Pyroxenite-rich mantle formed by recycled oceanic lithosphere: Oxygen-osmium isotope evidence from Canary Island lavas

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ABSTRACT

Plate tectonic processes result in recycling of crust and lithosphere into Earth's mantle. Evidence for long-term preservation of recycled reservoirs in the mantle comes from the enriched isotopic character of oceanic island basalt (OIB) lavas. Although recycled constituents can explain much of the geochemical variation in the OIB-source mantle, it has been shown that direct melting of these components would lead to magmas with evolved compositions, unlike OIB. Instead, it has been argued that either metasomatic pyroxene-rich peridotite that has inherited the trace element and isotopic character of subducted materials, or high-temperature intramantle metasomatism of lithosphere can explain OIB compositions. To test these models, we present new oxygen and osmium isotope data for lavas from the Canary Islands of El Hierro and La Palma. These islands have distinct $^{18}O/^{16}O$ and $^{187}Os/^{188}Os$ compositions that can be explained through melting of pyroxenite-enriched peridotite mantle containing <10% recycled oceanic lithosphere. We also assess O-Os isotope systematics of lavas from Hawai'i and the Azores and show that they also conform to addition of distinct recycled oceanic components, including lithosphere and pelagic sediment. We conclude that enriched isotopic signatures of some OIBs are consistent with pyroxenite-rich mantle sources metasomatized by recycled components.

INTRODUCTION

Oceanic island basalt (OIB) geochemistry (Hofmann, 1997) and seismic tomography (van der Hilst et al., 1997) provide powerful evidence that the convecting mantle is thermally and chemically heterogeneous at a range of scales. However, the cause of this heterogeneity is poorly understood, especially at the mantle length scales sampled by OIB. It has been proposed that recycling of oceanic lithosphere (including associated crust) at subduction zones is likely to be a significant cause of heterogeneity, reenriching the mantle with volatiles and incompatible elements that are otherwise depleted through partial melting processes (Hofmann, 1997). Direct melting of oceanic lithosphere, however, is improbable (Niu and O'Hara, 2003), given the magnesian-rich and incompatible element–rich character of HIMU (high $\mu = {}^{238}U/{}^{204}Pb$) OIBs that are thought to contain significant contributions from this source (Hofmann and White, 1982; Hofmann, 1997).

Experimental petrology (Yaxley and Green, 1998; Spandler et al., 2008) and mineral chemistry (Sobolev et al., 2005, 2007) have recently been used to argue that pyroxenite or eclogite (clinopyroxene and garnet) are important constituents in OIB-source mantle. Pyroxenite and eclogite might be generated by hybridizing mantle peridotite with recycled components (Sobolev et al., 2005, 2007), or via high-temperature intramantle metasomatism, similar to that invoked for oceanic lithosphere (Pilet et al., 2008). These two sets of processes are difficult to distinguish from one another using radiogenic isotope signatures alone, since both would result in similar parent-daughter fractionations (DePaolo and Wasserburg, 1976). Thus, in order to determine if OIB sources (1) contain material recycled from the Earth's surface, or (2) record high-temperature intramantle fractionation, it is critical to combine information from radiogenic isotopes with light stable isotopes (e.g., O) that are fractionated in response to low temperature processes within the crust and hydrosphere (Eiler, 2001).

O-OS ISOTOPE SYSTEMATICS OF CANARY ISLAND LAVAS

Canary Island lavas provide a test for the origin of OIB-source HIMU mantle geochemical heterogeneity due to their HIMU-like Sr-Nd-Pb isotope compositions (e.g., Marcantonio et al., 1995) and olivine populations that have high Ni contents and Mn/Fe ratios, implying that as much as 25%–75% of all melting (Gurenko et al., 2009) is from pyroxenite mantle source components (10%–20%; Sobolev et al., 2007). To assess whether any pyroxenite signature is reflected in isotopic data and if it has an intramantle or recycled origin, we performed oxygen and osmium isotope analyses on lavas spanning the entire exposed volcanic histories of the islands of La Palma and El Hierro, Canary Islands (Table 1). Samples range from olivine-phyric alkali basalts and picrite, to olivine- and pyroxene-rich ankaramites (GSA Data Repository Table DR1[1]), with Sr-Nd-Pb isotope and trace element compositions typical of western Canary Island lavas ($^{206}Pb/^{204}Pb$ = 19.1–20.1; e.g., Sun, 1980).

The $\delta^{18}O$ values of olivine phenocryst populations [where $\delta^{18}O = 1000 \times (^{18}O/^{16}O_{sample})/(^{18}O/^{16}O_{VSMOW}) - 1$; VSMOW is Vienna standard mean ocean water] from the two islands are strikingly different. La Palma lavas (4.85‰ ± 0.10‰) have, on average, ~0.3‰ lower $\delta^{18}O$ than El Hierro lavas (5.17‰ ± 0.08‰). This difference is considerably greater than analytical uncertainty. The $^{187}Os/^{188}Os$ values for La Palma lavas (0.145 ± 0.007) are less radiogenic, with a more restricted range of values, than El Hierro lavas ($^{187}Os/^{188}Os$ = 0.156 ± 0.017), which are some of the most radiogenic high-MgO OIBs measured. The new $^{187}Os/^{188}Os$ data are consistent with previously published $^{187}Os/^{188}Os$ measurements of La Palma lavas (Marcantonio et al., 1995), but significantly extend the known $^{187}Os/^{188}Os$ compositions of El Hierro lavas (Widom et al., 1999). Correlations with MgO indicate that Os is situated within early-formed minerals trapped within olivine, allowing direct comparison with olivine $\delta^{18}O$ values (Fig. DR1).

Although assimilation processes are important in the petrogenesis of many OIB suites (e.g., Gaffney et al., 2005), this cannot explain the isotopic differences between El Hierro and La Palma lavas. There is a lack of correlation between $^{187}Os/^{188}Os$ and indices of fractionation (e.g., MgO), and the Os-rich nature of many of the samples (>50 ppt) precludes significant crustal assimilation (Figs. 1A and 1B). Comparisons of olivine composition versus $\delta^{18}O_{olivine}$ have previously been used to demonstrate assimilation of low-$\delta^{18}O$ crust to Mauna Kea versus Mauna Loa lavas (Wang and Eiler, 2008). No such correlation is observed for El Hierro or La Palma lavas, either for olivine $\delta^{18}O$ values versus forsterite contents (Fig. 1C; Table DR1), or whole-rock MgO (Fig. DR2). Therefore, our results imply that only limited shallow-level (edifice) or deep-level (underlying oceanic lith-

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[1]GSA Data Repository item 2009128, supplementary methods, figures, and tables, is available online at www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

TABLE 1. $^{187}Os/^{188}Os$ AND $\delta^{18}O$ DATA FOR WESTERN CANARY ISLAND BASALTS

Sample number	Island	Unit*	Rock type	MgO (%)	$\delta^{18}O_{olivine}$ (‰)	Os (ppb)	Re (ppb)	$^{187}Os/^{188}Os$	(±2σ)
EH 01	El Hierro	PFE	Ankaramite	14.2	5.26	0.065	0.473	0.14579	0.00015
EH 03	El Hierro	Tinor	Basanite	12.8	5.12	0.133	0.287	0.16760	0.00048
EH 07	El Hierro	Tinor	Ankaramite	11.7	5.32 (0.03)	0.095	0.275	0.16686	0.00002
EH 08	El Hierro	Tinor	Basanite	9.3	5.21	0.026	0.248	0.16286	0.00012
EH 10	El Hierro	CFE	Ankaramite	14.2	5.04	0.184	0.188	0.14808	0.00005
EH 11	El Hierro	CFE	Alkali Basalt	11.5	5.22	0.055	0.337	0.15202	0.00007
EH 12	El Hierro	CFE	Alkali Basalt	13.5	5.23	0.141	0.105	0.17502	0.00006
EH 13	El Hierro	CFE	Ankaramite	14.2	5.15	0.058	0.251	0.16438	0.00006
EH 14	El Hierro	UEG	Alkali Basalt	8	5.13	0.024	0.462	0.15397	0.00001
EH 15	El Hierro	UEG	Ankaramite	17.6	5.08 (0.09)	0.158	0.121	0.15895	0.00004
EH 16	El Hierro	LEG	Basanite	11.7	5.08	0.089	0.226	0.15693	0.00005
EH 17	El Hierro	PFE	Alkali Basalt	13.3	5.13	0.041	0.505	0.13174	0.00051
EH 18	El Hierro	PFE	Ankaramite	10.9	5.26	0.099	0.482	0.15297	0.00006
LP 01	La Palma	Garafia	Ankaramite	13.4	4.88	0.143	0.188	0.14328	0.00001
LP 02	La Palma	Garafia	Ankaramite	9.4	4.73 (0.15)	0.060	0.478	0.14875	0.00007
LP 03	La Palma	Seamount	Picrite pillow lava	28.7	5.00	0.285	0.271	0.14406	0.00001
LP 04	La Palma	LTB	Ankaramite	7.9	4.74	0.032	0.455	0.14788	0.00017
LP 05	La Palma	LTB	Ankaramite	12.2	4.86	0.023	0.461	0.13783	0.00057
LP 07	La Palma	LTB	Ankaramite	9.8	4.72	0.053	0.377	0.14532	0.00002
LP 09	La Palma	Benejado	Amphibolite-Tephrite	13.5	4.93	0.157	0.067	0.14582	0.00006
LP 10	La Palma	UTB	Ankaramite	14.8	4.90	0.077	0.044	0.14584	0.00006
LP 11	La Palma	UTB	Basanite	8.9	4.71	0.052	0.253	0.14895	0.00005
LP 14	La Palma	CFE	Basanite	11.5	4.90	0.066	0.473	0.14162	0.00024
LP 15	La Palma	PFE (1949)	Basanite	10.5	4.92	0.053	0.197	0.14356	0.00006
LP 19	La Palma	PFE	Basanite	6.9	4.79	0.016	0.719	0.14858	0.00010
LP 24	La Palma	PFE (1677)	Basanite	8.6	4.96	0.054	0.602	0.13793	0.00009
LPF 96–66	La Palma	UTB	Ankaramite	15.5	4.83	0.209	0.231	0.14380	0.00031

Note: A detailed methods summary can be found in the GSA Data Repository item (see footnote 1) accompanying this paper. Osmium isotope measurements were performed at the University of Durham. $^{187}Os/^{188}Os$ reproducibility on two different standards was better than 2.1‰ (2σ); all Os isotope data are normalized to $^{192}Os/^{188}Os$ = 3.08271 and all data are blank corrected. Oxygen isotopes were measured at Royal Holloway, University of London, on 1.5–2 mg splits of fresh olivine. Yields for all unknown and standards were 98% ± 2%. Precision and accuracy were monitored by three internal standards (San Carlos Olivine 1 = +4.84‰ (±0.18, 2s, n = 22), San Carlos Olivine 2 = +5.22‰ (±0.16, 2s, n = 19), and University of Wisconsin GMG2 Garnet +5.71‰ (±0.18, 2s, n = 22).

*PFE—platform-forming eruptions (Holocene glacial period); CFE—cliff forming eruptions (interglacial periods); Tinor (0.88–1.12 Ma old); UEG—Upper El Golfo (~200 ka old); LEG—Lower El Golfo (~450 ka old); Garafia (1.21–1.78 Ma); Seamount (~2.9–4.0 Ma old), LTB—Lower Taburiente Basalts (0.83–1.12 Ma old); UTB—Upper Taburiente Basalts (0.4–0.77 Ma old), Benejado (0.49–0.58 Ma old). From Carracedo et al. (2002) and references therein. Figures in parentheses denote 2σ errors based on replicate analyses.

osphere) contamination has occurred to parental magmas. In combination with La Palma lava Sr-Nd-Pb isotope systematics (Marcantonio et al., 1995), which have been interpreted as mantle signatures, we conclude that El Hierro and La Palma lavas are derived from isotopically distinct mantle sources.

High-temperature intramantle metasomatism might cause sufficient parent-daughter fractionation to generate the range in $^{187}Os/^{188}Os$ measured in Canary Island lavas, given sufficient time. However, oceanic lithospheric plate beneath the Canaries is younger than 200 Ma (Carracedo et al., 2002), and so the older than 1 Ga HIMU Pb isotope signature of Canary Island lavas requires relatively ancient mantle sources (Thirlwall, 1997). Furthermore, oxygen isotope ratios of lithosphere generated by intramantle differentiation processes are not systematically different from anhydrous mantle (Mattey et al., 1994; Chazot et al., 1997), and so cannot be responsible for $\delta^{18}O$ differences between La Palma and El Hierro lavas. Indeed, contrasting $\delta^{18}O$-$^{187}Os/^{188}Os$ systematics between the two islands can be explained by contributions from different components of recycled oceanic lithosphere (Fig. 2). This conclusion is consistent with the distinctive young (≥1 Ga) HIMU geochemistry of lavas from La Palma and El Hierro, which has been attributed to the presence of recycled oceanic lithosphere in their source regions (Sun, 1980; Marcantonio et al., 1995; Thirlwall, 1997). In this scenario, La Palma might reflect the presence of hydrothermally altered layer 3 gabbros and peridotites that have low-$\delta^{18}O$ values (0‰–6‰; Eiler, 2001) and unradiogenic $^{187}Os/^{188}Os$ relative to layer 2 altered oceanic crust with elevated $^{187}Os/^{188}Os$ (Dale et al., 2007) and higher $\delta^{18}O$ values ($\delta^{18}O$ = 5‰–15‰; Eiler, 2001), which might feed El Hierro magmas. Another constraint on the mantle source of La Palma and El Hierro magmas is the MgO-rich character of erupted basalts that demonstrates that direct melting of recycled components, alone, is unlikely (Niu and O'Hara, 2003).

METASOMATIZED PYROXENITE-ENRICHED MANTLE

A possible model to explain O-Os isotope systematics of El Hierro and La Palma lavas is that a pyroxene-rich mantle source feeds their parental magmas and is a product of metasomatism of peridotite by siliceous melts derived from recycled oceanic lithosphere. Experimental results indicate that recycled lithosphere can be melted as eclogite at high pressures in the mantle (Spandler et al., 2008). In this model, downgoing basaltic and gabbroic portions of the oceanic lithosphere are transformed to silica-oversaturated eclogite at high pressures during subduction (P > 2.5 GPa; Kogiso et al., 2003; Kogiso and Hirschmann, 2006). The lower solidus temperature of eclogite will result in melting at higher pressures than peridotite (Yaxley and Green, 1998). At ~10%–15% partial melting, eclogite will be sufficiently permeable to allow melt extraction and infiltration into surrounding peridotite, generating a metasomatized orthopyroxene-rich peridotite (Yaxley and Green, 1998). Mafic lithologies, such as pyroxenite, melt preferentially versus peridotite at mantle pressures, such that they would provide melt fractions to OIB sources that would greatly exceed their absolute volume within the mantle (Sobolev et al., 2007). Furthermore, metasomatic reactions can generate a hybridized pyroxenite with nearly uniform chemical and isotopic composition to constitute a single

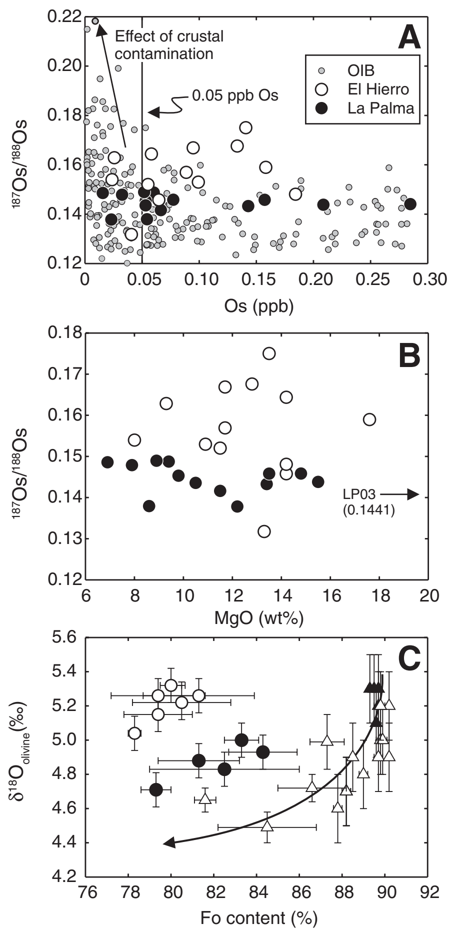

Figure 1. Plots of whole-rock ^{187}Os/^{188}Os versus Os content (A) and MgO content (B). C: Average olivine forsterite compositions (mol%; Table DR1; see footnote 1) versus δ^{18}O$_{olivine}$. Vector for crustal contamination is shown in A, along with 0.05 ppb Os cutoff based on a global ocean island basalt (OIB) data set in which low Os abundance lavas deviate from high Os abundance lavas in terms of their ^{187}Os/^{188}Os compositions. Data for Mauna Kea (unfilled triangles) and Mauna Loa lavas (filled triangles) are shown in C, along with curve interpreted to reflect contamination of Hawi'ian magmas by hydrothermally altered rocks (Wang and Eiler, 2008). Data for other OIBs in A are from Marcantonio et al. (1995), Lassiter and Hauri (1998), Schaefer et al. (2002) and references therein.

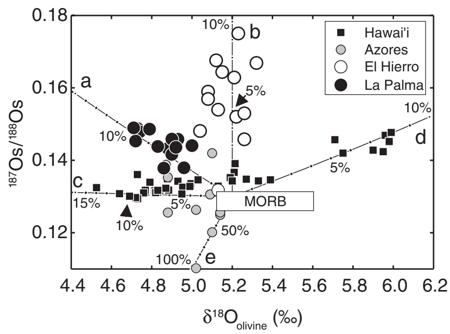

Figure 2. Oxygen-osmium isotope variations for western Canary Island, Azores, and Hawai'ian lavas. Modeling assumes two-component mixing between ambient upper mantle (represented by DMM [depleted MORB mantle] δ^{18}O ~5.2‰; ^{187}Os/^{188}Os 0.125–0.130; [Os] concentration = 3.3 ppb) and five recycled components. All models are shown in percent increments of mixing (%) between end members. Models a, b, c, and d assume 1 Ga or older materials. Model e assumes 2.5 Ga old recycled oceanic lithosphere (δ^{18}O ~5.0‰; ^{187}Os/^{188}Os 0.1100; [Os] 3.3 ppb). Model a is for refertilized pyroxenite-peridotite containing recycled oceanic layer 3 gabbroic crust (δ^{18}O ~0‰; ^{187}Os/^{188}Os 0.4; [Os] 2 ppb). Model b is for refertilized pyroxenite-peridotite containing recycled oceanic upper crustal basaltic crust (δ^{18}O ~5.2‰; ^{187}Os/^{188}Os 0.83; [Os] 2 ppb). Model c is for mixing between recycled oceanic altered lithospheric peridotite (δ^{18}O ~0‰; ^{187}Os/^{188}Os 0.124; [Os] 3.3 ppb). Model d assumes mixing between pelagic sediment (δ^{18}O ~20‰; ^{187}Os/^{188}Os 2; [Os] 0.5 ppb). Isotopic compositions and concentrations of end-member reservoirs are given in Table DR2 (see footnote 1). MORB—mid-ocean ridge basalt. Abbreviations for Hawai'ian lavas: MK—Mauna Kea, including west Maui lavas; ML—Mauna Loa. Published data from Gaffney et al. (2005), Turner et al. (2007), and references therein.

mixing end member in OIB petrogenesis (Sobolev et al., 2007).

There is physical and geochemical evidence for this form of metasomatism in the mantle. Pyroxenite layers in predominantly peridotite orogenic massifs at Ronda and Beni Bousera have been interpreted as high-pressure melting of precursor recycled oceanic crust (Reisberg et al., 1991; Pearson et al., 1991). Beni Bousera pyroxenites are characterized by δ^{18}O values ranging from 4.9‰ to 9.4‰ and highly radiogenic ^{187}Os/^{188}Os (up to 0.834), with relatively high Os concentrations (0.18–2.3 ppb Os; Pearson et al., 1991; Pearson and Nowell, 2004) compared with the low Os contents of obducted oceanic lithosphere (Dale et al., 2007).

RECYCLED OCEANIC LITHOSPHERE IN CANARY ISLAND LAVAS

The contrasting oxygen-osmium systematics of La Palma and El Hierro can be explained assuming a metasomatized pyroxenite-peridotite source containing at least two recycled oceanic lithosphere components, modeled as simple two-component mixtures to constrain their quantity and composition (Fig. 2). The model end-member compositions are based on observed mantle compositions, as well as previously published model values. For example, we assume that the recycled components are greater than 1 Ga, based on Pb isotope evidence for the young HIMU affinity of these lavas (Thirlwall, 1997). Estimates of O-Os isotope compositions of subducted basaltic and gabbroic materials were obtained from ophiolites and pyroxenites, and Os concentrations from Beni Bousera pyroxenite layers (Eiler, 2001; Pearson and Nowell, 2004; Dale et al., 2007).

The δ^{18}O values constrain the quantity of recycled layer 3 gabbro-type material in La Palma lavas to 4%–10%. El Hierro requires a mantle source with δ^{18}O characteristics close to that of mantle peridotite. However, a depleted peridotite source mantle cannot explain the highly radiogenic Os isotope compositions of El Hierro lavas. Better fits to the data come from assuming a pyroxenite-peridotite source (Yaxley and Green, 1998) having O isotope compositions that mimic layer 3 gabbro (model a in Fig. 2) for La Palma lavas and layer 2 altered basaltic oceanic crust for El Hierro (model b). In such a model, differences in ^{206}Pb/^{204}Pb between El Hierro and La Palma lavas would be accommodated by high time-integrated U/Pb in the mantle source beneath La Palma. The models constrain the amount of oceanic lithosphere in the mantle beneath the two islands to be consistent (≤10%). This estimate is also within the range previously estimated from OIB olivine compositions (Sobolev et al., 2005, 2007), but lower than the estimates based on ^{187}Os/^{188}Os (25%–45%; Widom et al., 1999), or olivine compositions (20%–75%; Gurenko et al., 2009). This discrepancy is due to the fact that we estimate the quantity of pyroxenite in the source and not in the resultant melt product (Sobolev et al., 2007). It is also striking that the quantity of pyroxenite from oceanic lithosphere (<10%) is within the range of pyroxenite lithologies typically observed in obducted peridotite massifs (<1%–10%; Pearson and Nowell, 2004).

O-OS ISOTOPE SYSTEMATICS FOR HAWAI'I AND THE AZORES

Oxygen-osmium isotope data sets have previously been obtained for Hawai'ian tholeiite lavas and alkali basalts from the Azores (e.g., Schaefer et al., 2002; Gaffney et al., 2005; Turner et al., 2007). Like Canary Island lavas, these islands have ranges in δ^{18}O and ^{187}Os/^{188}Os (Fig. 2). However, Hawai'ian and Azores lavas define trends in δ^{18}O-^{187}Os/^{188}Os space that cannot be accounted for solely through metasomatized enriched mantle like that invoked for La Palma or El Hierro. Instead, it has been suggested that Hawai'ian lavas are sourced from a mantle containing recycled hydrothermally altered oceanic mantle lithosphere (Kea trend; model c in Fig. 2) and pelagic sediments (Koolau trend; model d; Lassiter and Hauri, 1998) and that Azores lavas have a component of ancient depleted oceanic mantle lithosphere (model e; Schaefer et al., 2002). An important caveat to these models is that O isotope systematics of Kea trend lavas may also be explained through shallow-level processes (Fig. 2; Gaffney et al., 2005; Wang and Eiler, 2008), emphasizing the need for case-by-case interpretation of OIB suites. Nevertheless, there is broad agreement between the quantity of recycled components estimated from modeling Os-O isotope systematics of Koolau lavas (<10%) assuming a pyroxenite-enriched peridotite mantle source, compared with that implied from mineral chemistry (Sobolev et al., 2005, 2007).

IMPLICATIONS FOR OIB-SOURCE MANTLE HETEROGENEITY

Any models to explain the O-Os isotope systematics of La Palma and El Hierro require heterogeneity between the mantle sources of the two islands (~50 km). Our favored explanation is that they derive from melting of pyroxene-enriched peridotite mantle enriched by partial melting derived from different layers of oceanic lithosphere. Similar scales of spatial oxygen and osmium isotope heterogeneity have been observed from OIB, including Hawaii (Eiler et al., 1996; Lassiter and Hauri, 1998) and the Azores (Schaefer et al., 2002; Widom and Farquhar, 2003). Consequently, mantle heterogeneity beneath the Canary Islands and other OIBs appears consistent with the spatial scale of heterogeneity in the uppermost mantle (Meyzen et al., 2007). We conclude that OIB lavas sample a mantle where effects of pressure and temperature can lead to metasomatism and redistribution of recycled components, but cannot effectively redistribute or homogenize them, even at relatively short length scales (<50 km), or over extensive (>1 Ga) time periods.

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