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

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OBSERVATIONS

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 μ = 238U/209Pb) 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 (clinoptyroxene 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 LVAS

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 from the Canary Islands of El Hierro and La Palma. These islands have distinct δ18O and 187Os/188Os compositions that can be explained through melting of pyroxenite-enriched peridotite mantle containing <10% recycled oceanic lithosphere. We also assess O-Os isotopic 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.

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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 δ18O and 187Os/188Os compositions that can be explained through melting of pyroxenite-enriched peridotite mantle containing <10% recycled oceanic lithosphere. We also assess O-Os isotopic 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.

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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 intra-

High-temperature intramantle metasomatism might cause sufficient parent-daughter fractionation to generate the range in 187Os/188Os 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 δO differences between La Palma and El Hierro lavas. Indeed, contrasting δO-18O values (0‰–15‰; Eiler, 2001) and unradiogenic 18O/18O relative to layer 2 altered ocean crust with elevated 18O/18O (Dale et al., 2007) and higher δO values (δO = 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 basaltic lavas that demonstrate 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 pyroxenite-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
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 δ²⁰⁶⁸⁸ values ranging from 4.9‰ to 9.4‰ and highly radiogenic ¹⁸⁷Os/¹⁸⁸Os (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).

**O-OS ISOTOPE SYSTEMATICS FOR HAWAI‘I AND THE AZORES**

Oxygen-osmium isotopic systems have previously been obtained for Hawai‘i 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 δ¹⁸O and ¹⁸⁷Os/¹⁸⁸Os (Fig. 2). However, Hawai‘i and Azores lavas define trends in δ¹⁸O-¹⁸⁷Os/¹⁸⁸Os 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‘i 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

**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 δ¹⁸O 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 δ¹⁸O 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 (Yaalex 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 ²⁰⁶⁸⁸ 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 ¹⁸⁷Os/¹⁸⁸Os (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).
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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REFERENCES CITED


