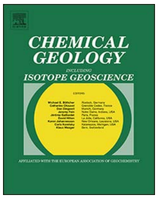
Chemical Geology xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Chemical Geology

journal homepage: www.elsevier.com/locate/chemgeo



The trace element and Sr-Nd-Pb isotope geochemistry of Juan Fernandez lavas reveal variable contributions from a high-$^{3}He/^{4}He$ mantle plume

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ARTICLE INFO

Editor: Catherine Chauvel

Keywords:
Juan Fernandez
$^{3}He/^{4}He$
Mantle plume
Sr-Nd-Pb isotopes
Isotope decoupling
FOZO

ABSTRACT

The Juan Fernandez Islands in the southeastern Pacific are an atypical linear volcanic chain that exhibits a considerable range in $^{3}He/^{4}He$ ratios (8 to 18 $R_{A,}$ where R_A is the $^{3}He/^{4}He$ ratio of air), but limited ranges of $^{87}Sr/^{86}Sr$ and $^{143}Nd/^{144}Nd$. Here we report new trace element abundance data and Sr-Nd-Pb isotope data for mafic lavas previously analyzed for their $^{3}He/^{4}He$ and He contents from the two main islands of Robinson Crusoe and Alexander Selkirk. Lavas from these islands have been previously grouped based on geochemical and petrological classification into Group I and III basalts, and Group II basanites. In general, samples have overlapping Sr-Nd-Pb isotope compositions that suggest a common, albeit slightly heterogeneous mantle source. In detail, the Group I and III tholeiitic and alkalic basalts have nearly identical incompatible trace element patterns, whereas the Group II basanites show elevated incompatible trace element abundances. Major and incompatible trace element modeling indicates that Group III basalts ($^{3}He/^{4}He$ = 7.8–9.5 R_A) from younger Alexander Selkirk Island were produced by the highest degree of partial melting (> 10%) of a common mantle source, followed by Group I basalts (13.6–18.0 R_A) and Group II basanites (11.2–12.5 R_A) from older Robinson Crusoe Island. The $^{206}Pb/^{204}Pb$ of Group I basalts and Group II basanites are slightly more radiogenic and limited in range (19.163 to 19.292) compared with those of Group III (18.939 to 19.221). The Group I and II lavas from Robinson Crusoe are consistent with an origin from the so-called focus zone (FOZO) mantle component, whereas the Alexander Selkirk basalts additionally contain contributions from a less-enriched or relatively depleted mantle component. Juan Fernandez lavas reveal limited ranges of Sr-Nd-Pb isotopes but variable $^{3}He/^{4}He$ as their parental magmas originated mainly from the FOZO component with high $^{3}He/^{4}He$ (> 9 R_A) and variably polluted with a depleted component with lower $^{3}He/^{4}He$ (ca. 8 R_A). Contributions from high-$^{3}He/^{4}He$ mantle sources to ocean island basalts can therefore vary both spatially and temporally, over meter to kilometer lengths and hundred to million-year time scales, and may not be strongly correlated to radiogenic lithophile isotope systematics.

1. Introduction

Ocean island basalts (OIB) exhibit a range of radiogenic isotope variability (e.g., $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$, $^{206}Pb/^{204}Pb$) that provides invaluable information on the long-term composition of OIB mantle sources (Gast et al., 1964; Kay et al., 1970). These traits have led to wide acceptance that OIB come from heterogeneous, variably enriched and ancient mantle sources. In the hotspot or plume hypothesis, which posits intraplate volcanoes are formed by magmas erupted through oceanic plates moving over pseudo-stationary heat sources originating within the mantle (Wilson, 1963; Morgan, 1972), the OIB mantle sources are comprised of 'reservoirs' containing high μ (HIMU), enriched mantle 1 (EM1) and enriched mantle 2 (EM2) end-components (Zindler and Hart, 1986; Hart et al., 1992). Together with the geochemically depleted mid-ocean ridge basalt (MORB) mantle (DMM) end-component, they define a tetrahedron in three-dimensional Sr-Nd-Pb isotopic space that contains a focus zone (FOZO), where the components appear to converge (Hart et al., 1992; Hauri et al., 1994). The alternative non-plume proposal, on the other hand, suggests that the heterogeneous composition of OIB reflects variable, but generally lower degrees of partial melting of the ubiquitously heterogeneous upper mantle (Foulger, 2011 and references therein).

Noble gases are key tracers of mantle geochemistry because they are chemically inert, are highly incompatible and thus partition into the melt phase, and display wide and diagnostic variations in their isotope characteristics (Hilton and Porcelli, 2014). Among the noble gases, He isotopic analyses of MORB and OIB are most abundant with early reports of high-$^{3}He/^{4}He$ values (> 8 ± 1 R_A, the nominal MORB value;

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https://doi.org/10.1016/j.chemgeo.2017.11.024
Received 31 May 2017; Received in revised form 7 November 2017; Accepted 20 November 2017
0009-2541/

Please cite this article as: Truong, T.B., Chemical Geology (2017), https://doi.org/10.1016/j.chemgeo.2017.11.024

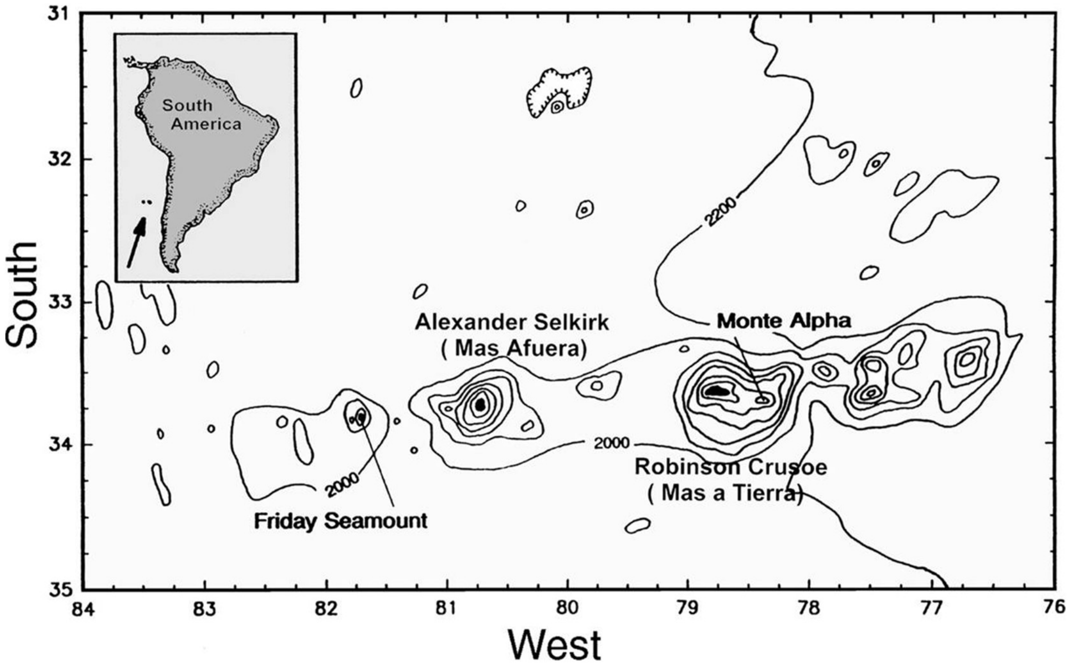

Fig. 1. Bathymetric map of Juan Fernandez Islands from Farley et al. (1993).

R_A = value relative to air $^3He/^4He$) in Hawaiian lavas used to bolster the deep mantle or plume origin of OIB (Craig and Lupton, 1976). In this model, portions of the lower mantle have not yet undergone significant mixing with, and/or may be relatively undegassed relative to, the upper mantle so they retain a greater proportion of their primordial volatile content (Craig and Lupton, 1981). Helium and Sr-Nd-Pb isotopes can correlate in OIB (e.g., Farley et al., 1992; Hanan and Graham, 1996; Hilton et al., 1999). Consequently, the plume model invokes a common, high-$^3He/^4He$ deep mantle component that has been termed PHEM (primitive helium mantle - Farley et al., 1992), "C" (common - Hanan and Graham, 1996) or the aforementioned FOZO (Hart et al., 1992); these terms differ only in the details of Sr, Nd and Pb isotopes, if at all (Hofmann, 2014). Thus, OIB with high-$^3He/^4He$ offer unique insights into the magma source and evolution of linear volcanic chains.

The east-west trending Juan Fernandez linear volcanic chain in the southeastern Pacific (Fig. 1) is an important case study for helium isotopic variations in OIB because its lavas span a range in $^3He/^4He$ values between 7.8 and 18.0 R_A (Farley et al., 1993). This variation spans the typical ratio of MORB (8 ± 1 R_A; Graham, 2002) into the range of the higher ratios measured for some intraplate lavas ($>$ 9 and up to ca. 50 R_A; Stuart et al., 2003). As with models for Hawaiian magmatic evolution, an early popular explanation is that a stationary mantle plume formed the Juan Fernandez linear volcanoes because of the eastward movement of the Nazca plate over the Juan Fernandez plume, creating new volcanoes in the west and cutting off supply to older ones in the east (Baker et al., 1987; Farley et al., 1993).

Results of these early investigations, however, also showed fairly homogeneous Sr-Nd isotopic ratios of Juan Fernandez lavas (Gerlach et al., 1986; Farley et al., 1993). This means that despite their large range of He isotopic variation, Juan Fernandez lavas show limited to no correlation between He and Sr-Nd isotope ratios. Similar to other high-$^3He/^4He$ OIB (e.g., from Heard, Samoa, Iceland, and Hawaii), however, the highest $^3He/^4He$ values of Juan Fernandez lavas generally converge at the PHEM, C or FOZO mantle component (e.g., Farley et al., 1992; Hanan and Graham, 1996; Hilton et al., 1999; Castillo et al., 2007). As FOZO is the convergence of almost all OIB, it is perhaps volumetrically and compositionally the most dominant component of mantle plumes (Castillo, 2015, 2017) and, thus, needs to be better understood. On the other hand, Natland (2003) argued that the He contents of olivine crystals in Juan Fernandez lavas were not derived from mantle plumes but were instead indicative of volatiles that permeated shallow magma reservoirs and subsequently became trapped in crystallizing olivine. This notion, together with the atypical lack of $^3He/^4He$ correlation with Sr-Nd isotopes, had been used as a major argument in favor of the plume counter-proposal that OIB composition is not definitive of distinct mantle end-components and, thus, is not directly connected to deep mantle plumes (Foulger, 2011 and references therein).

In this study, we further examine the petrology and geochemistry of Juan Fernandez lavas to better constrain their petrogenesis and the nature of their mantle source. Our new trace element and Sr-Nd-Pb isotopic analyses, combined with available He and Sr-Nd isotopes (Farley et al., 1993), indicate that sampling through variable degrees of partial melting and inherent heterogeneity of the nominally high-$^3He/^4He$ mantle plume source (or FOZO) can explain the distinct lava groups of Juan Fernandez lavas despite their limited Sr-Nd-Pb isotope variation.

2. Geologic background and samples analyzed

The island and seamount chain comprising the Juan Fernandez linear volcanoes is located at latitude 34°S in the southeastern Pacific, some 660 km west of the Chilean coast (Fig. 1). The chain spans about 800 km on the ca. 22 to 37 Ma old Nazca Plate (Baker et al., 1987; Corvalan, 1981; Gripp and Gordon, 2002; Rodrigo and Lara, 2014). The Juan Fernandez Islands consist of two main islands 180 km apart, Robinson (R.) Crusoe (also known as Mas a Tierra, closer to the land) and Alexander (A.) Selkirk (Mas Afuera, away from the land), and a small island located southwest of R. Crusoe, Santa Clara (Baker et al., 1987; Farley et al., 1993; Devey et al., 2000; Rodrigo and Lara, 2014). Two prominent seamounts, Friday and Domingo, lie west of A. Selkirk.

The stratigraphy of the islands is poorly known, but radiometric (K-Ar) ages for R. Crusoe lavas range from 5.8 to 3.1 Ma whereas those for A. Selkirk range from 2.5 to 0.85 Ma (Booker et al., 1967; Stuessy et al., 1984; Baker et al., 1987). Dredged fresh basalts suggest Friday and Domingo seamounts are younger than A. Selkirk (Farley et al., 1993). Devey et al. (2000) also noted that the larger Friday Seamount appears morphologically evolved with evidence of volcanic activity over a