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Galápagos and Easter: A Tale of Two Hotspots

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ABSTRACT

Spatial asymmetry in the isotopic composition of volcanic rocks has been identified at several Pacific hotspots, including Hawai'i, the Marquesas, Samoa, the Societies, and the Galápagos. At each hotspot, the volcanoes are arranged in two sub-parallel chains that also define distinct fields in isotopic space. Here we present interpretations of data from two additional ocean island systems that exhibit spatial isotopic asymmetry: the Galápagos and Easter hotspots. Both systems display geochemical asymmetry despite being near-ridge hotspots, suggesting that compositional zonation in plumes originates at depths greater than the plumbing systems supplying mid-ocean ridges. Furthermore, the correspondence of the compositional boundaries of the Galápagos and Easter hotspots with those of the Large Low Shear Velocity Province (LLSVP) is consistent with the assertion that spatial patterns of isotopic enrichment at hotspots may reflect the distribution of compositional heterogeneity within the thermal boundary layer at the base of the mantle that gives rise to the plumes. At the Galápagos hotspot, which is located along the northern side of the LLSVP, the southern side of the chain exhibits geochemical enrichment, whereas at the Easter hotspot, located along the southern side of the LLSVP, it is the northern side of the chain that is enriched. Consequently, spatial variations in the geochemistry of hotspot lavas may provide a method for mapping the geochemical structure of the lower mantle.

3.1. INTRODUCTION

Morgan [1971] attributed hotspot volcanism to thermally buoyant plumes that rise from the deep mantle. If this hypothesis is valid, then the lavas erupted at hotspot volcanoes provide a glimpse into the composition of the otherwise inaccessible deep mantle. Archipelago-scale geochemical zoning at several Pacific hotspots, including Hawai'i, the Marquesas, the Societies, and possibly Samoa [*Abouchami et al.*, 2005; *Chauvel et al.*, 2012; *Huang et al.*, 2011; *Payne et al.*, 2013; *Stille et al.*, 1983; *Weis et al.*, 2011] suggests that the mantle plumes feeding these hotspots are themselves compositionally zoned. At each of these hotspots, volcanoes are distributed geographically along two sub-parallel chains that are geochemically distinct, with the southern trend enriched relative to the northern trend. Geodynamical studies suggest that the spatial distribution of heterogeneities within the thermal boundary layer that gives rise to mantle plumes may be preserved within the plume conduit as material ascends from the core-mantle boundary (CMB) to the surface [*Farnetani and Hofmann*, 2009, 2010; *Farnetani and Samuel*, 2005; *Kerr and Mériaux*, 2004; *Lohmann et al.*, 2009]. Consequently, the observed bilateral geochemical asymmetry at hotspots may reflect the geometry of geochemical reservoirs in the lower mantle.

Weis et al. [2011] and *Huang et al.* [2011] proposed that geochemical zoning along individual hotspot tracks results from the plumes being located on the northern periphery of the Pacific Large Low Shear Velocity Province (LLSVP), a

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region of the lower mantle characterized by elevated densities and low seismic shear-wave velocities [e.g., *Dziewonski*, 1984; *Ishii and Tromp*, 1999; *Ritsema et al.*, 2011]. The Pacific LLSVP is steep-sided, several hundred kilometers high, and may be associated with compositional heterogeneity near the core-mantle boundary [*Burke et al.*, 2008; *Castillo*, 1988; *Ishii and Tromp*, 1999; *Kerr and Mériaux*, 2004; *Lekic et al.*, 2012; *Lohmann et al.*, 2009].

Payne et al. [2013] discovered that the geometry of geochemical enrichment in the Society Islands, located south of the center of the LLSVP, is the mirror image of that observed at Hawai'i, the Marquesas, and Samoa. The northern volcanic lineament of the Societies Archipelago is geochemically enriched compared to the southern lineament, supporting the hypothesis that the pattern of geochemical variation in the volcanic chain is related to a hotspot's position relative to the LLSVP. Prior to this work, the Societies was the only Pacific hotspot with documented north-side geochemical enrichment.

The Galápagos and Easter hotspots also exhibit bilateral geochemical asymmetry, providing a crucial test of the original hypothesis linking geochemical variation in plumes to the deep mantle. Unlike the other four bilaterally zoned Pacific hotspots, the Galápagos and Easter chains are located on the Nazca Plate and along the eastern margin of the Pacific LLSVP [e.g., *Ritsema et al.*, 2011]. The two hotspots display complementary bilateral asymmetry: the Galápagos have south-side enrichment, whereas Easter exhibits north-side enrichment. This observation is consistent with geographic patterns of asymmetry identified in the four Pacific-plate hotspots, where the northern hotspots are enriched along their southern chains (like the Galápagos) and the southern hotspot has north-side enrichment (like Easter).

3.2. THE GALÁPAGOS ISLANDS

The Galápagos Islands are located in the eastern Pacific on the Nazca Plate, less than 200 km south of the Galápagos Spreading Center (GSC) (Figure 3.1). Unlike some other Pacific island systems, the Galápagos volcanoes do not form clear parallel chains; instead, they define a broadly distributed array of islands extending eastward, in the direction of plate motion. Between the platform and the GSC, there are several small volcanic islands whose origins have been attributed to plume mantle flowing toward the GSC [*Harpp and Geist*, 2002; *Mittelstaedt and Ito*, 2005; *Morgan*, 1978].

Previous studies have documented complex geographic patterns in the isotopic ratios of Galápagos lavas [*Blichert-Toft and White*, 2001; *Geist et al.*, 1988; *Harpp and White*, 2001; *Hoernle et al.*, 2000; *White et al.*, 1993]. Depending on the isotopic system used to define geochemical enrichment, the most enriched signatures are observed in the west and southwest archipelago, at Fernandina, southern Isabela, and Floreana volcanoes. To the east, volcanoes become progressively depleted [*Geist et al.*, 1988; *White et al.*, 1993], with maximum isotopic depletion at Genovesa and surrounding seamounts. The isotopic compositions of these volcanoes are comparable to those of mid-ocean ridge basalts, and in fact the intraplate volcanoes in this region are more depleted than lavas erupted from the nearby GSC [*Harpp et al.*, 2002; *Harpp et al.*, 2003; *Sinton et al.*, Chapter 16, this volume]. *White et al.* [1993] describe the geographic distribution of isotopic signatures as a "horseshoe" open to the east, with enriched material at the periphery and depleted material in the center. The pattern has been attributed to either dilution of the plume by entrained depleted upper mantle as the plume is sheared by the eastward motion of the overlying plate [e.g., *Geist et al.*, 1988; *White et al.*, 1993; *Harpp and White*, 2001] or, alternatively, greater melting of a depleted component intrinsic to the Galápagos plume [*Gibson and Geist*, 2010]. The Cocos Ridge, which is the Galápagos plume track on the Cocos Plate, may preserve chemical zonation for more than 14 Myr. [*Hoernle et al.*, 2000]. Owing to the sparse data available from the ancient plume tracks, however, we only consider the present-day Galápagos Archipelago and seamounts immediately adjacent to the submarine platform in this study.

The observations of bilateral compositional asymmetry at Pacific plumes provide an alternate explanation for geochemical variations in the Galápagos Islands. The archipelago is divisible into two geographic zones on the basis of isotopic signatures (Figure 3.1), which are broadly similar to the geochemical regions of *Harpp and White* [2001] and some of the geochemical boundaries proposed by *Hoernle et al.* [2000]. Lavas from the southwest, including Fernandina, Floreana, most volcanoes of Isabela (Cerro Azul, Sierra Negra, Alcedo, Darwin, and Ecuador), and adjacent submarine lavas constitute the more enriched zone (Figures 3.2, 3.3); these islands have the highest $^{3}He/^{4}He$, $^{87}Sr/^{86}Sr$, and $^{206}Pb/^{204}Pb$ in the archipelago [*Geist et al.*, 2002; *Graham et al.*, 1993; *Kurz and Geist*, 1999; *White et al.*, 1993]. Volcanoes to the northeast, including San Cristobal, Santa Cruz, Santiago, Marchena, Wolf and Darwin Islands, Wolf volcano (on Isabela), Genovesa, and near-ridge seamounts constitute the depleted zone [e.g., *White et al.*, 1993; *Harpp et al.*, 2002; 2003; *Harpp and White*, 2001; *Geist et al.*, 2005] and have MORB-like $^{3}He/^{4}He$ [*Kurz and Geist*, 1999; *Kurz et al.*, 2010].

Pinta Island is exceptional [e.g., *White et al.*, 1993; *Harpp and White*, 2001). Lavas erupted at Pinta are distinctly enriched in Sr, Nd, and, to a lesser extent, Pb isotopic ratios [*Cullen and McBirney*, 1987; *White et al.*, 1993], despite being surrounded by volcanoes

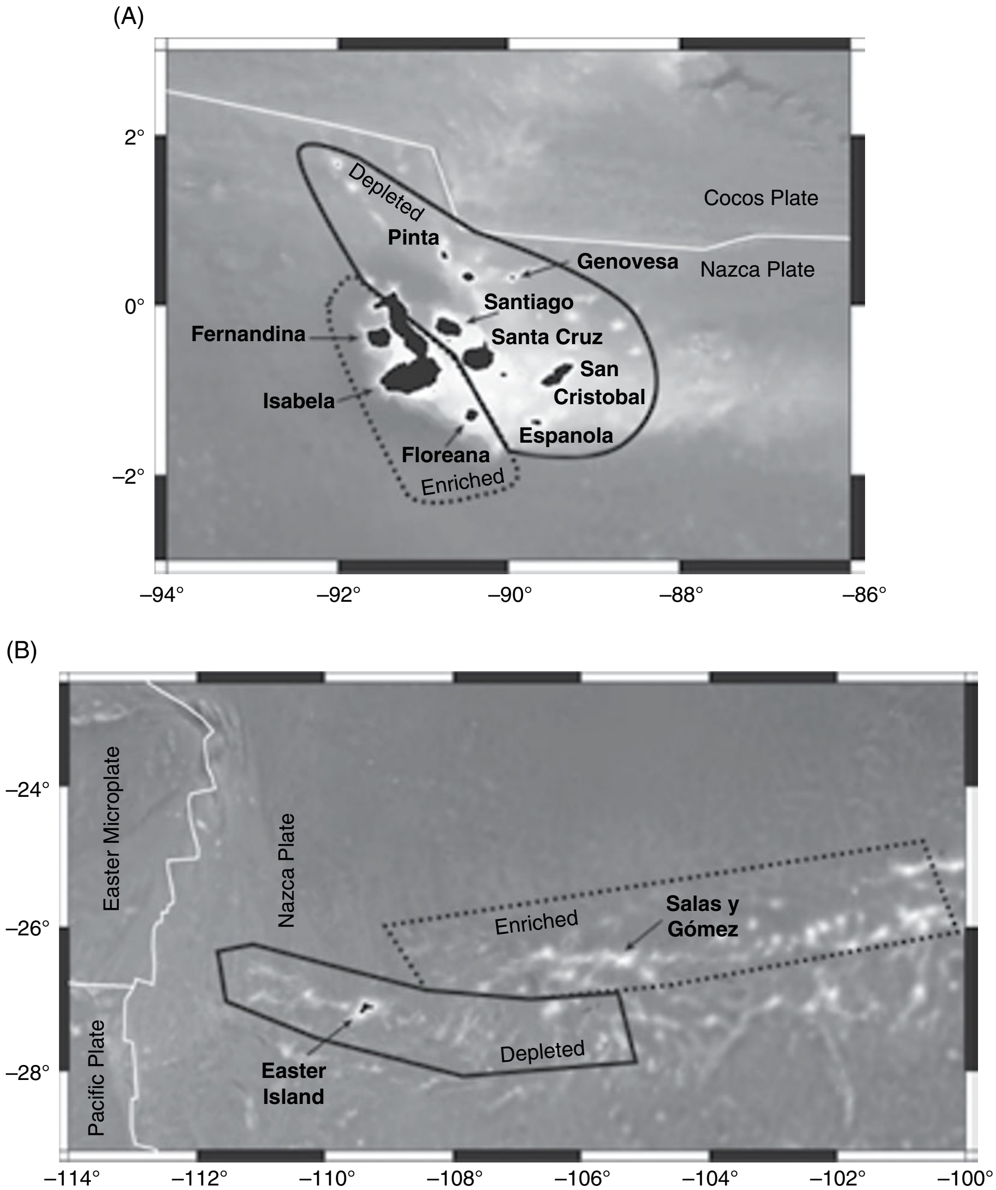

Figure 3.1 Location of the Galápagos and Easter hotspots. The fields on the maps indicate the geochemical zones identified at each hotspot.

with depleted isotopic compositions. In contrast, Pinta lacks the elevated $^{3}He/^{4}He$ signature associated with comparably enriched lavas in the western and southwestern archipelago (i.e., Fernandina and Floreana lavas) [*Kurz and Geist*, 1999]. Additionally, Pinta's variations in $^{207}Pb^{*}/^{206}Pb^{*}$ with $^{208}Pb^{*}/^{206}Pb^{*}$ (Figure 3.2E) and in $\Delta^{208}Pb/^{204}Pb$ with $^{87}Sr/^{86}Sr$ (Figure 3.2G) allow it to be grouped with the eastern Galápagos lavas, which makes more sense geographically (see below for further discussion). Pinta notwithstanding, the boundary between our proposed geochemical zones defines a NW-SE bearing, crosscutting the E-W plate motion-parallel axis of the island chain (Figure 3.1).

3.3. EASTER–SALAS Y GÓMEZ SEAMOUNT CHAIN

The Easter–Salas y Gómez Seamount Chain (ESC) is an E-W striking volcanic field that extends approximately 3,000 km across the Nazca Plate (Figure 3.1), from the East Rift of the Easter Microplate (EMP) in the west to the Nazca Ridge in the east. The present-day location of the hotspot is considered to be in the vicinity of Salas y Gómez or Easter Island [*Haase et al.*, 1996; *Kingsley and Schilling*, 1998; *O'Connor et al.*, 1995]. For much of its length, the ESC is composed of two subparallel, E-W trending volcanic lineaments, offset from each other by approximately 100 km (Figure 3.1).

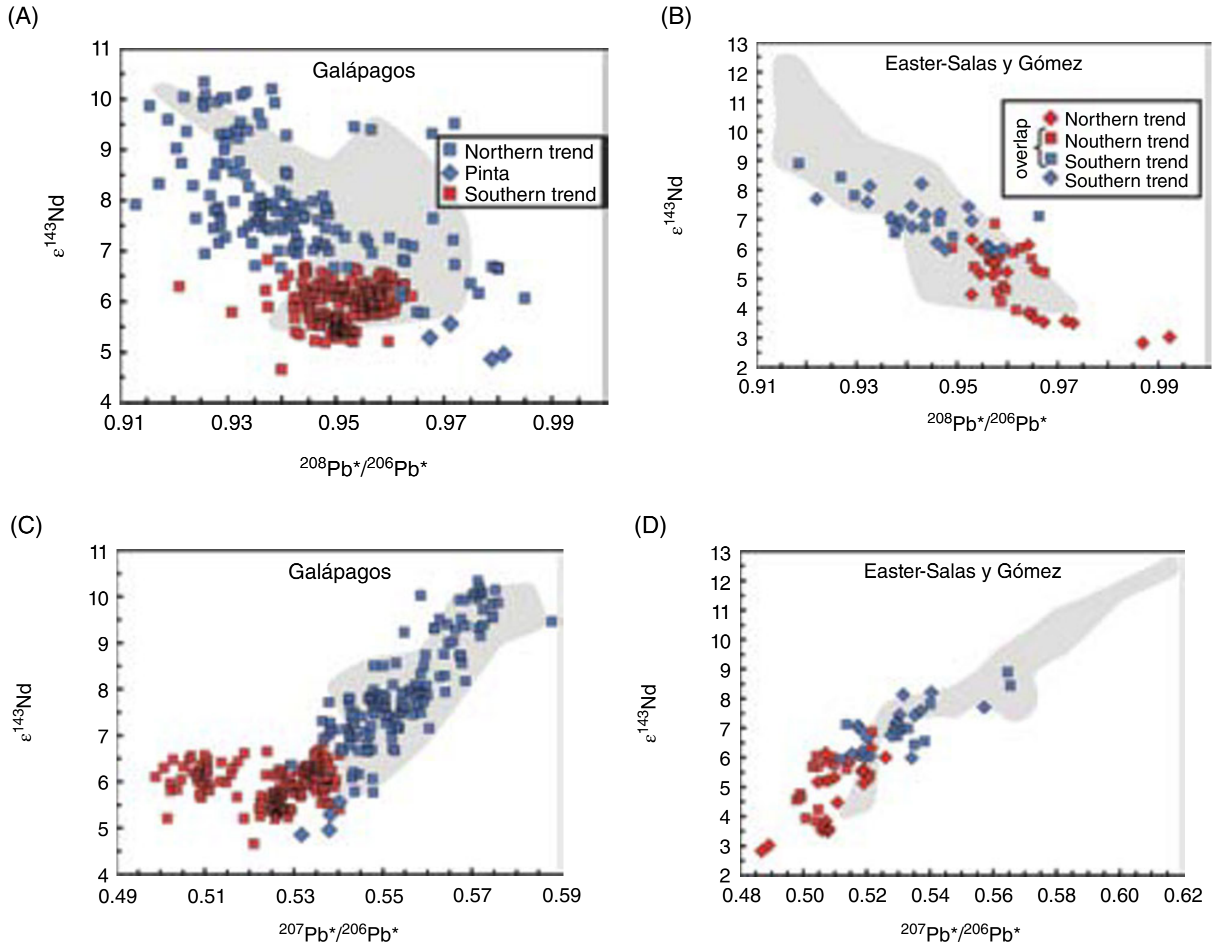

Figure 3.2 (A, B) The $^{208}Pb^*/^{206}Pb^*$ versus ε_{Nd} composition for the Galápagos and Easter Island-Salas y Gómez hotspots. (C, D) $^{207}Pb^*/^{206}Pb^*$ versus ε_{Nd}, see continuation of figure and caption below for further detail.

West of Salas y Gómez, the ESC is characterized by recent volcanism at Easter Island and numerous seamounts. This volcanism is thought to reflect the subhorizontal flow of plume mantle toward the EMP East Rift along the base of the lithosphere, a hypothesis supported by systematic along-strike variations in the geochemistry of rocks from this part of the ESC [*Schilling et al.*, 1985]. In particular, geochemical studies have shown that Salas y Gómez is the locus of melting of an enriched mantle source, resulting in alkali basalts with high $^{206}Pb/^{204}Pb$ and $^{87}Sr/^{86}Sr$ ratios, along with low $^{143}Nd/^{144}Nd$ and $^{176}Hf/^{177}Hf$ ratios. Furthermore, these isotope ratios grade along the ESC to low $^{206}Pb/^{204}Pb$ and $^{87}Sr/^{86}Sr$ and high $^{143}Nd/^{144}Nd$ and $^{176}Hf/^{177}Hf$ in the tholeiitic basalts of the EMP East Rift [*Fontignie and Schilling*, 1991; *Hanan and Schilling*, 1989; *Kingsley and Schilling*, 1998; *Kingsley et al.*, 2002; *Kingsley et al.*, 2007; *Pan and Batiza*, 1998; *Poreda et al.*, 1993; *Schilling et al.*, 1985]. This same trend is also observed in trace element ratios and the concentrations of incompatible elements and volatiles such as H_2O [*Kingsley et al.*, 2002; *Simons et al.*, 2002]. Along-strike geochemical gradients are believed to result from increasing depletion of the enriched component as plume mantle flows toward the EMP East Rift, coupled with an elevated contribution from ambient mantle-melting at shallow depths near the ridge [*Hall and Kincaid*, 2004; *Kingsley and Schilling*, 1998; *Kingsley et al.*, 2007; *Schilling et al.*, 1985].

Whereas the existence of systematic along-strike (E-W) variations in the isotopic composition of lavas from the ESC is well established, a second across-strike (N-S) variation is also apparent. In particular, rocks from the northern volcanic lineament of the ESC are more isotopically enriched than those from the southern trend (Figures 3.2, 3.4). Sampling of the two volcanic lineaments is geographically uneven, with geochemically characterized lavas from the northern trend coming mainly from the region east of Easter Island, whereas the geochemically characterized southern trend rocks mainly originate west of Easter Island (Figure 3.4). Nevertheless, the isotopic difference between the two

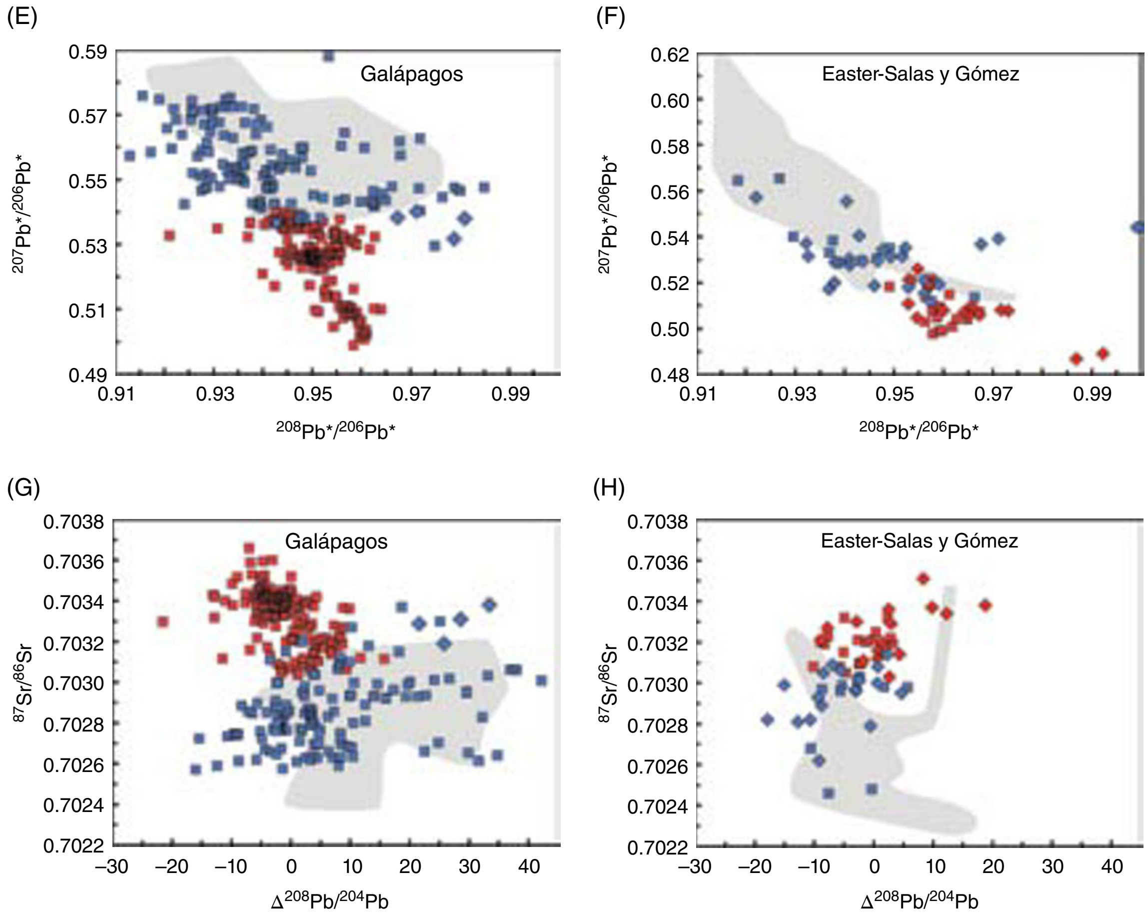

Figure 3.2 (Continued) (E, F) $^{207}Pb^*/^{206}Pb^*$ versus $^{208}Pb^*/^{206}Pb^*$. (G, H) $\Delta^{208}Pb/^{204}Pb$ versus $^{87}Sr/^{86}Sr$. The data indicate that the southwestern region of the Galápagos hotspot is more enriched than the northeast, and the northern trend of the Easter Island–Salas y Gómez hotspot is more enriched than the southern trend. The northern and southern volcanic lineaments of the Easter Island–Salas y Gómez hotspot overlap at the same longitude over a narrow geographic corridor (squares in right panels); lavas from the overlapping parts of the trends exhibit distinct geochemical separation, as do the sections of the trends that do not overlap (diamonds in right panels). GSC: Galápagos Spreading Center. $^{208}Pb^*/^{206}Pb^* = [(^{208}Pb/^{204}Pb)_{sample} - (^{208}Pb/^{204}Pb)_{Earth\ Initial}]/[(^{206}Pb/^{204}Pb)_{sample} - (^{206}Pb/^{204}Pb)_{Earth\ Initial}]$, with $(^{208}Pb/^{204}Pb)_{Earth\ Initial} = 29.475$ and $(^{206}Pb/^{204}Pb)_{Earth\ Initial} = 9.307$ based on Canyon Diablo Troilite [Galer and O'Nions, 1985]. $\varepsilon_{Nd} = (^{143}Nd/^{144}Nd)_{sample}/(^{143}Nd/^{144}Nd)_{CHUR} - 1] * 10{,}000$, where $(^{143}Nd/^{144}Nd)_{CHUR} = 0.512638$ for Nd isotopic measurements normalized to $^{146}Nd/^{144}Nd = 0.7219$, and $(^{143}Nd/^{144}Nd)_{CHUR} = 0.511836$ for Nd isotopic measurements normalized to $^{146}Nd/^{144}Nd = 0.636151$. $^{207}Pb^*/^{206}Pb^* = [(^{207}Pb/^{204}Pb)_{sample} - (^{207}Pb/^{204}Pb)_{Earth\ Initial}]/[(^{206}Pb/^{204}Pb)_{sample} - (^{206}Pb/^{204}Pb)_{Earth\ Initial}]$, with $(^{207}Pb/^{204}Pb)_{Earth\ Initial} = 10.294$ and $(^{206}Pb/^{204}Pb)_{Earth\ Initial} = 9.307$ based on Canyon Diablo Troilite [Galer and O'Nions, 1985]. $\Delta^{208}Pb/^{204}Pb = 100 * [(^{208}Pb/^{204}Pb)_{sample} - (1.209 * (^{206}Pb/^{204}Pb)_{sample} + 15.627)]$. (Galápagos data sources: [Allan and Simkin, 2000; Geist et al., 2006; Geist et al., 2002, 2008; Harpp and White, 2001; Kurz and Geist, 1999; Lyons et al., 2007; Reynolds and Geist, 1995; Schilling et al., 2003; White et al., 1993; Easter data sources: compilation from GEOROC, http://georoc.mpch-mainz.gwdg.de/georoc/].

volcanic lineaments is evident when the subset of lavas from 105°W–109°W, a region over which both trends are sampled (Figure 3.2), is considered on its own. We interpret this N-S variation as a reflection of the structure within the conduit of the underlying mantle plume. In particular, we suggest that the conduit of this plume exhibits a bilaterally asymmetric distribution of compositional heterogeneity.

3.4. DISCUSSION

Since the initial discovery of bilateral compositional asymmetry at several Pacific hotspots, determining whether mantle plumes with bilateral compositional asymmetry occur beyond the Pacific Plate has become a question with important implications for understanding

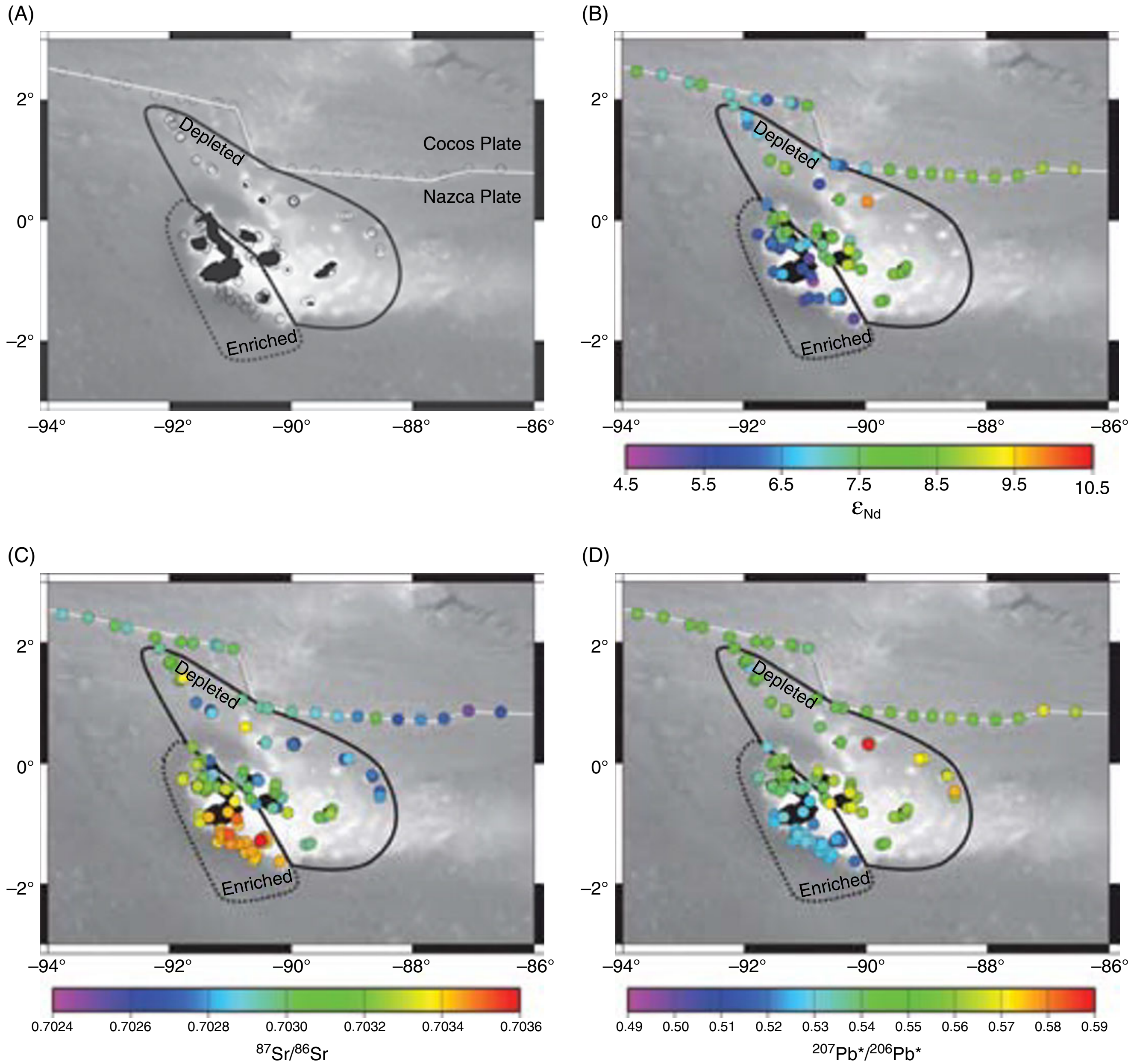

Figure 3.3 Maps showing spatial variations in the isotopic composition of lavas from the Galápagos Archipelago. (A) Sample locations. (B) ε_{Nd}; (C) $^{87}Sr/^{86}Sr$; (D) $^{207}Pb^*/^{206}Pb^*$.

the chemical structure of the lower mantle. Recently, *Rohde et al*. [2013] presented the case for 70 Ma of bilateral geochemical asymmetry at the Tristan-Gough hotspot in the South Atlantic, the first such mantle plume system identified near the African LLSVP. Our observations from the Galápagos and Easter mantle plumes further support the existence of zoned plumes beyond the Pacific Plate, indicating that they reflect deep mantle geochemical structure and are not simply related to plate motion or plate boundaries.

3.4.1. Plumes at the edges of the LLSVP

We posit that the geochemical zonation in the Galápagos and Easter hotspots (north-side enrichment at the Easter hotspot and south-side enrichment at the Galápagos) can be interpreted in light of recent observations of geochemical zoning at other Pacific hotspots. *Weis et al*. [2011] and *Huang et al*. [2011] attribute such geochemical asymmetry to the location of a hotspot along the margins of the Pacific LLSVP, which is proposed to be a compositionally

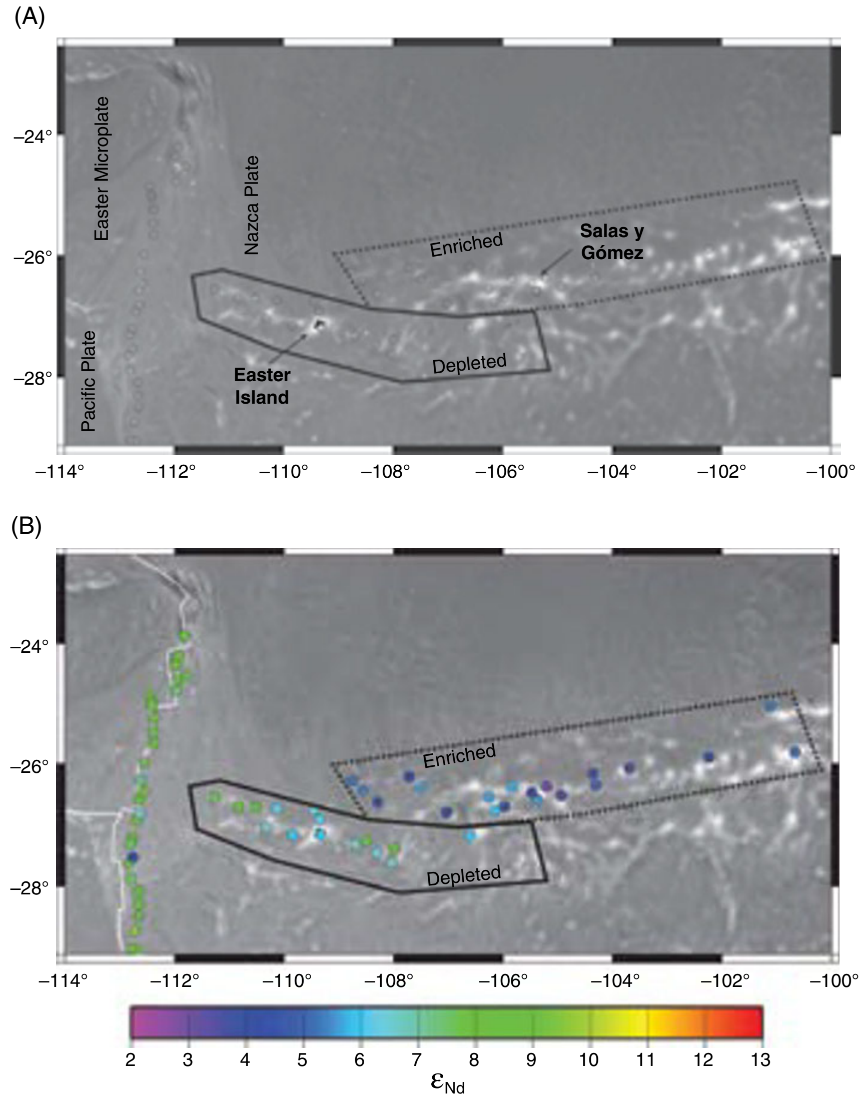

Figure 3.4 Maps illustrating spatial variations in the isotopic composition of lavas from the Easter–Salas y Gómez seamount chain. (A) Sample locations. (B) ε_{Nd}; see continuation of figure and caption below for further detail.

dense, geochemically enriched lower mantle domain [*Burke et al.*, 2008; *Castillo*, 1988; *Ishii and Tromp*, 1999; *Kerr and Mériaux*, 2004; *Lohmann et al.*, 2009]. Recent dynamic models [*Farnetani and Samuel*, 2005; *Farnetani and Hofmann*, 2009, 2010] predict that the spatial distribution of heterogeneity in the lowermost mantle is preserved within the plume conduit and reflected in the distribution of geochemical anomalies across the hotspot track. Like Hawai'i [*Weis et al.*, 2011; *Huang et al.*, 2011], the Marquesas [*Chauvel et al.*, 2012], and perhaps Samoa [*Workman et al.*, 2004; *Huang et al.*, 2011], the Galápagos (this study) are located along the northern boundary of the LLSVP and, in agreement with the interpretation of *Weis et al.* [2011] and *Huang et al.* [2011], the southern volcanoes at each hotspot host an enriched geochemical signature that reflects the enriched signature associated with the LLSVP (Figure 3.5). In contrast, the hotspots located in the southern part of the LLSVP, the Societies [*Payne et al.*, 2013] and Easter (this study), exhibit geochemical enrichment in the northern volcanic lineaments.

3.4.2. Plume-Ridge Interaction Effects

Unlike the four Pacific-plate hotspots that exhibit geochemical zonation, the Galápagos and Easter hotpots are situated near mid-ocean ridges. It is well-established that the enriched signatures observed in the plumes are communicated to the adjacent mid-ocean ridges [e.g., *Kingsley and Schilling*, 1998; *Schilling et al.*, 2003], but the influence of the ridges on the mantle sources of hotspots

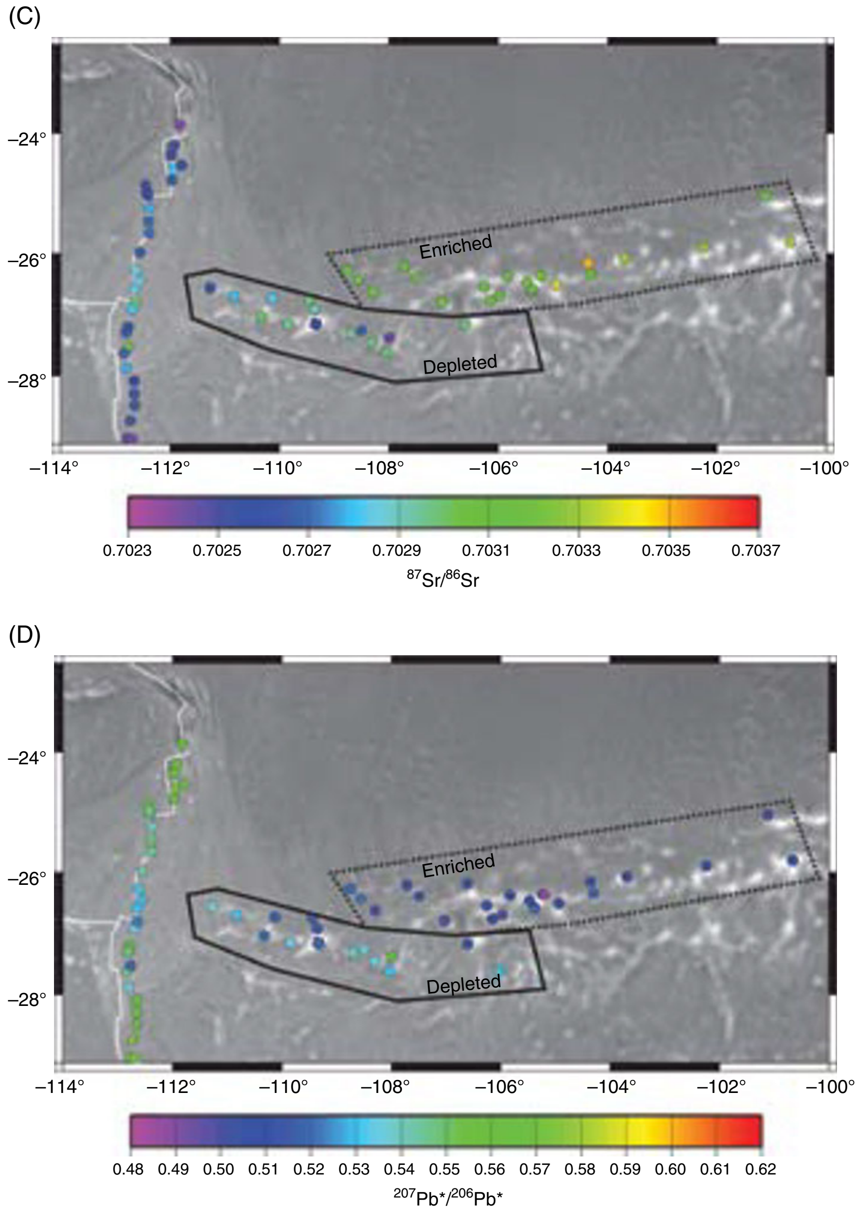

Figure 3.4 (Continued) (C) $^{87}Sr/^{86}Sr$; (D) $^{207}Pb^*/^{206}Pb^*$.

is not constrained as effectively. Despite progressively depleted signatures as the Easter chain approaches the EMP East Rift, the northern volcanic lineament maintains its geochemical enrichment relative to the southern lineament across the region where the two volcanic chains are sampled (Figure 3.4). Similarly, in the Galápagos, the influence of the ridge is strongest in the northeast volcanoes, yet the bilateral geochemical asymmetry is preserved across the archipelago despite the complex ridge-hotspot geometry (Figure 3.3). Interestingly, geochemical signatures detected in the Galápagos and Easter systems are consistently more depleted than those at the other Pacific hotspots [e.g., *Weis et al.*, 2011; *Huang et al.*, 2011; *Chauvel et al.*, 2012; *Payne et al.*, 2013]. We suggest that this phenomenon may be a manifestation of either plume-ridge interaction or of younger, thinner lithosphere underlying the near-ridge hotspots, resulting in greater extents of melting as a consequence of shallower upwelling. Regardless of the precise mechanism, bilateral asymmetry remains observable in both the Galápagos and Easter systems. We conclude, therefore, that interaction with the adjacent ridges does not eliminate the azimuthal geochemical gradient in the Easter and Galápagos hotspots, but instead shifts geochemical signatures to generally

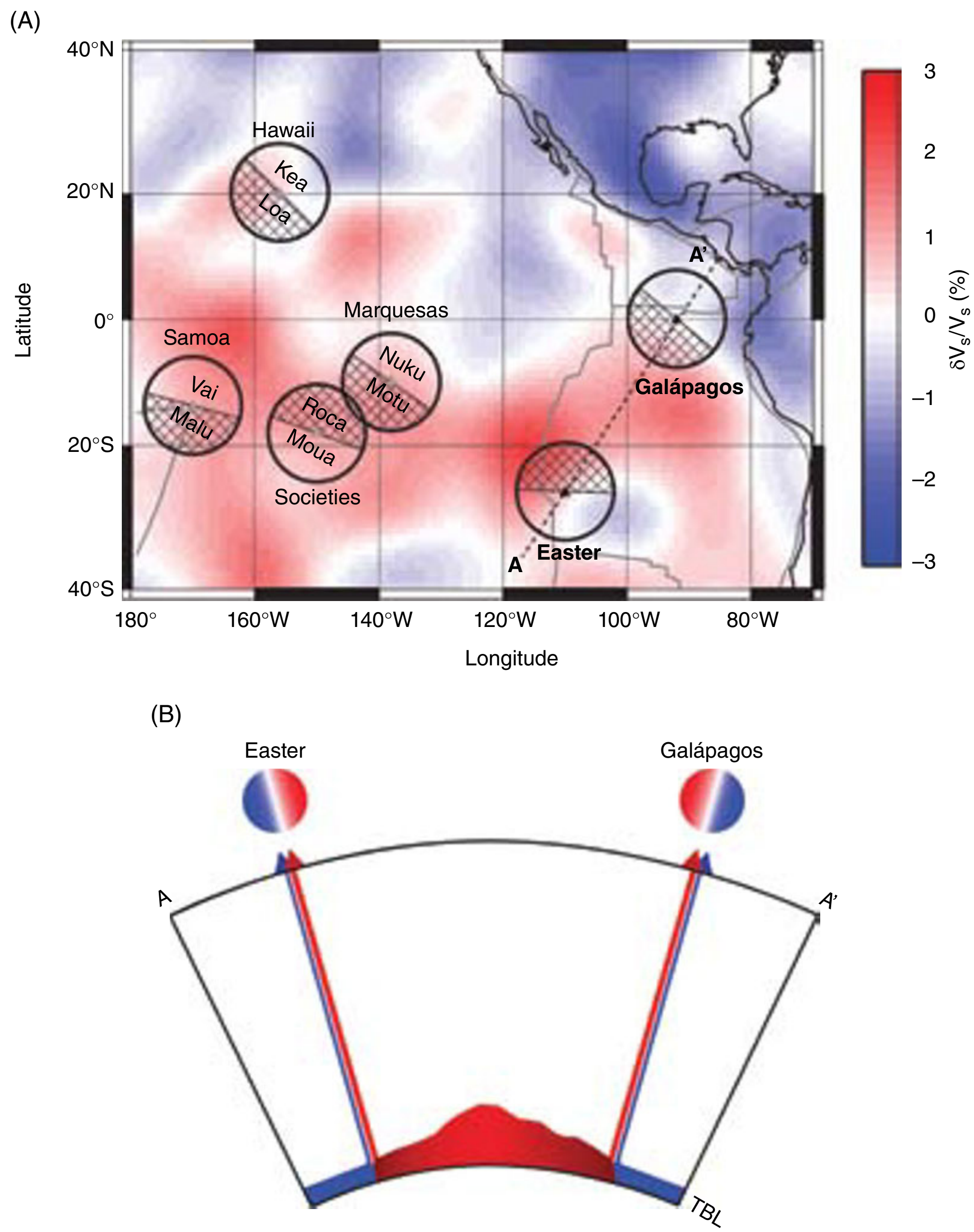

Figure 3.5 (A) Map of seismic shear wave velocity anomalies at 2,800 km depth from the SAW642AN model [Panning and Romanowicz, 2006]. The locations of active volcanism associated with the Galápagos and Easter hotspots are shown as black triangles and the plume footprint at the base of the mantle is shown schematically by the black circle, which corresponds to a region with a diameter of approximately 1,000 km [*Farnetani and Hofmann*, 2009]. The line bisecting the circles indicates the strike of the geochemical boundaries inferred from the isotopic compositions of lavas at the surface. The hatched half-circles correspond to the geochemically enriched side of the volcanic chain. Other Pacific hotspots identified previously to exhibit dual trend volcanism and geochemically distinct trends are shown similarly. (B) Conceptual model illustrating how the distribution of heterogeneities within the thermal boundary layer (TBL) at the base of the mantle may be reflected in the geochemistry of the individual volcanic trends. This figure shows a cross-section of the mantle along path A-A′ in Panel A. At both hotspots, the volcanic group closest to the enriched part of the TBL (red) erupts isotopically enriched magmas.

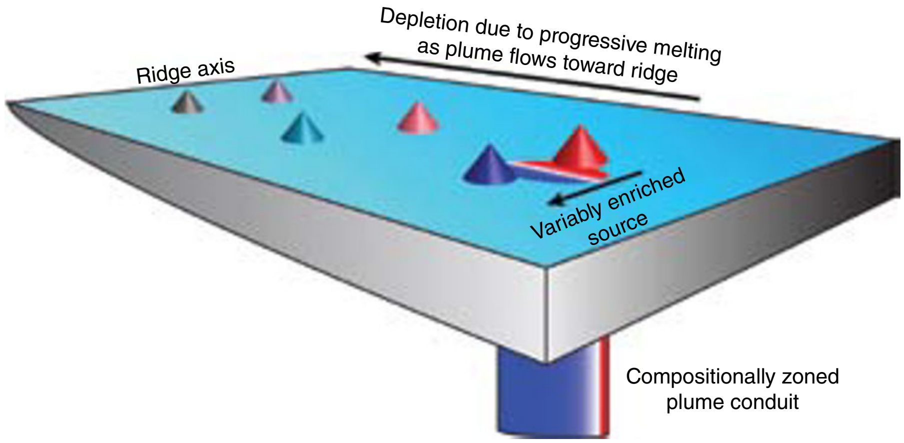

Figure 3.6 Schematic diagram illustrating simultaneous effects of bilateral compositional asymmetry originating in the deep mantle with the influence of progressive depletion and mixing with melts derived from the depleted upper mantle during plume-ridge interaction. Most notably, the bilateral asymmetry is preserved despite interaction with the adjacent mid-ocean ridges.

more depleted values while maintaining evidence of the original, deep-mantle bilateral symmetry (Figure 3.6).

Several additional lines of evidence support this hypothesis. The depleted component in the present-day northeast Galápagos has been proposed by *Hoernle et al.* [2000] to be a long-lived (>14 Ma), intrinsic component of the plume, present even when the Galápagos hotspot was located far from the ridge, and not the result of asthenospheric entrainment. Next, the GSC, at its closest approach to the archipelago, is more enriched than any of the lavas erupted from the near-ridge volcanoes of the northern Galápagos [e.g., *Harpp and Geist*, 2002; *Ingle et al.*, 2010], making it difficult to argue that plume-ridge interaction is exclusively responsible for the depleted signatures in the Galápagos. Finally, Easter and the Galápagos systems have distinctly different tectonic configurations in terms of the geometry of the mid-ocean ridges, plume location, and absolute plate motion. Despite these differences, bilateral asymmetry remains evident in both systems, suggesting that plume-ridge interaction is not the exclusive control on geochemical variations at near-ridge hotspots.

Instead, plume-ridge interaction probably has more of an influence on the dynamics of the shallow mantle and melt migration processes. The exceptional case of Pinta Island (Figure 3.1), in the Galápagos, may illustrate the specific effect of a ridge on the shallow mantle dynamics of an adjacent mantle plume. As described above, Pinta is more isotopically enriched than is predicted for its easterly location and, as such, does not conform consistently to the geochemical boundaries as drawn (Figures 3.2, 3.3). The tomographic studies of *Villagómez et al.* [2007] detect a low seismic velocity zone (−5%) between 50 and 100 km depth near Pinta Island. A similar low velocity zone, presumed to be the main plume conduit, is observed close to Fernandina Island at greater depths (>100 km). *Villagómez et al.* [2007] interpret these data to mean that the plume is spreading away from its locus near Fernandina, toward the NE archipelago. We suggest that the low seismic velocity zone near Pinta may reflect plume material that is being drawn into the GSC plumbing system and passing beneath (and therefore supplying) Pinta with enriched material. Consequently, Pinta has an anomalously enriched composition for its location in the eastern archipelago, resulting from shallow plume-ridge effects, not the actual location of the chemical boundary. Effectively, the spreading center blurs, but does not obscure, the geochemical boundary between the plume's compositional zones (e.g., Figure 3.6).

3.4.3. Orientation of the chemical boundary

At Hawai'i and the other, previously identified Pacific mantle plumes with bilateral compositional asymmetry [*Weis et al.*, 2011; *Huang et al.*, 2011; *Chauvel et al.*, 2012; *Payne et al.*, 2013], the strike of the boundary separating the more enriched from the more depleted zones runs parallel to plate motion direction; this is also the case for the Easter Island system (Figure 3.1). As a result, chemical zonation in the plume should be preserved downstream if the plume is sheared by plate motion or if it otherwise spreads beneath the plate (Figure 3.7). In contrast, the boundary delineating the more enriched zone from the more depleted material in the Galápagos runs NW-SE, oblique to the nearly eastward motion of the Nazca Plate [e.g., *Argus et al.*, 2011]. Because Galápagos volcanoes are active for upwards of 2 million years [e.g., *White et al.*, 1993], well past the time when they are located over the presumed hotspot center near Fernandina Island

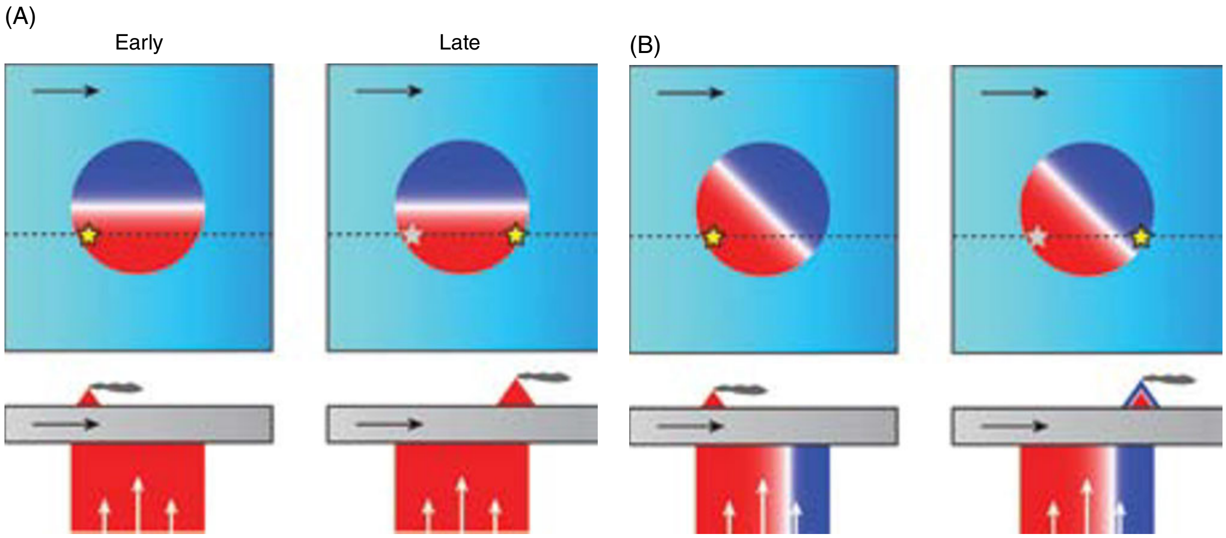

Figure 3.7 Schematic diagram illustrating the effect of the chemical boundary geometry on erupted compositions as a volcano is carried downstream by the plate. (A) Configuration in which the chemical boundary is parallel to plate motion, as in the Easter Island system. Volcanoes originally produced in a chemical zone remain supplied by that zone even if they continue to erupt for extended periods. (B) Configuration in which the chemical boundary is oblique to plate motion, as in the Galápagos Islands system. Volcanoes originally produced in one chemical zone (red, enriched) cross the boundary into the other (blue, depleted). If they are active during transport for extended periods (e.g., 2–3 million years in the case of the Galápagos), more recently erupted material will reflect supply by the depleted zone of the plume, a shift from more enriched signatures early in the volcano's history (e.g., Santa Cruz Island; see text).

[e.g., *Kurz and Geist*, 1999], they will be carried across the chemical boundary (Figure 3.1) from the enriched zone into the more depleted one. Younger material will be supplied by the plume's depleted zone, and will be deposited over the older, more enriched lavas, potentially obscuring the enriched signature from the earlier phases of the volcano's construction (Figure 3.7).

Santa Cruz Island is one of the older Galápagos volcanoes, located in the east-central part of the archipelago (Figure 3.1). Initial work by *Bow* [1979] and subsequently by *White et al.* [1993] and *Wilson* [2013] determined that the oldest material exposed at Santa Cruz (the Platform Stage; $^{87}Sr/^{86}Sr$: 0.70281–0.70312), erupted >1 Ma, has a more enriched isotopic signature than lava erupted during the more recent Shield Stage, which dates from 20–30 ka (e.g., $^{87}Sr/^{86}Sr$: 0.70261–0.70274). *White et al.* [1993], as well as *Harpp and White* [2001], proposed that such eastward depletion of signatures in the Galápagos reflects progressive entrainment of depleted upper mantle into a plume bent toward the east. An alternate interpretation of the data may be that the extended eruptive activity of Santa Cruz caused the volcano to be carried from the enriched to the depleted zones of a bilaterally asymmetric plume, which would result in the same trend toward more depleted signatures in younger lavas. *Geist et al.* [1986] observed a similar pattern at San Cristobal Island, with enriched older lavas and depleted younger ones.

3.4.4. Geochemical heterogeneity of the Pacific LLSVP

The mirror-image relationship of geochemical variations at Easter and the Galápagos, coupled with their location at the opposite margins of the Pacific LLSVP, suggest that the enriched zones of the two plumes are being supplied by what may be the same mantle reservoir. Several studies invoke the proposal originally made by *Castillo* [1988] that the geochemically defined DUPAL anomaly [*Dupré and Allegre*, 1983; *Hart*, 1984] corresponds with the geophysically defined LLSVP [e.g., *Dziewonski*, 1984; *Lekic at al.*, 2012]. The DUPAL anomaly is characterized primarily by elevated $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ for a given $^{206}Pb/^{204}Pb$ (expressed as $^{207}Pb^{*}/^{206}Pb^{*}$ and $^{208}Pb^{*}/^{206}Pb^{*}$; see Figure 3.2), as well as higher $^{87}Sr/^{86}Sr$ values [e.g., *Dupré and Allegre*, 1983; *Hart*, 1984]. In their comparison of Hawaiian, Marquesan, and Samoan geochemical variations, *Huang et al.* [2011] point out that the southern chains in all three systems exhibit geochemical variations consistent with the DUPAL signature, which supports the contention that the LLSVP may correspond with the DUPAL mantle reservoir, providing further evidence that the LLSVP may be a lower mantle repository for recycled material [e.g., *Castillo*, 1988]. Consistently, *Harpp et al.* [Chapter 6, this volume] provide isotopic and trace element evidence that lavas erupted in the southern Galápagos Archipelago are strongly influenced by recycled material—most likely ancient, altered ocean crust.

With the growing number of bilaterally asymmetric hotspots, however, comes the inevitable increase in the complexity of the geochemical story. In their detailed study of Marquesas isotopic variations, *Chauvel et al.* [2012] observe that the distinction between the geochemical trends is expressed primarily in terms of $^{87}Sr/^{86}Sr$ and ε_{Nd}, but is less apparent in Pb isotopic variations. In the Galápagos and Easter, the highest $^{207}Pb^*/^{206}Pb^*$ and $^{208}Pb^*/^{206}Pb^*$ signatures and the most extreme $^{87}Sr/^{86}Sr$ values are not associated with each other, but with opposing geochemical zones (Figure 3.2). At a more regional scale, *Farnetani et al.* [2012] point out that $^{208}Pb^*/^{206}Pb^*$ increases from Hawai'i southward to Samoa. Their modeling results demonstrate that such large-scale latitudinal variations in isotopic signatures do not obscure bilateral asymmetry in the Hawaiian plume, but only add azimuthal and radial variations within the compositional hemispheres. Thus, whereas it may not be possible to characterize the geochemical properties of the LLSVP precisely at this time, it may be fair to conclude conservatively that the Pacific LLSVP is geochemically heterogeneous on the scale of the Pacific, and that its chemical composition is influenced by a variety of different recycled materials [e.g., *Blichert-Toft et al.*, 1999; *Castillo*, 1988; *Harpp et al.*, Chapter 6, this volume; *Hart*, 1984; *Jackson et al.*, 2007; *Tanaka et al.*, 2008; *Weis et al.*, 2011; *Workman et al.*, 2004].

3.5. CONCLUSIONS

Bilateral compositional zoning of the Galápagos and Easter mantle plume systems provide important insight into the behavior of mantle plumes and the geochemical structure of the lower mantle. Specifically, we conclude the following:

1. On the basis of the distribution of their geochemical signatures, the Galápagos [e.g., *White et al.*, 1993; *Harpp and White*, 2001; *Hoernle et al.*, 2000] and Easter Island systems [*Kingsley et al.*, 2007] should be added to the growing list of other recently identified, bilaterally asymmetric plumes in the Pacific, including Hawai'i [*Abouchami et al.*, 2005; *Huang et al.*, 2011; *Weis et al.*, 2011], the Marquesas [*Chauvel et al.*, 2012], Samoa [*Huang et al.*, 2011; *Jackson et al.*, 2010; *Wright and White*, 1987], the Society Islands [*Payne et al.,* 2013], and Tristan-Gough [*Rohde et al.*, 2013]. The Galápagos and Easter plumes underlie the Nazca Plate, strengthening the hypothesis for the location of mantle plumes relative to global LLSVPs. The mirror-image relationship between geochemical asymmetry in the Galápagos (south-side enrichment, located on the northern margin of the Pacific LLSVP) and Easter mantle plumes (north-side enrichment, located on the southern margin of the Pacific LLSVP) [*Ritsema et al.*, 2011] further supports proposals by previous researchers that mantle plumes rising from the margins of the LLSVP [e.g., *Burke et al.*, 2008; *Steinberger and Torsvik*, 2012] preserve compositional heterogeneity that originates in the deep mantle [e.g., *Farnetani and Hofmann*, 2009, 2010; *Farnetani and Samuel*, 2005].

2. Despite their near-ridge locations and straightforward evidence of plume-ridge interaction, the azimuthal geochemical asymmetry of the Galápagos and Easter Island systems is preserved. This suggests that the compositional variation inherent in asymmetric mantle plumes is a property originating in the lower mantle.

3. The geometric orientation of the boundary between compositionally distinct zones in mantle plumes has a profound influence on the geochemical characteristics of lavas erupted downstream of the active end of a hotspot system. When the boundary is parallel to plate motion, geochemical variations are preserved downstream in sub-parallel volcanic chains (e.g., Easter, Hawai'i); when the boundary is oblique to the direction of plate motion, as in the Galápagos, an active volcano may cross the boundary and display compositional differences as it taps material from the adjacent geochemical zone.

4. On the basis of significant differences in isotopic compositions across the Pacific region's mantle plumes, it is clear that the LLSVP is geochemically heterogeneous, but it is dominated by contributions from a variety of recycled materials. There is some evidence that the geochemically defined DUPAL anomaly coincides with the seismically defined LLSVP located at the base of the Pacific mantle, supporting the hypothesis that DUPAL enrichment may be a feature tied to the deepest mantle. Ultimately, coupled seismic and geochemical studies may permit detailed mapping of the compositional structure of the lower mantle beyond the Pacific basin and definition of the extent of the geochemically enriched DUPAL reservoir.

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3.7. AUTHOR CONTRIBUTIONS

All three authors contributed equally to this work.

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