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# Evidence against an ancient non-chondritic mantle source for North Atlantic Igneous Province lavas

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ABSTRACT

North Atlantic Igneous Province (NAIP) lavas host olivine with the highest $^3He/^4He$ ever measured for terrestrial igneous rocks (up to 50 $R_A$, or $^4He/^3He = \sim 15{,}300$). The relationship of high-$^3He/^4He$ with Pb isotope compositions close to the terrestrial geochron and $^{143}Nd/^{144}Nd$ plausibly consistent with supra-chondritic mantle Sm/Nd in Baffin Island and West Greenland lavas has been interpreted to reflect an ancient 'non-chondritic' mantle source signature. Alternatively, assimilation of continental crustal rocks with unradiogenic Pb isotope compositions and low $^{143}Nd/^{144}Nd$, into magmas with high-$^3He/^4He$, and derived from variably depleted mantle sources, could impart similar geochemical signatures. Radiogenic and stable isotope data for NAIP lavas are consistent with origins as melts from upper mantle sources that contain low-$^{18}O/^{16}O$ recycled lithosphere and/or hydrothermally altered crust, or that have experienced pervasive contamination by crustal gneisses. Olivines from NAIP lavas with $^3He/^4He$ spanning from 8 to 48 $R_A$ have $\delta^{18}O$ ranging from 3.5 to 5.5‰. These compositions are consistent with sources of ambient mantle and low-$\delta^{18}O$ recycled lithosphere, or with concomitant crustal assimilation and He-loss during fractional crystallization. Limited assimilation ($\leq$1%) of incompatible element rich crustal gneisses with low $^{206}Pb/^{204}Pb$ and $^{143}Nd/^{144}Nd$ by melts from variably depleted mantle sources can explain Nd-Pb isotope compositions of Baffin Island and West Greenland picrites. Icelandic lavas provide supporting evidence that the ancestral mantle plume responsible for generating NAIP magmatism sampled variably enriched and depleted mantle, with no evidence for ancient non-chondritic mantle sources. Pervasive crustal contamination and partial melting of heterogeneous mantle sources, generated by plate tectonic processes, can account for the compositions of continental flood basalts (CFB), without the requirement of a non-chondritic terrestrial reservoir. Combined with evidence that the $^{142}Nd/^{144}Nd$ composition of the bulk silicate Earth is due to nucleosynthetic *S*-process deficits in chondrite meteorites, these observations cast doubt that NAIP lavas sampled a non-chondritic mantle source with Sm/Nd higher than in chondrites. If short-lived radiogenic (e.g., $^{146}Sm$-$^{142}Nd$, $^{182}Hf$-$^{182}W$) isotope anomalies are found in CFB, they must either reflect assimilation of isotopically anomalous crustal materials, or partial melting of early-formed mantle heterogeneities produced by differentiation and late accretion.



## 1. Introduction

A long-standing paradigm for Earth is that it possesses a composition similar to some chondrite meteorite groups (e.g., Jacobsen and Wasserburg, 1980; Sun and McDonough, 1989; Javoy et al., 2010). This paradigm has recently been challenged by the observation that the accessible Earth has $^{142}Nd/^{144}Nd$ approximately 20 ppm greater than in ordinary or CV chondrites (Boyet and Carlson, 2005). Because $^{142}Nd$ forms from the decay of $^{146}Sm$, with a half-life of 103 Ma (Meissner et al., 1987), this difference has been interpreted to require a supra-chondritic Sm/Nd ratio for the accessible Earth, presumably generated during differentiation in the first 30 Ma of Solar System formation (Boyet and Carlson, 2005). To account for a supra-chondritic accessible Earth reservoir, a complementary low Sm/Nd reservoir must have existed, now isolated in Earth, or that was lost by erosion during catastrophic impacts in the final stages of planetary accretion (e.g., Campbell and O'Neill, 2012). Jackson et al. (2010) and Jackson and Carlson (2011) recognized that, if a supra-chondritic Earth is valid, all known modern terrestrial mantle reservoirs should have evolved with Sm/Nd ratios approximately 5% higher than that of chondrites. They reasoned that combinations of Pb isotopic compositions on or close to the geochron, high-$^3He/^4He$ and unradiogenic $^{143}Nd/^{144}Nd$ would represent characteristics expected for an ancient non-chondritic 'primitive terrestrial reservoir'. This hypothetical reservoir is referred to as the ancient non-chondritic mantle source for the remainder of this article.

Helium isotopes in particular provide key geochemical information on the origin of lavas and their parental magmas. $^3He/^4He$ measured in olivines from LIP lavas can be higher than mid-ocean ridge basalt (MORB $= 8 \pm 1$ $R_A$; Graham, 2002; where $R_A$ is the present-day $^3He/^4He$ ratio in the atmosphere, $1.38 \times 10^{-6}$), continental intraplate

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alkaline volcanic rocks (CIAV = 5.9 ± 1.2 $R_A$; Day et al., 2005), or the continental lithospheric mantle (6.1 ± 2.1 $R_A$; Gautheron and Moreira, 2002; Day et al., 2015). Continental flood basalts (CFB), such as the 65 Ma Deccan Traps (Basu et al., 1993), the ~250 Ma Siberian Traps (Basu et al., 1995), the <17.5 Ma Columbia River Flood Basalts (Dodson et al., 1997), and quaternary lavas from Ethiopia (Marty et al., 1996) all have lavas containing olivines with $^3He/^4He$ higher than canonical MORB or CIAV. These results imply that less-degassed mantle sources with elevated abundances of primordial $^3He$ are sampled by many large igneous provinces. The highest $^3He/^4He$ ratios measured in any terrestrial materials have come from olivine-rich basalts from the North Atlantic Igneous Province (NAIP) (Fig. 1). Olivine separates from lavas at Baffin Island (up to 50 $R_A$; Stuart et al., 2003; Starkey et al., 2009), West Greenland (up to 48 $R_A$; Graham et al., 1998; Starkey et al., 2009), North East Greenland (up to 20 $R_A$; Marty et al., 1998), East Greenland (18 $R_A$; Peate et al., 2003), and Skye in the British Palaeogene Igneous Province (up to 22 $R_A$; Stuart et al., 2000), indicate derivation from a mantle source with similar He isotope characteristics to present-day Icelandic volcanism (up to 38 $R_A$; e.g., Condomines et al., 1983; Hilton et al., 1999; Breddam et al., 2000; Macpherson et al., 2005). A long-lived, deep-seated mantle plume that has sustained volcanism since the Tertiary in the North Atlantic region has been posited to explain this relationship (e.g., Saunders et al., 1997).

It has recently been suggested that NAIP lavas with high-$^3He/^4He$, lead isotope compositions close to the 4.5 Ga terrestrial geochron, and unradiogenic $^{143}Nd/^{144}Nd$ sample an ancient non-chondritic mantle source (Jackson et al., 2010). Alternatively, it has been proposed that noble gases are strongly decoupled from other geochemical tracers at Baffin Island, West Greenland (Stuart et al., 2003; Starkey et al., 2012) and elsewhere, due to the highest He concentration mantle reservoir dominating the $^3He/^4He$ composition during upper mantle partial melting processes (Day and Hilton, 2011). There is also strong evidence that trends in $^{143}Nd/^{144}Nd$ and Pb isotopes reflect contamination by continental crust (e.g., Thirlwall and Jones, 1983; Peate et al., 2008; Larsen and Pedersen, 2009). It is therefore equally possible that high-$^3He/^4He$ melts from depleted mantle sources, which assimilate crustal rocks with low $^{206}Pb/^{204}Pb$ and enriched $^{143}Nd/^{144}Nd$ compositions, could explain the isotopic signatures preserved in NAIP lavas. Indeed, a persistent problem for evaluating potential mantle source contributions to large igneous provinces is that they transit through crust and lithosphere on their way to Earth's surface, so that there is always potential for crust-mantle interaction.

It is well-demonstrated that crustal contamination modifies Sr-Nd-Pb-Os isotope compositions in CFB (e.g., Carter et al., 1978; Cox, 1980; Carlson et al., 1981; Carlson, 1984; Day et al., 2013), and in NAIP lavas in particular (Carter et al., 1978; Dickin, 1981; Dickin et al., 1984; Thompson, 1982; Thirlwall and Jones, 1983; Gibson, 1990; Lightfoot et al., 1997; Geldmacher et al., 2002; Larsen and Pedersen, 2009). Fresh minerals from igneous rocks from Skye in the NAIP have anomalously low-$^{18}O/^{16}O$, due to assimilation of hydrothermally altered country rock (Taylor and Forester, 1971; Gilliam and Valley, 1997; Monani and Valley, 2001). This phenomenon also occurs in Iceland, where the assimilation of hydrothermally altered country rock by melts leads to variations in O isotopes and incompatible trace-element abundances, and leads to a large range in $^3He/^4He$ due to degassing and assimilation processes (Condomines et al., 1983; Gautason and Muehlenbachs, 1998; Macpherson et al., 2005; Bindeman et al., 2006; Thirlwall et al., 2006; Pope et al., 2013). In this study, combined O-He-Nd-Pb isotope and trace element abundance data for picrites (>13.5 wt% MgO), olivine-rich basalts and intrusive rocks from Skye (Scotland), East and West Greenland, Baffin Island and Iceland are used to evaluate whether ancient non-chondritic mantle reservoirs can be unambiguously identified. NAIP picrites from Baffin Island and West Greenland represent near-primary highly-magnesian magma compositions, interpreted to reflect melting at mantle potential temperatures 100 to 300 °C hotter than ambient asthenosphere (Francis, 1985; Gill et al., 1992; Bell and Williamson, 1994; Brown and Lesher, 2014). The lavas have both 'enriched' and 'depleted' Sr-Nd-Pb isotope and trace-element melt compositions, similar to modern Icelandic lavas (Robillard et al., 1992; Holm et al., 1993; Kent et al., 2004; Starkey et al., 2009, 2012). Combined, these petrogenetic features and identification of some NAIP lavas as potentially originating from an ancient non-chondritic mantle source (Jackson et al., 2010) make samples from this large igneous province important for further study.

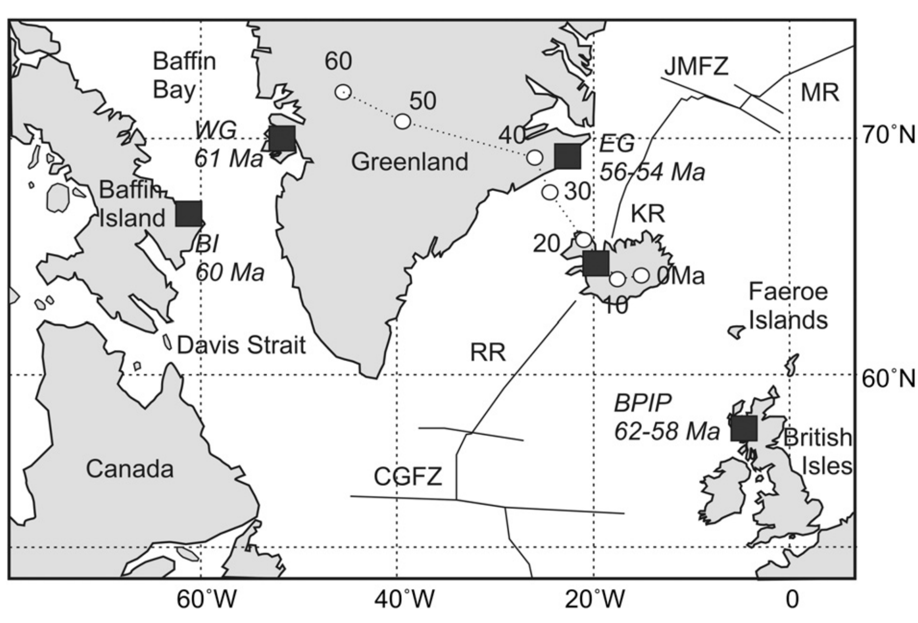


**Fig. 1.** Location map of olivine-rich igneous rocks from the North Atlantic Igneous Province discussed in this study (filled squares). Also shown is the inferred plume-track from 60 Ma to the present day (after Saunders et al., 1997). Age information and discussion of locations are provided in the text. Abbreviations: BPIP = British Palaeogene Igneous Province; BI = Baffin Island; WG = West Greenland; EG = East Greenland; KR = Kolbeinsey Ridge; RR = Reykjanes Ridge; MR = Mohns Ridge; JMFZ = Jan Mayen Fracture Zone; CGFZ = Charlie Gibbs Fracture Zone.