

Alternative Mechanisms for Volcanic Activity in Hotspot-Ridge Systems: The Northern Galapagos Province

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Many geologic features of the Galápagos Archipelago conform to the Hawaiian-style hotspot model (Morgan, 1971). Most importantly, the islands near the central axis of the chain get older to the east as predicted from Nazca plate motion, and recent volcanic activity is focused in the western archipelago. Upon closer inspection, however, the Galápagos deviate from the simple hotspot model: (1) the islands are broadly distributed instead of forming a linear chain in the direction of plate motion; (2) most of the volcanoes are active (e.g., White et al., 1993); (3) geochemical variations define complex spatial patterns, reflecting contributions from multiple mantle reservoirs (Geist et al., 1988; White et al., 1993; Kurz and Geist, 1999; Harpp and White, 2001); and (4) the hotspot may be interacting extensively with the adjacent Galápagos spreading center (e.g., Schilling et al., 1982).

Many of the deviations from the conventional hotspot model are most prominently expressed by the enigmatic volcanic features that grace the northern perimeter of the archipelago, including Genovesa, Marchena, and Pinta Islands, the northeast platform seamounts, and a bathymetric lineament including Wolf and Darwin islands and several elongate seamounts (Figure 1). In general, the northern volcanoes have been challenging to incorporate into regional models for the plume (e.g., Harpp and White, 2001). The present-day hotspot is thought to be centered near Fernandina Island (Kurz and Geist, 1999), and absolute motion of the Nazca plate is essentially eastward (Gripp and Gordon, 1990). Therefore, the northern volcanoes do not lie “downstream” from the plume and cannot be explained by the traditional mantle plume hypothesis.

Lavas erupted on the northern islands exhibit a wide range of chemical compositions, from enriched (Pinta) to depleted (northeast platform seamounts), spanning nearly the entire range observed in the archipelago (White et al., 1993). The northern islands are some of the smallest volcanic centers in the Galápagos, exhibiting little resemblance to the large western shields. Many are morphologically unusual, and possess elongate, composite structures rather than symmetrical, conical shapes (Christie et al., 1992). Perhaps most importantly, the northern volcanoes are located between the main archipelago and the Galápagos spreading center, one of the few places in the world where two fundamental mantle processes operate in such proximity.

We present results from a series of detailed field studies of Northern Galápagos volcanic centers, including Genovesa Island, a submarine ridge that extends from Genovesa, and the Wolf-Darwin Lineament.

A. Genovesa Island and Genovesa Ridge

Genovesa Island, which lies between the central Galápagos Platform and the Galápagos Spreading Center, is unusual in several respects. Exposed Genovesa lavas are the most isotopically depleted intraplate ocean island basalts on the planet (Georoc database). Despite its circular coastline and calderas, it is crosscut by both eruptive and non-eruptive fissures trending NE-SW. The 075° bearing of the fissures parallels that of Genovesa Ridge, a 55 km-long volcanic rift zone that is the most prominent submarine rift in the Galápagos and constitutes the majority of the volume of the Genovesa magmatic complex (Figure 1). Genovesa Ridge was the focus of detailed multibeam and side-scan sonar surveys during the Revelle/Drift04 cruise in 2001. The ridge consists of three left-stepping en echelon segments; the abundances of lava flows, volcanic terraces, and eruptive cones are all consistent with constructive volcanic processes. The non-linear arrangement of eruptive vents and the ridge's en echelon structure indicate that it did not form over a single dike.

Major and trace element compositions of Genovesa Ridge glasses are modeled by fractional crystallization along the same liquid line of descent as the island lavas, but some of the glasses are more primitive than any lavas sampled from the island. Most lavas on both the ridge and island have accumulated plagioclase. Incompatible trace element abundances of dredged Genovesa Ridge rocks are lower than the island's lavas, but ratios of the elements are similar in the two settings. The geochemical similarities indicate that the island and ridge lavas have nearly identical mantle sources. Glass inclusions in plagioclase phenocrysts from the ridge are compositionally diverse, with both higher and lower MgO than the matrix glass, suggesting homogenization at shallow levels.

The structural and geochemical observations are best reconciled if Genovesa Ridge did not form in response to injection of magma laterally from a hotspot-supplied central volcano, which is how Kilauea's Puna Ridge is thought to operate. Instead, Genovesa Ridge and its western extension appear to be the result of passive upwelling directed by far-field tectonic stresses that are generated by tension across the 91°W transform. The proximity of the hotspot system causes magmatism in the extensional zones where it would not ordinarily occur.

B. The Wolf-Darwin Lineament

The Wolf-Darwin Lineament (WDL) lies between the focus of the Galápagos hotspot and the Galápagos Spreading Center, extending to the SE from its intersection with the ridge (Figure 1). Consequently, most researchers have attributed its origin to interaction between the plume and the adjacent ridge. We propose that the WDL is caused only partially by plume-ridge interaction, and instead that it is primarily the result of tensional stresses emanating from the inside corner of the transform fault at 91°W . An additional factor that amplifies the tension in this region is the oblique orientation of the major transform fault with respect to the Nazca plate's spreading direction. This setting creates a transtensional zone whereby strain is partitioned into strike-slip motion along the transform and extension throughout the inside corner of the ridge-transform system (Figure 2). The area under tension is magmatic owing to the overlapping effects of the ridge and the Galápagos plume.

The extensional model predicts no age progressive volcanism, which is supported by observed age relationships. The WDL volcanoes define two distinct chemical groups; lavas erupted south of Wolf Island have compositions similar to those produced along the GSC west of 93°W, while those from the northern WDL resemble GSC lavas from the segment directly north of the lineament. This geographic distribution implies that the WDL is supplied by the same type of hotspot-affected mantle as the segment of the GSC that produced the lithosphere underlying the volcanoes. The observed WDL geochemical gradients are consistent with the extension model; the region under tension simply taps hybrid products of mixing at the margins of the sub-ridge convection system and the periphery of the hotspot.

The results of our Genovesa Ridge and WDL studies, in essence, are pointing toward a single, coherent explanation for the distribution, orientation, eruptive behavior, and compositional variations of all the Northern Galápagos volcanoes. These volcanic centers may be explained not as the direct result of hotspot activity, but instead as the serendipitous product of the proximity of a plume hotspot to the major transform that offsets the GSC at 91°W. The adjacent plume and mid-ocean ridge magmatic systems serve to generate widespread melting throughout the northern Galápagos region by causing upwelling in the mantle where it might not otherwise occur. The melts then migrate to the surface along tectonically controlled zones of tension imposed by an extensional transform (Figure 2). In effect, then, the adjacent plume illuminates the regional stress field with magma; at mid-ocean ridge systems without a proximate plume, such zones are not rendered observable. The range of lava compositions erupted throughout the Northern Galápagos, then, reflects the heterogeneous nature of the underlying mantle and provides a rare opportunity to assess the extent and distribution of the Galápagos plume as well as its interaction with the nearby ridge.

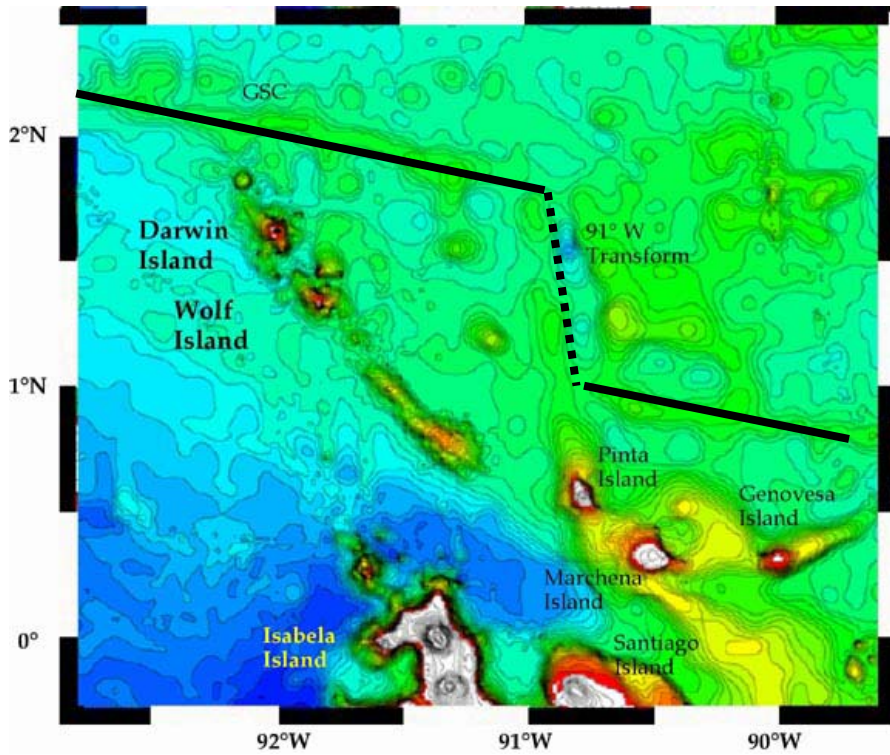


Figure 1. Bathymetric map of the northern Galápagos region, as compiled by Dr. William Chadwick of NOAA and Oregon State University and available at <http://newport.pmel.noaa.gov:80/~chadwick/Galápagos.html>. Solid and dashed black line is the Galapagos Spreading Center (GSC).

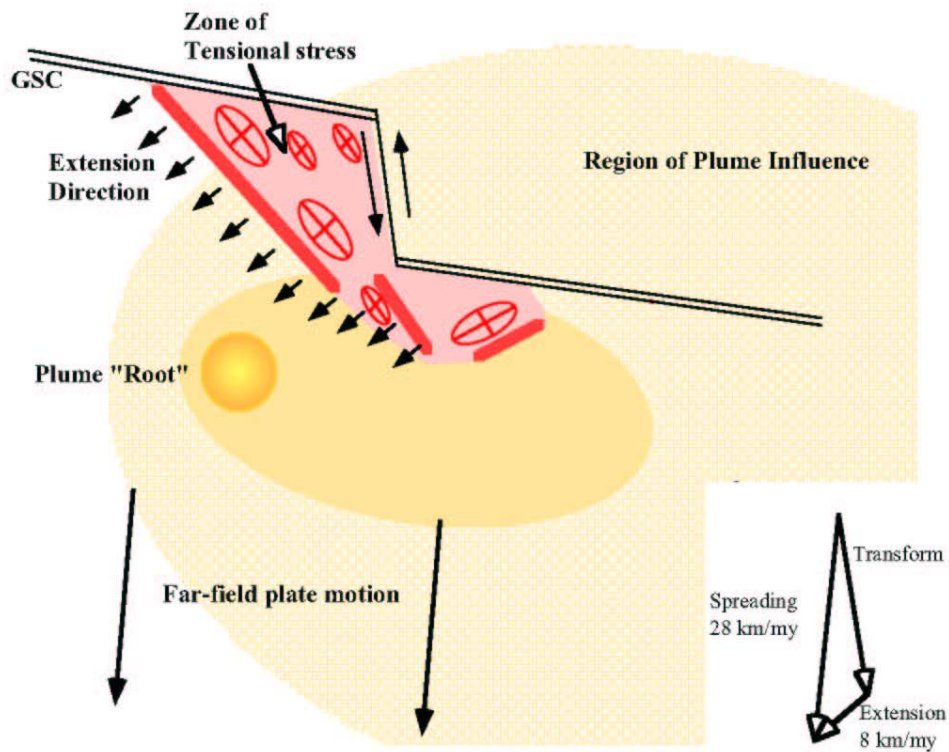


Figure 2. Conceptual model of the tectonic origin of the WDL. Orange tones indicate zone of influence of the Galápagos plume. Long arrows at the bottom of the figure oriented 186° show spreading direction of the Nazca plate. Short arrows represent extension necessary to accommodate plate spreading after strike-slip component of transform fault is removed. Bold red lines are observed volcanic lineaments (interpreted from bathymetric map, Figure 1). Ellipses are from the model of Gudmundsson [1995] for stresses around a transform fault-ridge intersection. Inset shows vector representation in velocity space of a model for strain partitioning through a combination of transform and extensional motions.