of the Archipelago) by prohibiting potentially dangerous fishing techniques within this area. This is not only for the protection of single species, but for the well being of the ecosystem.

I would like to thank David Parer and Elizabeth Parer-Cook for giving me the opportunity to travel with them. Also to the crew of the *Samba* for the use of their keen eyes and especially to David Day.

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GALÁPAGOS PLUMOLOGY

By: Karen Harpp and Dennis Geist

INTRODUCTION

Although the Galápagos Islands are best known as one of the world's greatest natural laboratories for biological studies, they have also lent considerable insight into the dynamics of the earth's interior. Modern accounts of the geologic origin of the Galápagos Islands, including popular descriptions (e.g., Boyce 1994, Jackson 1990), attribute their formation to a "hotspot" or "mantle plume." The term "hotspot" refers to localities where volcanoes occur in the middle of one of the earth's great tectonic plates; hotspots are unusual, because over 90% of the world's volcanic activity occurs at plate boundaries. It is thought that hotspots result from "mantle plumes," conduits of hot, plastic (but not molten) rocks that ascend from deep within the earth's mantle (Figure 1). As these plumes of hot rock rise to depths of about 100 km from earth's surface, they begin to melt. When the melted fraction of the rock reaches several percent, it segregates from the rock (like water being squeezed from a damp sponge), eventually erupting to form volcanoes. No one knows the depth to the roots of mantle plumes, but most geologists believe they come from a layer in the earth's mantle either at 650 km or from the bottom of the mantle at 2700 km depth. Recent work on Galápagos lavas has identified some problems with the simple mantle-plume theory, but has taught us much about the origin, composition, and behavior of hotspots.

THE GALAPAGOS HOTSPOT

Although the Galápagos were proposed as resulting from a mantle plume early in the development of the theory (Morgan 1972), there are two problems with the simple plume model when it is applied to Galápagos. First, at more conventional hotspots such as Hawaii and Yellowstone, only one to four volcanoes at the young "upstream" (in terms of plate motion) end of the chain are active. In contrast, nearly all of the Galápagos islands have erupted in the recent geologic past, regardless whether they sit at the easternmost, or oldest, end of the chain, or at the westernmost, or youngest, end of the archipelago.

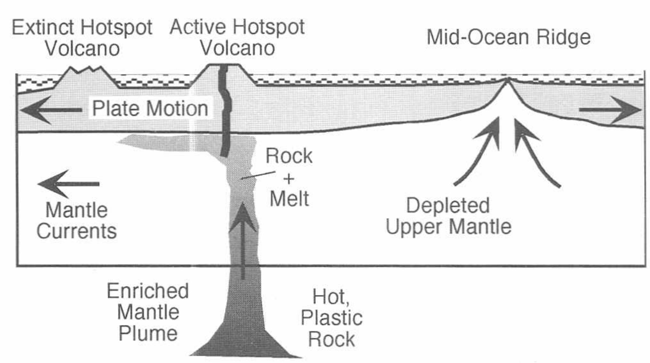

Figure 1. Cartoon of a simple plume rising from the lower mantle. The plume is a plastic solid which begins to melt as it nears the bottom of the overlying plate.

Second, the compositions of Galápagos magmas are unusual for hotspots. Generally, basalts erupted from hotspot volcanoes are compositionally distinct from those erupted in other tectonic environments, and each volcano evolves in a compositionally similar way. Galápagos lavas exhibit a wider range of chemical compositions than is usual, and compositional differences are more related to the volcanoes' location than to their stage of development.

Some of these complexities may arise from the fact that the Galápagos hotspot lies only about 100 km from the Galápagos Spreading Center, an active mid-ocean ridge. Great volumes of magma are produced beneath mid-ocean ridges, and in the islands these appear to contaminate the hotspot magmas produced by the Galápagos plume. Furthermore, the plates are strongly fractured, thin, and weak near mid-ocean ridges, which may permit magmas to ascend through the plate and erupt in places where they would not normally reach the surface.

This contribution describes recent studies using isotopic ratios of the elements lead, strontium, and neodymium, which have shed some light on the structure of the Galápagos hotspot and the dynamics of mantle plumes.

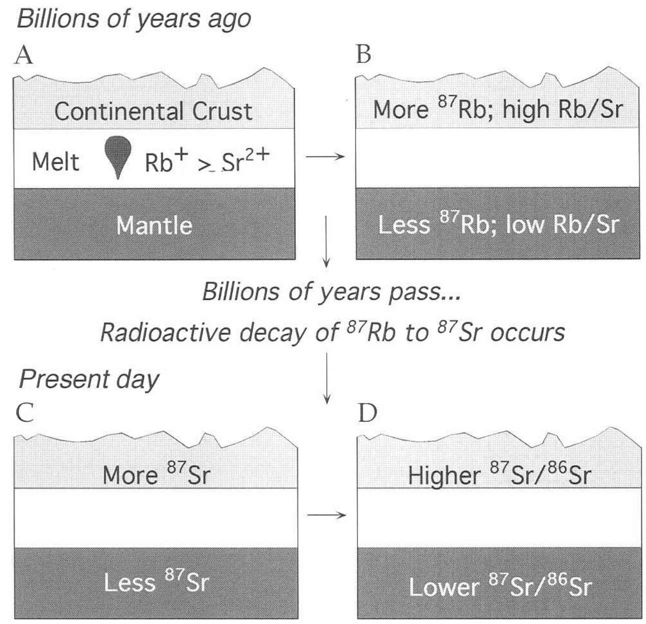

Figure 2. Schematic diagram showing how the $^{87}Sr/^{86}Sr$ ratios of the crust and the depleted mantle have evolved and changed with time.

GEOCHEMISTRY OF PLUMES

Before considering the details of the isotopic ratios of Galápagos lavas, we shall describe how they are used as a diagnostic tool in studies of volcanic systems. Some naturally-occurring elements are radioactive, which means that their nuclei decay spontaneously into nuclei of other elements. The isotopes we focus on have half-lives (the time for half of the nuclei to decay) of billions of years. The original radioactive element is called the "parent" isotope, and the element resulting from the decay transformation is referred to as the "daughter," or "radiogenic," isotope. For example, naturally-occurring rubidium of atomic mass 87 (^{87}Rb) is radioactive and decays to produce strontium of atomic mass 87 (^{87}Sr) with a half-life of 50 billion years.

Isotopes such as ^{87}Sr and ^{87}Rb are useful in the study of young magmas such as those of the Galápagos hotspot because of processes that have taken place over the course of geologic time. This concept is best illustrated by tracking the behavior of a typical parent-daughter isotope pair through the early part of earth history. The elements Rb and Sr, for example, were partly segregated from each other when the continental crust formed from magma made by partial melting of the earth's mantle billions of years ago. When rock begins to melt, larger ions migrate preferentially into the liquid fraction, with the smaller ions remaining behind in the residual solid. Because Rb^+ is a larger ion than Sr^{2+}, more Rb^+ partitions into the melt than Sr^{2+} (Figure 2A). It is simplest to consider the variations of the Rb/Sr ratio during melting; the melt that goes on to form the crust will have higher Rb/Sr relative to the source material, and the rock left behind in the mantle will have relatively lower Rb/Sr (Figure 2B).

The continental crust began to form about 4 billion years ago, and, as time passed, some of the radioactive ^{87}Rb isotope decayed, producing increasing amounts of ^{87}Sr. Meanwhile, in the part of the mantle depleted of melt, where there was less ^{87}Rb, less ^{87}Sr was produced during the same time (Figure 2C). When abundances of isotopes are determined, the concentration of the daughter isotope (^{87}Sr) is measured with respect to another isotope of the same element whose abundance in the earth has not been affected by radioactivity (e.g., ^{86}Sr). Thus, as a result of the melting process and the passage of billions of years, the old continental crust has a distinctly higher $^{87}Sr/^{86}Sr$ ratio than does the depleted mantle (Figure 2D).

A very important aspect of such isotopic systems is that present-day geologic processes, such as weathering, melting, and solidification, are incapable of changing the ratios of isotopes of the same element (for example, $^{87}Sr/^{86}Sr$). This is because natural chemical and physical processes do not differentiate between isotopes of the these heavy elements. Moreover, in young magmatic systems, the time for decay of the radioactive parent isotopes is very long relative to the ages of the erupted material. In other words, although a partial melt has a higher $^{87}Rb/^{86}Sr$ ratio than the rock it leaves behind, the melt and rock have identical $^{87}Sr/^{86}Sr$ ratios, until many millions of years have passed.

Because oceanic basalts derive directly from the earth's mantle, the isotopic ratios of the basalts faithfully record the isotopic ratios of the mantle, thus serving as a "fingerprint" of their mantle sources. Several other isotopic systems are similar to the Rb-Sr system, including the samarium-neodymium (Sm-Nd) and uranium-thoriumlead (U-Th-Pb) systems; for these we measure present day values of $^{143}Nd/^{144}Nd$, $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$, and $^{208}Pb/^{204}Pb$.

Lavas erupted from mid-ocean ridges such as the Galápagos Spreading Center have isotopic fingerprints identical to the melt-depleted mantle. The source of mid-ocean ridge lavas is known to be shallow, thus the upper mantle is the isotopically-depleted material left over from formation of the continental crust. Ocean island lavas have distinctly higher Sr and Pb ratios than depleted mantle values, and lower Nd ratios (^{147}Sm, the parent isotope, is smaller than its daughter isotope ^{143}Nd; this size relationship is opposite to that in the Rb-Sr system described above). It follows, then, that ocean islands are "enriched" relative to the depleted mantle and cannot have been derived from it; they must come from mantle that was not depleted by melting early in earth's history, or from depleted mantle that was re-enriched at least a billion years ago. Other evidence suggests that ocean island lavas come from the lower mantle, which must therefore be isotopically enriched.

Not all magmas come from a single source. Some magmas originate from parts of the earth where two sources have mixed prior to melting, and some magmas form by mixing melts from two separate sources. If two materials with different isotopic ratios are mixed, the hybrid will exhibit an intermediate isotopic ratio that is the weighted average of the two components. In other words, in a geologically young system where time does not alter the isotopic ratios significantly, such as the Galápagos, we can use isotope ratios to determine the sources of the magmas. We have taken this approach in the Galápagos.

THE TOROIDAL AND BENT PLUME MODELS

Early work on the compositions of Galápagos lavas indicated that they are unusual for a hotspot (McBirney and Williams 1969, Baitis and Swanson 1974). In particular, it was shown that some Galápagos lavas have compositions essentially identical to those of mid-ocean ridge lavas, whereas others have more typical hotspot compositions. White and Hofmann (1979) made the key observation that lavas from Santiago, Santa Cruz, and San Cristóbal in the central part of the archipelago have isotopic compositions that suggest the magmas were derived from the shallow depleted mantle, the same source as mid-ocean ridge magmas, with little hotspot contribution. Most lavas from the west, north, and south, in contrast, have more typical hotspot-like isotopic signatures, with higher Sr and Pb isotopic ratios, and lower Nd ratios.

Geist *et al.* (1988) subsequently obtained more detailed isotope data from the archipelago. They added to White and Hofmann's observations by backtracking older volcanoes to their location at the time of eruption, to account for the drift of the volcanoes by plate tectonics. For example, lavas from Santa Fe are nearly 3 million years old. Because the plate on which the Galápagos Islands lie is moving about 5 cm/yr to the east, then at the time that Santa Fe was active, it was located about 150 km to the west of where it is now, approximately where Fernandina is currently. When the isotopic data were corrected for plate motion, a horseshoe-shaped pattern emerged, with the hotspot-like component increasingly concentrated to the north, south, and west, and the shallow-mantle component focused along the central axis of the archipelago.

This observation presented a substantial problem. One could easily imagine a rising plume being polluted by the surrounding mantle as it ascends, but with the contamination occurring mostly around the margins of the mantle plume, just as smoke is progressively diluted with air around the margins of a plume of smoke. Unfortunately, this model would yield exactly the opposite pattern to what is observed in the Galápagos. A breakthrough came from a group of fluid dynamics modellers (Griffiths 1988), who showed that instead of mantle plumes being like a column of smoke above a chimney, they might be more like rising drips or bubbles. The importance of this is that rising drips entrain their surroundings not through their sides, but up through their bottoms, like a smoke ring. This makes a doughnut-shaped torus, with pristine plume material around the margins and entrained shallow mantle in the center (Geist *et al.* 1988).

It was then shown that the toroidal-plume model is unlikely to work in the Galápagos. This is mostly because the fluid dynamicists believe that under the conditions of the earth's mantle, plumes are likely to resemble continuous chimneys; only at their initiation would plumes act like large, ascending drips (Richards and Griffiths 1989). The Galápagos hotspot has been active for at least 20 million years, and maybe as long as 90 million years, so there could be no appeal to the Galápagos plume being in the initiation phase.

With yet more detailed isotopic and age data, White *et al.* (1993) have developed a consistent dynamic plume model. If a continuous, chimney-like plume is bent, like a smoke column in the wind, it can entrain the surrounding material in a horseshoe-shaped pattern (Richards and Griffiths 1989). According to this hypothesis, the Galápagos plume rises beneath Fernandina and is bent to the east by currents in the plastic mantle. As it is dragged along by the overlying plate, the plume's central part is progressively contaminated, or diluted, by the surrounding shallow mantle material.

THE CURRENT MODEL FOR THE GALAPAGOS PLUME

In 1990, a group of researchers carried out a research cruise in the Galápagos to collect submarine lavas erupted onto the Galápagos platform. The fundamental idea behind the project was to determine whether the isotopic pattern throughout the archipelago was consistent with either the bent plume or the toroidal plume model by collecting samples from submarine volcanoes. If the bent plume model held, then the isotopic pattern should remain a horseshoe, whereas if the toroidal model was more appropriate, the horseshoe should close to a circular pattern with the acquisition of more data to the east of the islands. Remarkably, every newly-acquired lava fit into the existing east-facing horseshoe pattern observed previously (Figure 3), suggesting that the bent plume model was more appropriate for the Galápagos than the toroidal plume model.

The new data also made it clear that Galápagos magmas cannot result from mixing between just two mantle reservoirs, the depleted mantle and the plume source (Harpp, 1995). On a plot of $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$, the endmember compositions of a typical mantle and plume are shown (Figure 4A); any mixture of these endmembers must fall along a straight line between the two extreme compositions. Similarly, on a plot of isotopic ratios of two different elements, e.g., $^{87}Sr/^{86}Sr$ versus $^{143}Nd/^{144}Nd$, the mixing array is hyperbolic, but the hybrids must plot along a single hyperbola (Figure 4B).

The Galápagos data clearly do not fall along simple mixing curves (Figure 4). Principal component statistical analysis indicates that at least four separate, distinct isotopic reservoirs are required to explain the variation in the geochemical data. Four plausible compositions for these sources, when mixed in varying proportions, can produce all of the Galápagos lavas (Figure 5). The four reservoirs have the following characteristics:

1) PLUME has an isotopic signature characteristic of ocean island lavas from some other archipelagos, with intermediate Sr, Nd, and Pb ratios;

2) DGM (Depleted Galápagos Mantle) has a composition typical of ocean ridge lavas from the shallow mantle throughout the Pacific basin, including the Galápagos Spreading Center, with low Sr and Pb isotope ratios, but high Nd;

3) FLO (short for Floreana, where lavas most closely resemble this composition) has elevated Sr and Pb isotope ratios, low Nd, and high concentrations of many trace elements. FLO appears to have been enriched in trace elements within the past 2 billion years and may be a piece of recycled oceanic crust that was subducted and later captured by the upwelling plume;

4) WD has a unique combination of Pb isotopic ratios and appears in lavas from Wolf and Darwin islands and seamounts in the northwestern quadrant of the archipelago. Such signatures are rare in the Pacific basin, and this is clearly the most mysterious of the various sources

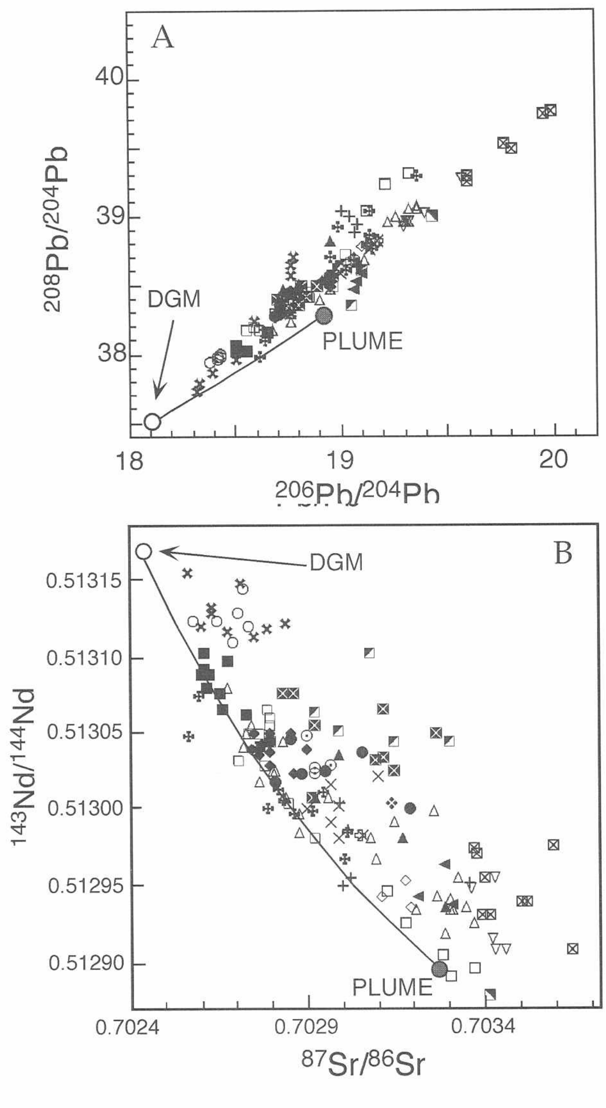

Figure 4. Covariation plots of Pb isotopes (top) and Sr and Nd isotopes (bottom). The typical endmember compositions for a plume (PLUME) and the depleted mantle (DGM) are indicated by the large circles. The line connecting the two endmember compositions is a two-component mixing curve. Symbols for the Galápagos data correspond to different regions of the archipelago; the legend is included with Figure 5.

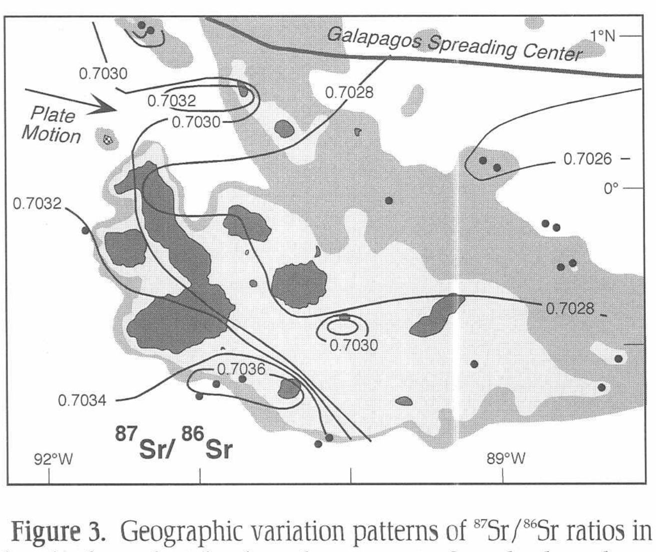

Figure 3. Geographic variation patterns of $^{87}Sr/^{86}Sr$ ratios in basalts from the islands and seamounts. Samples have been corrected for the distance they have travelled since eruption due to plate motion. Data from Harpp (1995) and White *et al.* (1993).

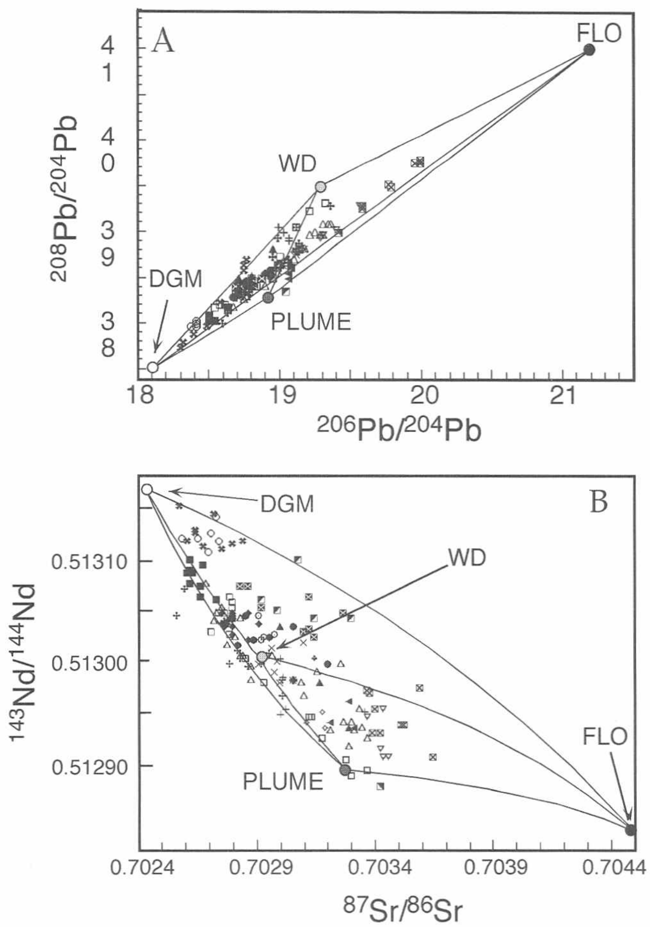

Figure 5. Covariation plots of Pb isotopes (top) and Sr and Nd isotopes (bottom). The compositions for the four component mixing model are shown as the large circles: PLUME, the depleted mantle (DGM), a recycled, enriched composition (FLO), and an anomalous composition observed only on Wolf and Darwin Islands and northeastern seamount areas (WD). Mixing lines are shown connecting the four components. The Galápagos lava data are superimposed on the mixing curves. From Harpp (1995).

of Galápagos magmas. In some ways, WD resembles material collected from the Indian Ocean ridge system thought to be the dregs of the subcontinental mantle. It is, however, a minor component of most Galápagos magmas.

The proportions of the mantle reservoirs that contribute to each volcano are mapped in Figure 6. The major contribution from the PLUME component arises, as expected, in the western part of the archipelago, where the volcanoes are most active. Correspondingly, the contribution from DGM, the depleted mantle, increases continuously eastward and northward, consistent with dilution of the plume away from its center by mantle mixing. The enriched endmember, FLO, is localized in the southwest near Floreana . FLO may be a peripheral part of the plume that was incorporated from a small, highly altered part of the upper mantle. Regardless of its origin, the pocket of FLO seems to be affected by the same mantle dynamics as the plume, with increasing dilution eastward and northward from its center.

The distributions of both PLUME and FLO illustrate the two primary forces at work in the mantle beneath the Galápagos. First, downstream flow related to currents in the mantle decreases the contributions of PLUME and FLO in the direction of plate motion (approximately east). Second, there is a deep, strong lateral flow of mantle to-

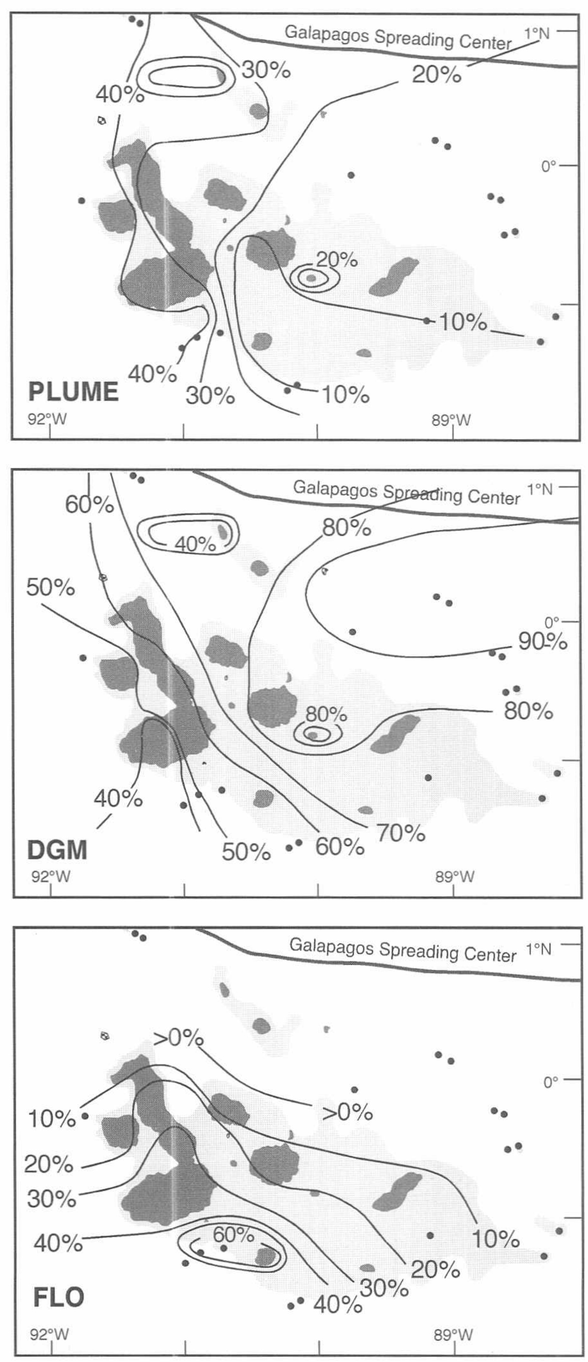

Figure 6. Contours of maximum contributions to Galápagos lavas from three of the proposed endmembers, the plume (PLUME), the depleted mantle (DGM), and the Floreana-like composition (FLO). The 1000 m bathymetric limit is shown.

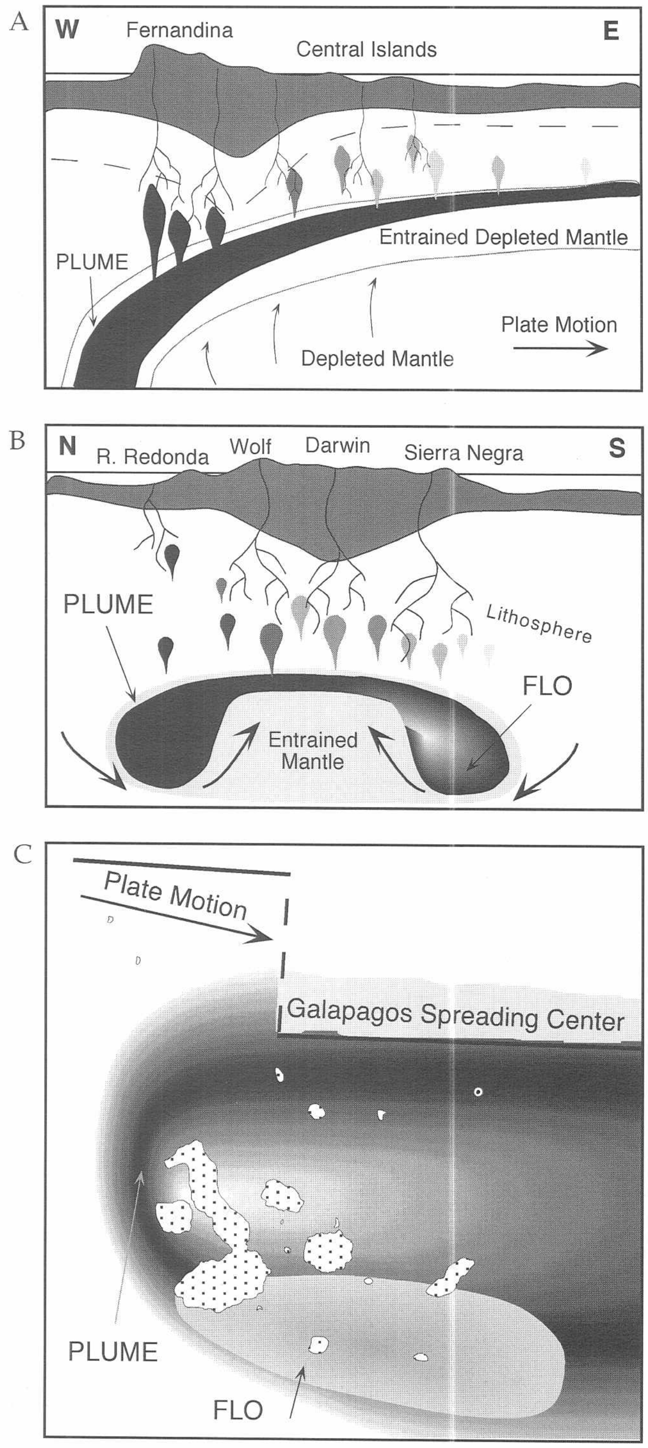

Figure 7. Schematic views of the present model for the Galápagos plume. These are for illustrative purposes, and are not drawn to scale. Black represents pure PLUME; white represents pure depleted mantle (DGM); gradations of grey represent mixing among the components. Arrows trace entrainment of depleted mantle into the plume conduit. A. West-east cross-section of the plume; note the progressive eastward dilution of the bent plume as it entrains depleted mantle; FLO is not shown in this view. B. North-south cross-section in the bent part of the plume (i.e. the main conduit is farther west in this figure). Note that depleted mantle is being entrained into the center of the plume, and FLO is localized in the south. C. Top view of the Galápagos plume, at shallow mantle levels. Flow of plume is eastward, in the direction of plate motion. Note the distibution of concentration (i.e. darkest) plume in a horseshoe-like pattern, with depleted (i.e. lighter) material at the center. FLO is indicated in the southwest corner, and mixes eastward in the direction of plate motion. Views A and B modified from White *et al.* (1993).

ward the adjacent spreading ridge, feeding mantle which is upwelling beneath the ridge system.

If the hot plume conduit is being bent to the east by mantle flow and plate motion, a pattern consistent with the observed geochemical variations might result. Depleted mantle is drawn into the center of the plume because the plume heats up its surroundings, which become warmer, less dense, and begin to rise into the interior of the bent plume (Figure 7); such effects have been reproduced in laboratory-scale tank experiments. As the plume is progressively diluted with depleted mantle material "downstream," less melting occurs, and the volume of erupted material decreases, accounting for waning volcanic activity to the east within the archipelago (Figure 7).

The decrease in PLUME and FLO contributions to the north may result from interaction of the plume with the adjacent Galápagos Spreading Center. It is clear that Galápagos plume material is being incorporated into the mantle beneath the Galápagos Spreading Center, based on plume-like signatures in lavas erupted along the ridge. The upwelling currents feeding the ridge may be responsible for transporting some of the plume material northward, on an archipelago-wide scale.

More than five million years ago, the Galápagos plume was located directly on top of the spreading center; the ramifications this has for the early history of the Galápagos are not clear at this point, although it is possible that magmatic production was enhanced by this coincidence. Thus, there may have been more, larger volcanoes in the Galapagos island chain than there are now. By studying drowned islands and seamounts "downstream" of the Galápagos, we may be able to shed some light on the extent of land present in the Galápagos prior to 5 million years ago (Christie *et al.* 1992).

CONCLUSIONS

The Galápagos hotspot is more complex than originally believed, due to dynamic processes in the earth's upper mantle. Our heightened understanding of these processes leads to new insights into how mantle plumes work. Unlike strong plumes such as Hawaii, the Galápagos plume is relatively weak and interacts strongly with surrounding mantle as it is tilted by prevailing mantle currents. As it is bent, the plume thermally entrains surrounding upper mantle. This results in the horseshoe-shaped distribution of depleted mantle and enriched hotspot material. Currently, our research group is trying to decipher the intricacies of the Galápagos plume via more detailed sampling of individual volcanoes to examine how compositional evolution of single volcanoes can be used to constrain plume models.

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NATURALIST GUIDES ASSIST IN MONITORING FLAMINGOS

By: Christine Breuker and Hernán Vargas

INTRODUCTION

The population of the Caribbean flamingo (*Phoenicopterus ruber ruber*) in the Galápagos Islands is a small one and has been for at least 30 years. The total number of adult birds is almost certainly less than 500. Given this small size, it is necessary to evaluate the status of the population, so the Charles Darwin Research Station (CDRS) and the Galápagos National Park Service (GNPS) monitor the flamingos by three methods:

- The annual census, conducted since 1967, usually in January, of the birds in most of the lagoons in the Archipelago where flamingos occur.
- The monthly census of the flamingo populations found in lagoons in southern Isabela Island, where the main breeding sites for these birds are located.
- The counts conducted by naturalist guides for the lagoons located near the visitor sites Punta Cormorant (Floreana), Cerro Dragón and Bachas (Santa Cruz), Punta Moreno (Isabela), Rábida, as well as "sail-by" counts of the lagoon on one of the Bainbridge Rocks.

The purpose of this paper is to analyze and summarize the flamingo data submitted to the CDRS by naturalist guides, primarily from the lagoon at Punta Cormorant on Floreana, but also from other lagoons near visitor sites.

The lagoon at Punta Cormorant is a place of great interest for both tourists and biologists. Located at the northern tip of Floreana, the brackish, shallow water is home to a number of wading birds and surrounded by interesting dry-zone vegetation. The water level varies seasonally and yearly. Both a greenish beach (of olivine crystal origin) and a white beach (of coral origin) are nearby. The area is a popular site and is visited by a more or less steady flow of tourists, accompanied by their naturalist guides. The prospect of seeing flamingos on the lagoon is an attraction. The trail taken by tourists overlooks the large lagoon from its northern and eastern shorelines. However, a review of the carrying capacity of the site in 1995-96 showed heavy overuse and resulted in recommendations for reducing use by tourists (Amador *et al.* 1996, Cayot *et al.* 1996).