

# Existence of complex spatial zonation in the Galápagos plume for at least 14 m.y.

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## ABSTRACT

**Basalts from intraplate or hotspot ocean islands (e.g., the Hawaiian, Galápagos, and Canary Islands) are believed to be formed by mantle plumes, which emanate from mantle boundary layers such as the core-mantle boundary. The long-term chemical structure of mantle plumes, however, remains poorly constrained. Spatial variation in the chemical composition has long been recognized in lavas from the Galápagos Islands: Enriched plume material forms a horseshoe-shaped region with depleted mantle, similar in composition to mid-ocean ridge basalt, in its inner part. The enriched horseshoe-shaped region can be subdivided into three distinct geochemical domains. We show that these same domains occur in the same relative positions with respect to morphology in a geochemical profile across the Galápagos hotspot track off the coast of Costa Rica, indicating that the asymmetrical spatial zonation of the Galápagos hotspot has existed for at least 14 m.y. Combined with published He isotope data, the results of this study imply that plume material can ascend from the lower mantle, possibly from the core-mantle boundary, with little stirring occurring during ascent, and that zonation in hotspot lavas may in some cases reflect spatial heterogeneity within the lower mantle source.**

**Keywords:** Galápagos, hotspot tracks, plume, Cocos Ridge, spatial chemical zonation, major element, trace element, isotope geochemistry.

## INTRODUCTION

The Galápagos Islands (<4 Ma; White et al., 1993) are located on the Nazca plate just south of the Galápagos spreading center. The archipelago can be divided into four geochemical domains (Fig. 1) with distinct Sr-Nd-Pb isotopic compositions (e.g., Fig. 2). The Southern, Central, and Northern domains form a crude horseshoe with enriched chemical compositions (e.g., high Sr and Pb but low Nd isotope ratios) (White and Hofmann, 1978; Geist et al., 1988; White et al., 1993). The Eastern domain, located in the inner part of the enriched horseshoe, has more depleted compositions (e.g., low Sr and Pb but high Nd isotope ratios) and shows significant overlap with mid-ocean ridge basalts (MORB) from the Galápagos (or Cocos-Nazca) spreading center and East Pacific Rise.

As a result of its proximity to the Galápagos spreading center, the Galápagos hotspot has formed two aseismic ridge tracks: the Cocos and Carnegie Ridges and associated seamounts on the Cocos and Nazca plates, respectively (Fig. 1). In order to evaluate if the spatial zonation in geochemistry observed in the Galápagos Islands reflects random heterogeneity or long-term zonation of the Galápagos plume, we selected a profile perpendicular to the oldest part of the Cocos Ridge where it approaches the subduction zone off Costa Rica. Volcanic samples from this profile (from the *SONNE* 81 and 107 cruises) have been dated between 13.0 and 14.5 Ma with the  $^{40}\text{Ar}/^{39}\text{Ar}$  laser technique (Werner et al., 1999). Although the sampled volcanic structures are currently located at water depths of 1–3 km, vol-

canological, geochemical, morphological, and geophysical evidence indicate that parts of the Cocos Ridge and many of the seamounts to the northwest formed under subaerial or shallow-water conditions, showing that a Galápagos archipelago existed 14.5 m.y. ago and probably significantly earlier (Werner et al., 1999; Christie et al., 1992). The morphology of the paleoarchipelago was similar to the morphology of the present-day Galápagos Islands: the Cocos Ridge with its drowned island volcanoes was equivalent to the central Galápagos platform with its many islands, whereas the drowned islands and seamounts northwest of the Cocos Ridge were similar to the isolated islands and seamounts north of the archipelago and along the Wolf-Darwin lineament. In contrast to the present location of the Galápagos spreading center north of the Galápagos hotspot, 14 m.y. ago it was located above or to the south of the hotspot (Meschede et al., 1998; Werner et al., 1999).

## RESULTS

Major elements and trace elements and Sr, Nd, and Pb isotope ratios were determined on volcanic glasses and lavas from the Cocos track profile off Costa Rica.<sup>1</sup> Central and southeastern Cocos Ridge samples, ranging from tholeiites to basaltic andesites, have lower contents of alkalis ( $\text{Na}_2\text{O}$  and  $\text{K}_2\text{O}$ ) and moderately to highly incompatible trace elements and lower ratios of more to less incompatible elements (e.g.,  $[\text{Th}, \text{Nb}, \text{La}]/[\text{Sm}, \text{Yb}], \text{Nb}/[\text{Zr}, \text{Y}]$ ) than samples with similar MgO contents from northwestern Cocos Ridge and the northwest seamounts, which consist primarily of alkali basalts and hawaiites (Fig. 3). In contrast to the Cocos track profile, where these incompatible element contents and ratios are lower in the south, they are highest in basalts with similar MgO contents from the southern Galápagos Islands.

All samples from the Cocos track profile have enriched Sr, Nd, and Pb isotopic compositions compared to MORB from the Galápagos spreading center and East Pacific Rise (Fig. 2). Depleted compositions, which occur in the Eastern Galápagos Island domain (inner part of the enriched horseshoe), were not found. The Cocos track profile can be divided into three geochemical domains, which we refer to as the Southern, Central, and Northern Cocos track domains. Both the locations relative to the morphology of the paleoarchipelago and the geochemical compositions of the Cocos track domains correlate closely to the enriched Galápagos Island domains with the same names (Figs. 1 and 2). The striking similarity in both the composition and geographical distribution of enriched domains in the Galápagos Islands and the Cocos profile suggests that the complex asymmetrical zonation currently observed in the Galápagos Islands has been a feature of the plume for at least the past 14 m.y.

## DISCUSSION AND CONCLUSIONS

Major and trace elements in basalts from the Galápagos Islands show systematic spatial variations that have been related to differences in melting

<sup>1</sup>GSA Data Repository item 200046, EMP, XRF, ICP-MS, and Sr-Nd-Pb isotope data and sample locations, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at [www.geosociety.org/pubs/drprint.htm](http://www.geosociety.org/pubs/drprint.htm).

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Data Repository item 200046 contains additional material related to this article.

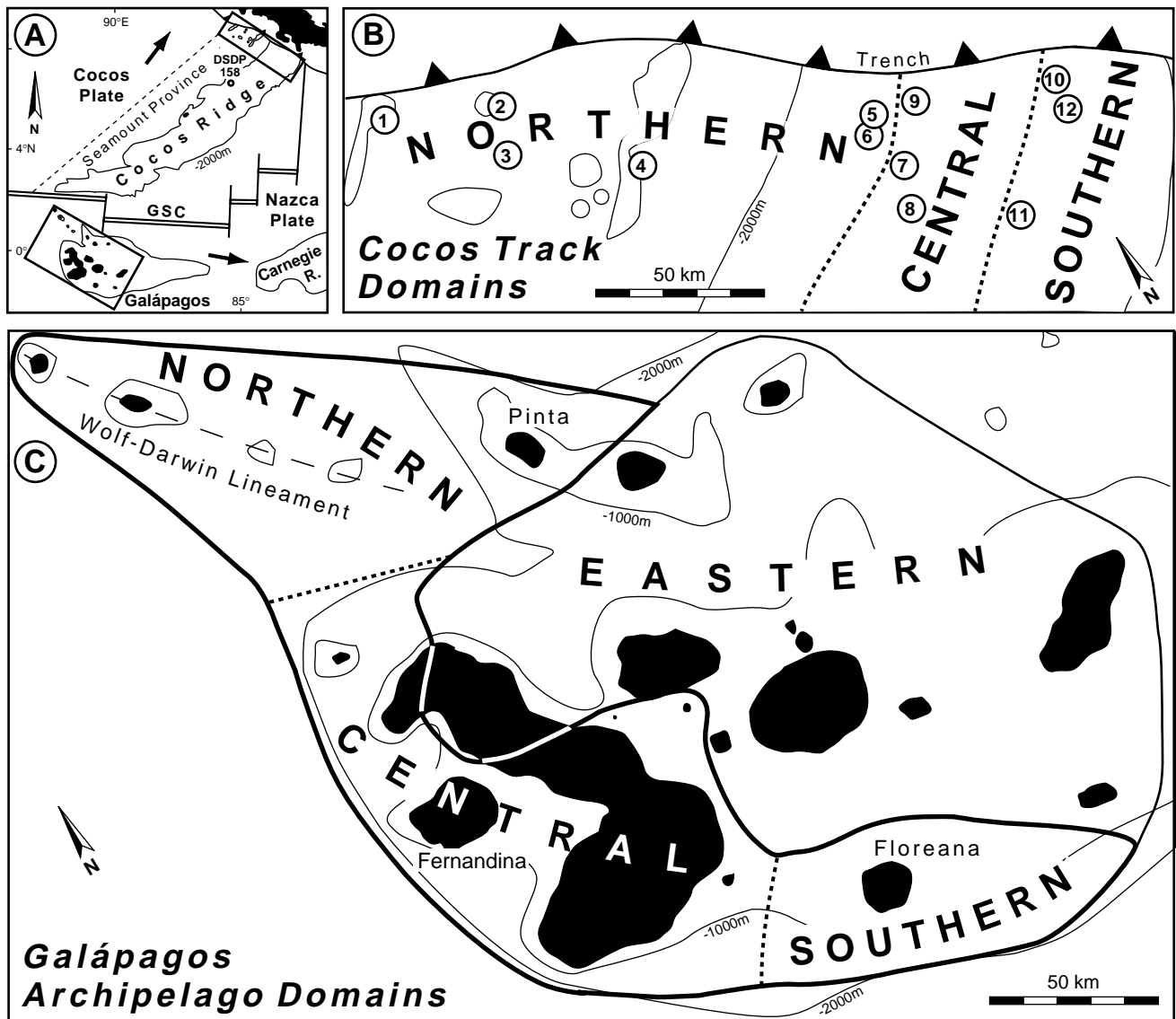
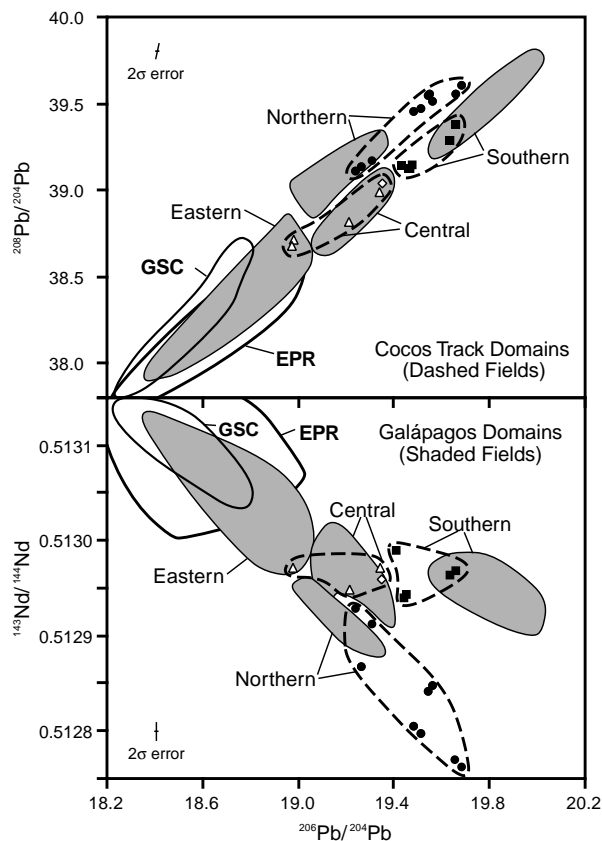


Figure 1. A: Overview map of Galápagos Islands and Galápagos hotspot tracks and blow-ups (locations denoted by boxes in overview map) of (B) Cocos track profile off Costa Rica (see footnote 1) and (C) Galápagos Islands. Galápagos Islands have been divided into four geographical domains based on their geochemical composition (see Figure 2): (1) Southern (Floreana Island), (2) Central (Fernandina, Roca Redonda, Isabela [Volcan Alcedo, Volcan Ecuador, Cerro Azul, and Sierra Negra], Rabida, and Cowley Islands), (3) Northern (Pinta, Wolf, and Darwin Islands), and (4) Eastern (Española, Genovesa, Isabela [Volcan Darwin and Volcan Wolf], Marchena, Nameless Rock, San Cristobal, Pinzon, Santa Cruz, Santa Fe, and Santiago Islands). Southern, Western, and Northern domains form horseshoe-shaped region of enriched material (denoted by thick line), which encloses depleted Eastern domain. Three enriched domains occur in same relative geographic positions in 14 m.y. Cocos track profile, and Galápagos Islands are thus given same domain names. Domain names used in this study do not correlate directly with subprovince terminology used in some previous studies. Rates for plate motion for Cocos and Nazca plates are from Kellogg and Vega (1995). GSC—Galápagos spreading center, DSDP—Deep Sea Drilling Project.

reflecting the thermal structure of the plume and the surrounding asthenosphere (Geist, 1992; White et al., 1993). The contrasting variations in incompatible elements between the Cocos track profile and the Galápagos Islands must also primarily reflect differences in extent of melting rather than source variation, because the compositional structure of the plume appears to have remained constant over the past 14 m.y. If the thermal structure of the plume also remained constant, extent of melting and presumably ambient asthenospheric temperature appear to increase toward the spreading center (White et al., 1993), which in contrast to the present (Fig. 1) was located above or south of the hotspot 14 m.y. ago.

The Sr-Nd-Pb isotope geochemistry of basalts from the Galápagos Islands and the Cocos track profile indicates that the plume contains at least three mantle components (Geist et al., 1988; White et al., 1993). The

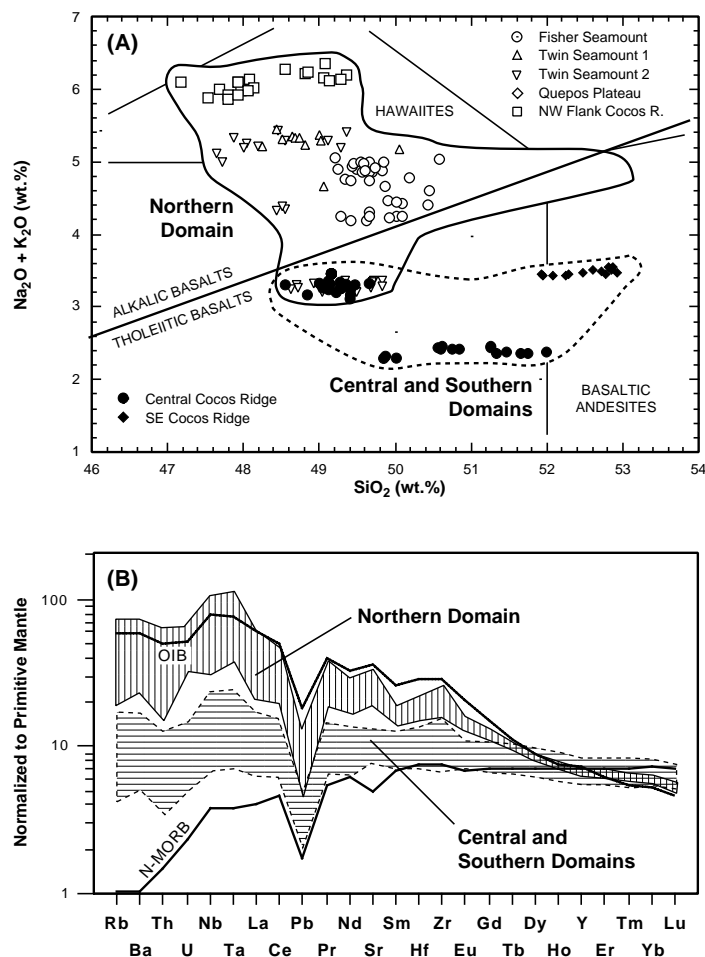
volcanic rocks from the Eastern Galápagos domain have compositions that extend from the fields for the enriched domains well into the field for East Pacific Rise and Galápagos spreading center basalts and therefore most likely reflect mixtures of enriched plume components and either MORB source material or recycled lower oceanic crust or lithospheric mantle (Hauff et al., 2000a). The Southern and Northern domains require at least two enriched components within the plume, which may represent different types of recycled altered oceanic crust based on the radiogenic Pb isotopic composition of these components. Although the Central domains have intermediate Sr-Nd-Pb isotopic compositions, they contain the highest  $^3\text{He}/^4\text{He}$  ratios (to  $27 R_A$ ), possibly indicating the presence of a third enriched component in the plume (Graham et al., 1993; Kurz and Geist, 1999). The lower  $^3\text{He}/^4\text{He}$  of the other domains, however, could



**Figure 2.** Southern, Central, Northern, and Eastern Galapagos Island domains (shaded fields) have distinct Sr-Nd-Pb isotopic compositions, as illustrated here. Southern, Central, and Northern Cocos track domains (dashed fields) have isotopic compositions similar to those of three enriched Galapagos Island domains with same names. Data from Deep Sea Drilling Project Site 158 (diamond) are from Hauff et al. (2000b). Galapagos Island data and fields for East Pacific Rise (EPR) and Galapagos spreading center (GSC) are from White et al. (1993).

reflect dilution of He by degassing or melt extraction and subsequent radiogenic ingrowth or crustal assimilation with increasing distance from the leading edge of the plume. In any case, the high  $^3\text{He}/^4\text{He}$  ratios are consistent with a lower mantle origin for the Galapagos plume, possibly from the core-mantle boundary.

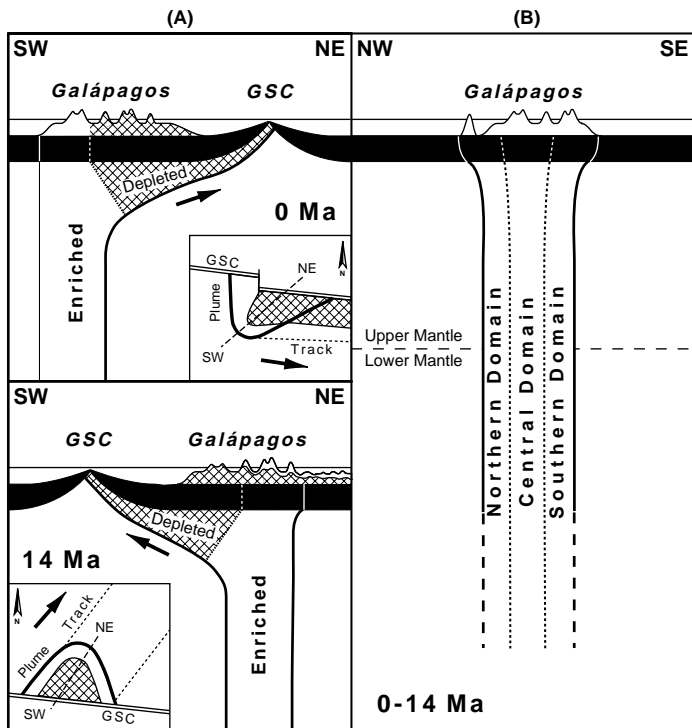
Thermal entrainment of depleted asthenosphere by an enriched mantle plume bent by velocity shear in the uppermost asthenosphere has been proposed to explain the presence of depleted lavas (Eastern domain) within a horseshoe of more enriched material (Northern, Central, and Southern domains) at the Galapagos Islands (White et al., 1993). This model predicts a hotspot track with stripes of enriched material, similar in isotopic composition to the Northern and Southern domains, bounding a depleted central stripe, with a MORB-like isotopic composition similar to the Eastern domain. Volcanic rocks from the Central domain are presumably buried beneath those of the Eastern domain as the plate moves over the hotspot. Analyzed samples from the Central Cocos track domain, however, have compositions primarily in the range of samples from the Central Galapagos domain instead of from the Eastern domain (Fig. 2). In addition, the enriched horseshoe at the Galapagos, seen best on contoured isotope diagrams (e.g., White et al., 1993), opens to the northeast instead of to the south-southeast, the direction of plate motion. These observations suggest that flow of plume material to the spreading center (e.g., Morgan, 1978; Schilling et al., 1982; Verma and Schilling, 1982) along the shallowing



**Figure 3.** Major (A) and trace element (B) data from 14 m.y. Cocos track profile. Volcanic rocks from northern Cocos Ridge and northwest seamounts (Northern domain) primarily have alkalic compositions and incompatible element characteristics similar to ocean island basalts (OIB), whereas those from central and southern Cocos Ridge (Central and Southern domains) have tholeiitic compositions and incompatible element compositions between average OIB and normal mid-ocean ridge basalt (MORB). Incompatible element normalization to primitive mantle is from Hofmann (1988). OIB and MORB patterns are from Sun and McDonough (1989). Major element data are from volcanic glass; trace elements are from glass and whole rock.

base of the lithosphere also plays an important role in generating the geochemical variations at the Galapagos Islands.

As noted here, the major and trace element data are compatible with increasing temperature and extent of melting toward the spreading center. The isotope data indicate that the plume is heterogeneous, consisting of enriched and depleted components, for example in the form of enriched pyroxenitic layers, representing recycled altered oceanic crust, within a depleted matrix of peridotite and possibly unaltered lower oceanic crust. We propose that continuous melt extraction during flow of plume material toward the spreading center will result in progressive depletion of the enriched components in the plume toward the spreading center (Fig. 4A). Melts will also become systematically more depleted and extents of melting will decrease in the flow direction. Because the hotter core of the plume will melt to greater extents than the cooler margins of the plume, flow of plume material to the spreading center forms a horseshoe with the most depleted residual plume material in its interior. Considering the depleted composition of the plume melts from the interior of the horseshoe, it is difficult to detect the presence of such melts at the spreading center with con-



**Figure 4. A:** Southwest-northeast profiles through Galápagos hotspot at 0 and 14 Ma illustrate flow of plume material (arrows) toward Galápagos spreading center (GSC) along shallowing base of lithosphere. Note different locations of GSC with respect to plume. Insets show map views at 0 and 14 Ma and location of southwest-northeast profiles (dashed lines). Thick solid line shows borders of plume at base of lithosphere, whereas thin dashed lines indicate margins of hotspot track. Enriched and depleted (shading) portions of plume head and hotspot track are also denoted. Arrows indicate direction of plate motion. **B:** Northwest-southeast profile through Galápagos plume depicts striped chemical zonation of Galápagos plume over past 14 m.y. Diagrams are not to scale.

ventional geochemical techniques. The influence of the plume is only detected along the spreading center where less depleted material from the plume margin reaches it, the current situation between 89.5° and 92.5°W along the Galápagos spreading center (e.g., see White et al., 1993). The overall degree of depletion of melts in the interior of the horseshoe correlates with the distance that the plume material flows toward the spreading center. If the Galápagos spreading center was located above the hotspot 14 m.y. ago, then it is unlikely that depleted, MORB-like melts were formed. If the ridge was located south of the hotspot 14 m.y. ago, then depleted melts may have formed during flow of plume material toward the ridge, but these depleted lavas were buried by younger enriched lavas, which formed as the plate moved to the northeast over the plume stem (Fig. 4A).

The remarkable similarity in the composition and geographical distribution of the three enriched domains in the Galápagos Islands and the Cocos profile is intriguing and suggests chemical zonation of the Galápagos plume for at least 14 m.y. This could be possible if flow is laminar or if little stirring occurs during plume ascent, and the plume is draining two or three chemically distinct regions at its boundary layer source (Loper, 1984; Sleep, 1987), i.e., that the plume is zoned in geochemical flavor, similar to the multicolor striping of some popular toothpastes (Fig. 4B). If so, the high  $^3\text{He}/^4\text{He}$  isotopic composition of the Galápagos plume would imply that such geochemical stripes and possibly spatial source heterogeneity can be preserved during plume ascent from the lower mantle, possibly the core-mantle boundary. In conclusion, the surprising spatial and temporal longevity of Galápagos plume heterogeneity is an important observation to incorporate into future models of hotspot melting and plume dynamics.

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