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-ocean 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 melts preferentially relative to depletions of upper mantle to form OIBs (Hofmann and White, 1982). If the altered upper crust and sediments 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 (Fiton 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 depletions component intrinsic in the plume. Both will melt down 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 geochronological 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\textsuperscript{1}). The complex includes an assemblage of Cretaceous to Eocene oceanic sequences predominantly composed of...
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., 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 basalts 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.

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)i versus (Nb/Y)i diagram (N—primitive mantle normalized). B: Zr/Y versus Nb/Y diagram (after Fitton et al., 1997). C: Nb/Y versus Th/Yb diagram (after Pearce, 2008). D: Nb/Y versus TiO2/Yb diagram (after Pearce, 2008).

Figure 3. Thorogenic and 206Pb/204Pb versus eNd isotope correlations of Osa basalts. Average 62 m.y. radiogenic ingrowth vector for group 3 basalt 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).

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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 depleting 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 depleting (La/Sm)$_n$ = 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 incompatible element compositions and Nd isotopic compositions found to date in oceanic basalts, in particular in those from hotspot plume volcanism, e.g., Gorgona komatiites (Kerr et al., 1995). In all these cases, the depleted Nd and incompatible element compositions and Nd isotopic compositions are distinct from modern oceanic basalts at hotspots: (1) plume-ridge interaction 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 plume (Hoernle et al., 2000), e.g., Genovesa Island and Genovesa ridge in the Galapagos plume (Huene et al., 2000), and depleted 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 depleting component in the early Galapagos plume, but also shows that this component contributed to formation of the earliest Galapagos hotspot tracks.

**Depleted Component in the Early Galapagos Plume**

Paleocene (group 3) basalts accreted in the outer OIC exhibit one of the most depleting 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 interplate oceanic igneous rocks from the Caribbean and central-eastern Pacific (Fig. 2), could account for formation of depleting 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 plume, 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 (Pinell 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 depleting 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 depleting 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 depleting 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...
settings, a depleted component has been associated with particular melting conditions due to plume-rift 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-rift 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 21500 °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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