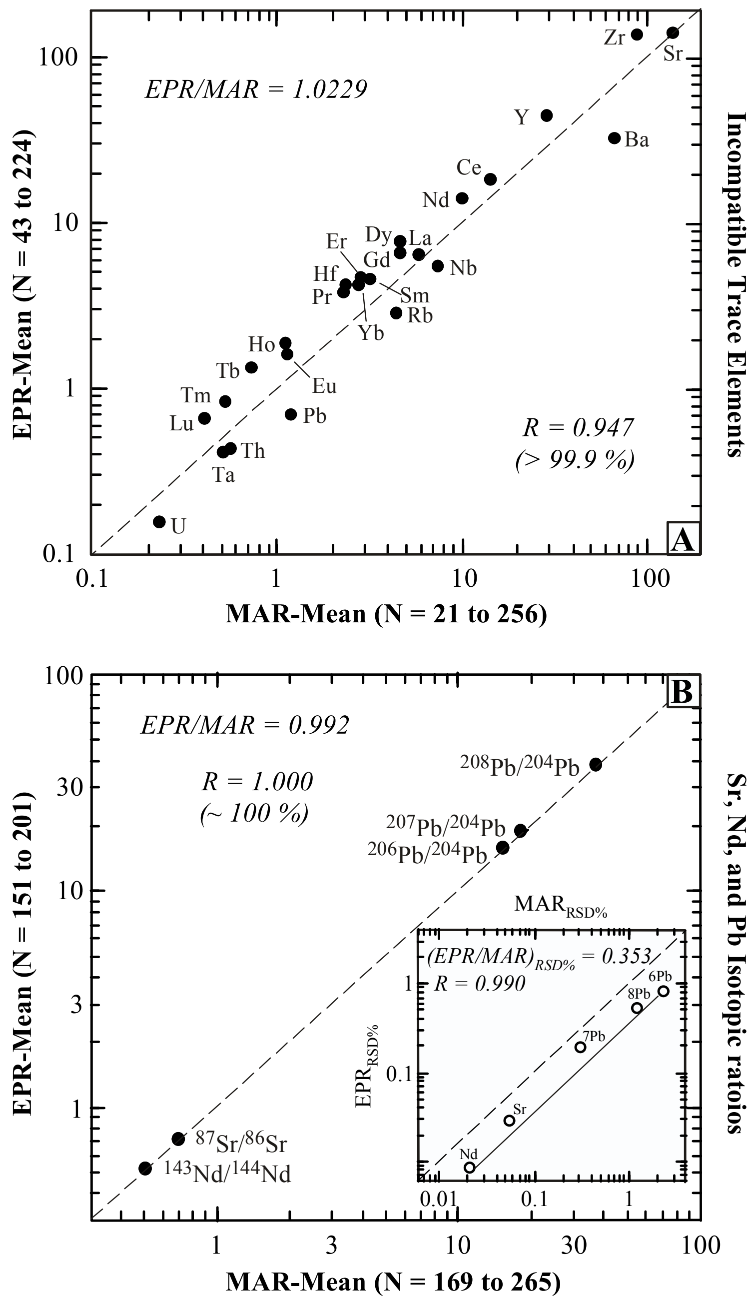

Figure 3. Comparison of mean abundances of incompatible elements (***A***) and Sr-Nd-Pb isotopic ratios (***B***) between MORB from the fast-spreading EPR (23°S to 23°N) and the slow-spreading MAR (55°S to 52°N) using the recently available global MORB data base [33]. Note the statistically significant correlation with a nearly unity (1.0229) slope in ***A***, suggesting similar "plume material" contributions to the two ocean ridge systems. In ***B***, the mean Sr-Nd-Pb isotopic ratios are statistically identical, which reinforces that "plume material" contributions are identical at the EPR and MAR. The correlated smaller variability (RSD% = 1σ/mean x 100) of EPR MORB isotopic ratios plotted in the inset reflects a well-known effect of greater extents of melt homogenization in EPR MORB. The RSD% for incompatible element abundnaces are not correlated, thus not shown, which is largely due to inhomogeneity in data quality (analyzed by different means in different laboratories with variable precisions and accuracy) in the literature, whereas Nd-Sr-Pb isotopes are all determined by TIMS normalized to international standards in all laboratories. Note that logarithmic scales are used to show all the details.