

# Evidence from accreted seamounts for a depleted component in the early Galapagos plume

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## ABSTRACT

The existence of an intrinsic depleted component in mantle plumes has previously been proposed for several hotspots in the Pacific, Atlantic, and Indian Oceans. However, formation of these depleted basalts is often associated with unusual tectonomagmatic processes such as plume-ridge interaction or multistage melting at plume initiation, where depleted basalts could reflect entrainment and melting of depleted upper mantle. Late Cretaceous to middle Eocene seamounts that accreted in Costa Rica and are part of the early Galapagos hotspot track provide new insights into the occurrence and nature of intrinsic depleted components. The Paleocene (ca. 62 Ma) seamounts include unusually depleted basalts that erupted on the Farallon plate far from a mid-ocean ridge. These basalts closely resemble Gorgona komatiites in terms of trace element and radiogenic isotope composition, suggesting formation from a similar, refractory mantle source. We suggest that this source may be common to plumes, but is only rarely sampled due to excessive extents of melting required to extract melts from the most refractory parts of a heterogeneous mantle plume.

## INTRODUCTION

It is generally assumed that ocean-island basalts (OIBs) are derived from mantle plumes and that these melts commonly have more enriched compositions than mid-oceanic ridge basalts (MORBs). The most widely accepted explanation for the enriched composition of hotspot lavas is that plumes carry recycled material such as altered oceanic crust and recycled sediment, which can be stored for tens of millions to billions of years in the mantle before returning to the surface, where the recycled material melts preferentially relative to depleted upper mantle to form OIBs (Hofmann and White, 1982). If the altered upper crust and sediment of the oceanic lithosphere are recycled into the mantle, then it is likely that the lower, unaltered depleted crust and lithospheric mantle are

also recycled, thus forming an intrinsic depleted component in mantle plumes (Kerr et al., 1995).

Basalts with depleted incompatible element and isotopic compositions have been found at numerous hotspots, e.g., Iceland (Fitton et al., 1997; Thirlwall et al., 2004), Galapagos (White et al., 1993), and Hawaii (Keller et al., 2000). The depleted basalts are most common when the plume is located near a mid-ocean ridge. The origin of the depleted component, however, remains controversial in most cases due to the similarity in composition between melts from entrained depleted upper mantle and from a depleted component intrinsic in the plume. Both will melt due to shallow upwelling and high-degree melting of the plume beneath a ridge potentially coupled with previous extraction of enriched melts at depth. It has been proposed

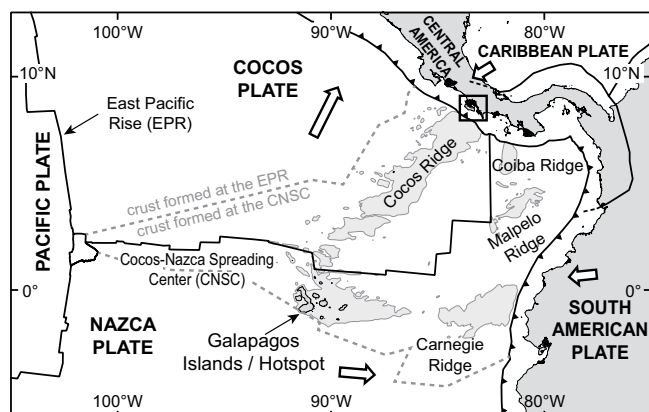
that ca. 90 Ma depleted komatiites from Gorgona Island (Kerr et al., 1995) and ca. 80 Ma depleted basalts from Ocean Drilling Program (ODP) Site 1001 in the Caribbean large igneous province (CLIP) (Kerr et al., 2009) provide additional evidence for the existence of an intrinsic depleted component in the Galapagos hotspot. However, Site 1001 basalts formed on the top of the CLIP by second-stage melting of a mantle plume source that had already been melted to form the base of the CLIP (Kerr et al., 2009), thus making a direct link with plume magmatism questionable. Gorgona komatiites are arguably the best evidence for the existence of an intrinsic depleted plume component; however, these rocks are very unusual, without known equivalents in the Mesozoic, and their exact provenance and link to the nearby Galapagos hotspot is unclear (Kerr and Tarney, 2005).

Due to ambiguities concerning the origins of depleted basalts formed in oceanic plateaus or at hotspots where a plume interacts with a mid-ocean ridge, it remains essential to provide additional constraints on the possible existence of an intrinsic depleted component in mantle plumes. Novel support for the existence of this component is provided here by new geochemical data from Late Cretaceous to middle Eocene accreted seamounts in the Osa Igneous Complex (Costa Rica), which formed at the early Galapagos hotspot far from a mid-ocean ridge.

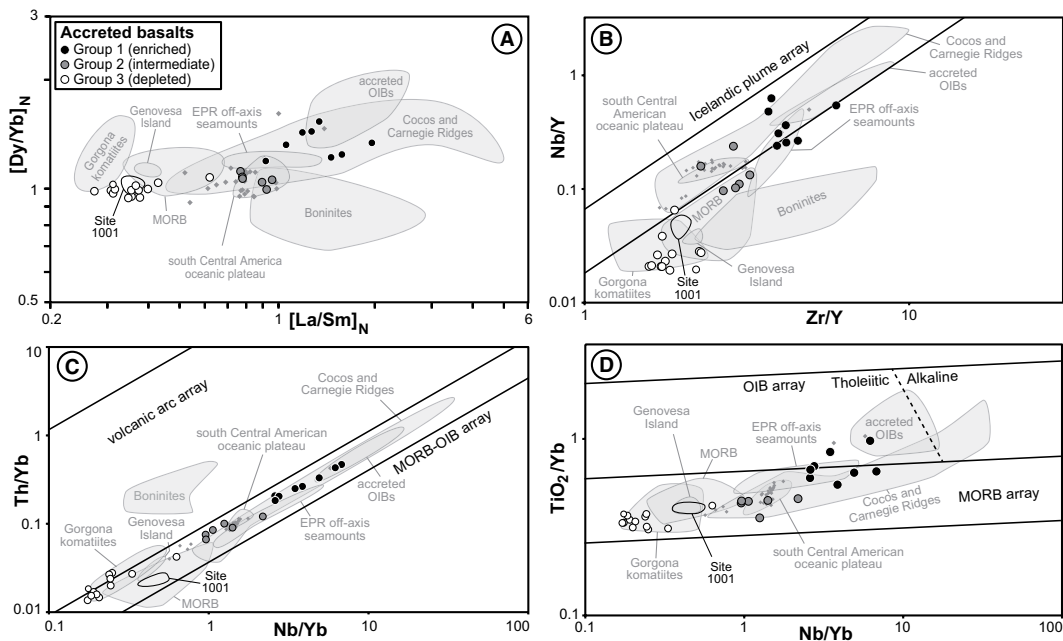
## GEOLOGICAL BACKGROUND AND METHODS

The Osa Igneous Complex (OIC) is exposed on the Osa and Burica Peninsulas at the southwestern edge of the CLIP (Fig. 1; Fig. DR1 in the GSA Data Repository<sup>1</sup>). The complex includes an assemblage of Cretaceous to Eocene oceanic sequences predominantly composed of

<sup>1</sup>GSA Data Repository item 2016125, data tables, Figures DR1–DR3 (geological map and geochemical figures), and additional comments on tectonostratigraphy, analytical methods, data selection, and isotope data, is available online at [www.geosociety.org/pubs/ft2016.htm](http://www.geosociety.org/pubs/ft2016.htm), or on request from [editing@geosociety.org](mailto:editing@geosociety.org) or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.



**Figure 1. Tectonic map of the central-eastern Pacific Ocean. Black areas in Central America represent accreted oceanic sequences; square outlines the location of Figure DR1 (see footnote 1).**



**Figure 2.** Selected geochemical characteristics of igneous rocks from the outer Osa Igneous Complex (small diamonds are samples from the inner Osa Igneous Complex). Data sets used for comparison include whole-rock and glass analyses from representative settings. EPR—East Pacific Rise; MORB—mid-oceanic ridge basalt; accreted OIBs—accreted ocean-island basalts in Central America (for references, see the Data Repository [see footnote 1]; all selected samples have MgO > 5.5 wt%). Site 1001 is from the Ocean Drilling Program. A:  $(Zr/Y)_N$  versus  $(Nb/Y)_N$  diagram (N—primitive mantle normalized). B: Zr/Y versus Nb/Y diagram (after Fitton et al., 1997). C: Nb/Yb versus Th/Yb diagram (after Pearce, 2008). D: Nb/Yb versus  $TiO_2/Yb$  diagram (after Pearce, 2008).

pillow and massive basalt flows with subordinate gabbro (locally pegmatitic) and thin (<10 m thick) interbeds of pelagic and volcanoclastic sedimentary rocks (e.g., Di Marco et al., 1995; Hauff et al., 2000; Hoernle et al., 2002; Buchs et al., 2009). The complex has been subdivided into an inner OIC interpreted as a Late Cretaceous (ca. 85 Ma) oceanic plateau and an outer OIC including several accreted seamounts ranging in age between the Late Cretaceous (ca. 85 Ma) and middle Eocene (ca. 41 Ma) (Buchs et al., 2009). Tectonostratigraphic constraints define pre-late Eocene accretion ages for the outer OIC (see the Data Repository). Here we report new geochemical data that confirm an oceanic plateau origin for the inner OIC; our main focus is on the poorly constrained origin of the outer OIC.

In order to determine the composition of the OIC, 54 whole-rock samples of basalt and noncumulative gabbro were selected for X-ray fluorescence and laser ablation–inductively coupled plasma–mass spectrometry analyses at the University of Lausanne (Switzerland). Nd–Pb isotope data on a subset of 7 samples from the outer OIC were analyzed at the GEOMAR Helmholtz Center (Kiel, Germany). Results, full analytical methods, and detailed evaluation of whether initial or measured radiogenic isotopes provide the least biased source information are provided in the Data Repository, in and Tables DR1–DR4 therein.

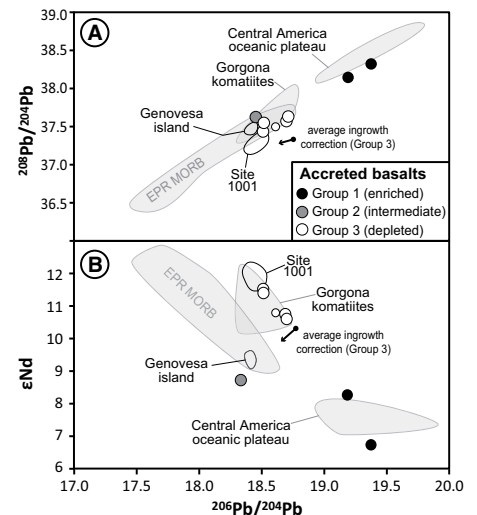
## RESULTS

Analyzed basalts and gabbros have only been exposed to low-grade metamorphism. Low to moderate hydrothermal alteration, however, is frequent with local replacement of glass, olivine, and feldspar by secondary phases. Alteration is

additionally indicated by loss on ignition values of 0.55–5.45 wt% (Table DR2). As a consequence, the origin of the outer OIC is determined based on a combination of immobile trace element discrimination diagrams (Fitton et al., 1997; Pearce, 2008), radiogenic isotope ratios that are relatively insensitive to alteration, geochemical comparison with a selection of possible volcanic analogues, field observations, and existing regional constraints. New geochemical data from the inner OIC confirm an oceanic plateau origin; they have a composition indistinguishable from contemporaneous Late Cretaceous oceanic plateau sequences observed elsewhere in south Central America (Hauff et al., 2000; Hoernle et al., 2002; Buchs et al., 2010). These data are reported here only for comparison with the outer OIC (Fig. 2; Figs. DR2 and DR3).

In contrast to oceanic plateau sequences of the inner OIC, accreted igneous rocks of the outer OIC display large compositional heterogeneity, with three geochemical groups defined by distinct immobile trace element contents (Fig. DR3). Group 1 has an enriched (OIB like) signature with  $(La/Sm)_N = 0.91–1.94$  (N is primitive mantle normalized),  $(Dy/Yb)_N = 1.19–1.53$ , and transitional tholeiitic to alkaline affinities (Fig. 2; Figs. DR2 and DR3). Two samples have  $\epsilon_{Nd} = 6.7–8.3$  and  $^{206}Pb/^{204}Pb = 19.2–19.4$  (Fig. 3). Basalts of this group occur predominantly close to boundaries of the outer OIC and are locally in contact with the Osa Mélange and inner OIC (Fig. DR1). Pelagic limestones interbedded with pillow lavas and peperites of group 1 define Campanian to middle Eocene ages of formation (Buchs et al., 2009). The absence of suprasubduction geochemical characteristics (e.g., low Nb and Th/Yb for a given Nb/Yb ratio; Fig. 2) and the occurrence of interbedded

pelagic sedimentary rocks in igneous sequences of this group unambiguously support formation in a mid-ocean ridge or intraplate setting. The trace element composition of group 1 closely resembles that of seamount chains formed at the Galapagos hotspot since the Miocene (Fig. 2). Isotope compositions are clearly enriched compared to those of East Pacific Rise (EPR) MORBs (Fig. 3). This suggests that group 1 could represent late-stage volcanic sequences



**Figure 3.** Thorogenic and  $^{206}Pb/^{204}Pb$  versus  $\epsilon_{Nd}$  isotope correlations of Osa basalts. Average 62 m.y. radiogenic ingrowth vector for group 3 basalts is minor compared to overall variability of the data and reference fields. EPR—East Pacific Rise; MORB—mid-oceanic ridge basalt. For data sources of reference fields and a discussion on the effects of age correction, see the Data Repository (see footnote 1).

of seamounts, which accreted before and after emplacement of the bulk of the outer OIC.

Most of the outer OIC includes an assemblage of group 2 and 3 igneous rocks interpreted from field relationships as accreted seamounts with moderately to very depleted compositions. A seamount origin is also in good agreement with geochemical constraints (see following) and the paucity of sedimentary rocks found in association with group 2 and group 3 sequences. This latter point is a common characteristic of accreted seamounts that clearly contrasts with accreted MORB sequences that are generally associated with thick pelagic-hemipelagic sedimentary deposits (e.g., Kusky et al., 2013).

Group 2 igneous rocks have tholeiitic affinities with intermediate incompatible element compositions, characterized by nearly flat multielement patterns, except for slightly lower Nb and Th primitive mantle-normalized contents with  $(La/Sm)_N = 0.76-0.98$ ,  $(Dy/Yb)_N = 0.97-1.12$ , and  $(Th/Yb)_N = 0.37-0.67$  (Fig. 2; Figs. DR2 and DR3). The trace element composition of these rocks overlaps with that of enriched MORB, oceanic plateau sequences of the inner OIC, and the Cocos and Carnegie Ridges (Fig. 2). A sample from group 2 has depleted  $\epsilon_{Nd}$  (8.9) and  $^{206}Pb/^{204}Pb$  (18.5) and plots close to the compositional field of EPR MORB and Genovesa Island, Galapagos Archipelago (Fig. 3). Although a MORB origin cannot be totally excluded based on geochemical data alone, a seamount origin is in better agreement with lithostratigraphic observations. Radiolarite interbedded with the lavas constrain the age of formation of group 2 to the Coniacian-Santonian (ca. 85 Ma; Buchs et al., 2009).

Group 3 igneous rocks have tholeiitic affinities (Fig. 2D; Fig. DR2) with an extreme depletion in the most incompatible trace elements [ $(La/Sm)_N = 0.27-0.61$ ;  $(Dy/Yb)_N = 0.95-1.08$ ;  $(Th/Yb)_N = 0.09-0.23$ ] (Fig. 2A). Incompatible trace element contents of this group resemble those of depleted komatiites from Gorgona Island. Isotope data for five samples (including sample OS6 from Hauff et al. 2000) have depleted  $\epsilon_{Nd}$  (10.6–11.4) and  $^{206}Pb/^{204}Pb$  (18.5–18.7) distinct from EPR MORB but similar to Gorgona komatiites (Fig. 3), indicating the existence of unusually depleted oceanic basalts in the outer OIC (group 3). The age of formation of group 3 is Paleocene, based on a  $62.1 \pm 0.8$  Ma age determined by  $^{40}Ar/^{39}Ar$  dating (Hauff et al., 2000).

## DISCUSSION

### Support for a Galapagos Provenance

A paleo-Galapagos hotspot origin for the Cretaceous to Paleocene seamounts accreted in the OIC is in good agreement with regional tectonic, age, and lithostratigraphic constraints. The compositional range of the three groups resembles that of the Galapagos hotspot tracks

(Werner et al., 2003; Harpp et al., 2005; Fig. 2). Unlike MORB and small off-axis seamounts that only form minor topographic anomalies, larger volcanic structures in a hotspot track are more likely to be accreted. In addition, the Galapagos hotspot has been the sole source of intraplate volcanism in the central-eastern Pacific since the Late Cretaceous (e.g., Pindell and Kennan, 2009). Numerous studies along the Central American forearc support continuous formation of oceanic islands and large seamounts in the central-eastern Pacific since the Late Cretaceous and their subsequent accretion to the Central American margin (Hauff et al., 2000; Hoernle et al., 2002; Buchs et al., 2011; Trela et al., 2015). The preceding observations provide strong support for the formation of the outer OIC from the older Galapagos hotspot track (ca. 85–41 Ma) (Fig. 4). The outer OIC therefore serves as an important archive of the nature and dynamics of the early Galapagos plume, shortly after final emplacement ca. 90 Ma of the CLIP above the starting plume head of the Galapagos hotspot.

### Depleted Component in the Early Galapagos Plume

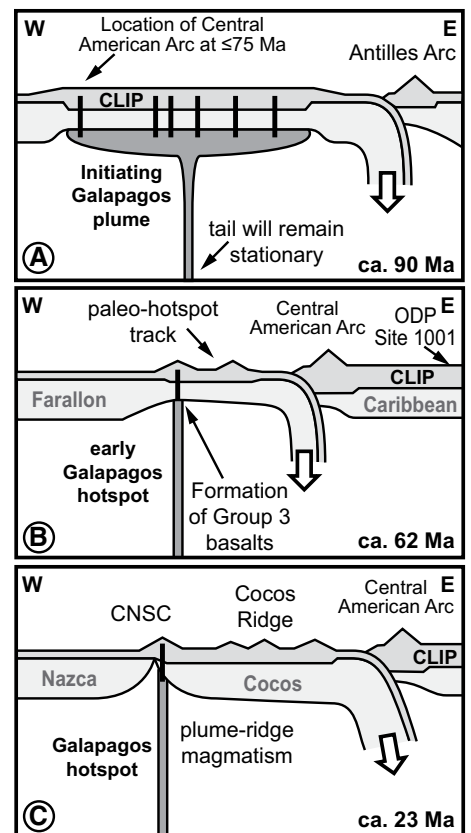
Paleocene (group 3) basalts accreted in the outer OIC exhibit one of the most depleted incompatible element compositions and Nd isotopic compositions found to date in oceanic basalts, in particular in those from hotspot tracks, suggesting unusual melting conditions and/or petrogenetic processes in the early Galapagos plume. Two main petrogenetic models, exemplified by intraplate oceanic igneous rocks from the Caribbean and central-eastern Pacific (Fig. 2), could account for formation of depleted basalts at hotspots: (1) plume-ridge interaction associated with entrainment of MORB asthenosphere in a hot mantle plume (White et al., 1993; Harpp et al., 2002) or melting of an intrinsic plume component (Hoernle et al., 2000), e.g., Genovesa Island and Genovesa ridge in the Galapagos Archipelago; and (2) high-temperature or hydrous melting of a depleted, intrinsic mantle plume component during the earliest stages of plume volcanism, e.g., Gorgona komatiites (Kerr et al., 1995; Kamenetsky et al., 2010).

An origin through plume-ridge interaction involving melting of the upper mantle due to increased heat from the plume and very shallow upwelling is not likely because break-up of the Farallon plate to form the Cocos-Nazca spreading center did not occur until 23 Ma (Barckhausen et al., 2008), i.e., nearly 40 m.y. after formation of the accreted seamounts (Fig. 4). There is no evidence for the presence of a spreading center in the vicinity of the Galapagos hotspot before 23 Ma (Pindell and Kennan, 2009). In addition, incompatible element ratios for group 3 basalts largely are outside of the MORB field (Fig. 2) and radiogenic isotope compositions do not overlap with modern and

Mesozoic MORB compositions, which have notably less radiogenic Nd at a given  $^{206}Pb/^{204}Pb$  (Fig. 3B), thus ruling out significant involvement of a depleted upper mantle source in the formation of group 3 basalts. Instead, the incompatible element and isotopic composition of these basalts is very similar to that of Gorgona komatiites. We conclude therefore that melting of an intrinsic depleted plume component is required to account for the formation of depleted Paleocene seamounts found in Costa Rica. This is a significant result that not only reveals the existence of an intrinsic depleted component in the early Galapagos plume, but also shows that this component contributed to formation of the earliest Galapagos hotspot tracks.

### Implications for Plume Magmatism

The existence of an intrinsic depleted component in mantle plumes was previously proposed based on depleted basalts in oceanic islands and/or seamounts of the Iceland, Galapagos, and Hawaii hotspots (e.g., Kerr et al., 1995; Hoernle et al., 2000; Keller et al., 2000) and depleted komatiites in oceanic plateau sequences of Gorgona Island (Kerr et al., 1995). In all these



**Figure 4.** The evolution of the Galapagos plume. **A:** Initiation. **B:** Migration of the Caribbean large igneous province (CLIP) away from the early Galapagos hotspot. ODP—Ocean Drilling Program **C:** Present-day situation, following break-up of the Farallon plate into the Cocos and Nazca plates 23 Ma. CNSC—Cocos and Nazca spreading center.

settings, a depleted component has been associated with particular melting conditions due to plume–ridge interaction (Iceland, Galapagos, Hawaii), formation of an oceanic plateau above a starting plume head (Gorgona Island), or remelting of plume material after previous melt extraction (ODP Site 1001 in the Caribbean). Because they did not form over a plume head or through plume–ridge interaction, group 3 basalts from the outer OIC represent a new occurrence of plume-related depleted basalts that formed ~30 m.y. after the peak of plume head volcanism that formed the Caribbean large igneous province at ca. 90 Ma (Fig. 4).

As shown by Herzberg and Gazel (2009), early Galapagos lavas with ages of ca. 65 Ma were formed at potential temperatures of  $\geq 1500$  °C, whereas lavas younger than 15 Ma belonging to the Galapagos Archipelago and hotspot tracks formed at lower potential temperatures (1400–1500 °C). Although melting of pyroxenite could occur at lower melting temperatures (Trela et al., 2015), we speculate that hotter conditions in the early hotspot setting promoted melting of the most refractory component of a heterogeneous Galapagos plume to form group 3 basalts. If this is correct, this component could be ubiquitous in mantle plumes, but is only rarely sampled in significant proportions in ocean basalts due to particular petrogenetic conditions required to melt refractory sources. The exact nature and compositional variability of this component remains to be more fully investigated through a systematic comparison of depleted basalts at hotspots and mid-ocean ridges globally. However, due to relatively limited occurrence of depleted basalts at modern hotspots, the study of ancient OIBs will remain essential in helping characterize this component.

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