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^{182}W and HSE constraints from 2.7 Ga komatiites on the heterogeneous nature of the Archean mantle

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Abstract

While the isotopically heterogeneous nature of the terrestrial mantle has long been established, the origin, scale, and longevity of the heterogeneities for different elements and isotopic systems are still debated. Here, we report Nd, Hf, W, and Os isotopic and highly siderophile element (HSE) abundance data for the Boston Creek komatiitic basalt lava flow (BCF) in the 2.7 Ga Abitibi greenstone belt, Canada. This lava flow is characterized by strong depletions in Al and heavy rare earth elements (REE), enrichments in light REE, and initial $\varepsilon^{143}Nd = +2.5 \pm 0.2$ and intial $\varepsilon^{176}Hf = +4.2 \pm 0.9$ indicative of derivation from a deep mantle source with time-integrated suprachondritic Sm/Nd and Lu/Hf ratios. The data plot on the terrestrial Nd-Hf array suggesting minimal involvement of early magma ocean processes in the fractionation of lithophile trace elements in the mantle source. This conclusion is supported by a mean $\mu^{142}Nd = -3.8 \pm 2.8$ that is unresolvable from terrestrial standards. By contrast, the BCF exhibits a positive ^{182}W anomaly ($\mu^{182}W = +11.7 \pm 4.5$), yet is characterized by chondritic initial $\gamma^{187}Os = +0.1 \pm 0.3$ and low inferred source HSE abundances (35 ± 5% of those estimated for the present-day Bulk Silicate Earth, BSE). Collectively, these characteristics are unique among Archean komatiite systems studied so far. The deficit in the HSE, coupled with the chondritic Os isotopic composition, but a positive ^{182}W anomaly, are best explained by derivation of the parental BCF magma from a mantle domain characterized by a predominance of HSE-deficient, differentiated late accreted material. According to the model presented here, the mantle domain that gave rise to the BCF received only ~35% of the present-day HSE complement in the BSE before becoming isolated from the rest of the convecting mantle until the time of komatiite emplacement at 2.72 Ga. These new data provide strong evidence for a highly heterogeneous Archean mantle in terms of absolute HSE abundances and W isotopic composition, and also indicate slow mixing, on a timescale of at least 1.8 billion years. Additionally, the data are consistent with a stagnant-lid plate tectonic regime in the Hadean and Archean, prior to the onset of modern-style plate tectonics.

Keywords: ^{182}Hf-^{182}W; ^{187}Re-^{187}Os; ^{176}Lu-^{176}Hf; $^{146,147}Sm$-$^{142,143}Nd$; Highly siderophile elements; Abitibi greenstone belt; Boston Creek; Komatiite; Stochastic late accretion; Mantle mixing

1. INTRODUCTION

The heterogeneous nature of the terrestrial mantle in terms of its chemical composition and physical properties has long been established from previous pioneering studies of the Earth rock record (*e.g.*, Hart and Brooks, 1977; Zindler et al., 1982; Hofmann, 1984; Hart and Zindler, 1986; Zindler and Hart, 1986; Jacobsen, 1988; Galer and Goldstein, 1991), but the origin of these heterogeneities and their length scales and residence times in the mantle are not fully understood and are further complicated by

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differing for different elements and isotopic systems. Some of the chemical heterogeneities may have been primordial in nature, reflecting initial planetary accretion/differentiation and magma ocean crystallization processes (Goldstein and Galer, 1992; Albarède et al., 2000; Drake, 2000; Boyet and Carlson, 2005; Carlson and Boyet, 2008; Frost et al., 2008; Caro, 2011; Touboul et al., 2012; Carlson et al., 2015; Jacobsen and Yu, 2015; Puchtel et al., 2016a; Rizo et al., 2016b). Others likely were the result of a protracted terrestrial accretion history (Willbold et al., 2011; Kruijer et al., 2015; Touboul et al., 2015), or later processes associated with the dynamic regime of the planet, especially crustal recycling (*e.g.,* DePaolo, 1980; Armstrong, 1981; Hofmann and White, 1982; Patchett et al., 1984; Shirey and Hanson, 1986; Chase and Patchett, 1988; Galer et al., 1989; Bowring and Housh, 1995; Bennett et al., 1996; Salters and White, 1998).

The ^{142}Nd and ^{182}W anomalies found in some early Earth rocks formed within the first ~500 and ~50 Ma, respectively, of Earth's history, while ^{146}Sm and ^{182}Hf were still extant, as a result of early planetary differentiation event(s). The largest ^{142}Nd anomalies, ranging as high as +20 ppm and as low as −15 ppm, have been reported for the Eoarchean or older supracrustal rocks from the Isua greenstone belt, Greenland (Boyet et al., 2003; Caro et al., 2003; Boyet and Carlson, 2005, 2006; Caro et al., 2006; Bennett et al., 2007; Rizo et al., 2011, 2012, 2013), the Nuvvuagittuq greenstone belt, Québec (O'Neil et al., 2008, 2012; Roth et al., 2013), and the Ukaliq supracrustal belt, Québec (Caro et al., 2017). Only few terrestrial samples younger than 3.5 Ga are known to have μ^{142}Nd values deviating from terrestrial standards by more than ±3 ppm (Rizo et al., 2012; Debaille et al., 2013). Similarly, positive ^{182}W anomalies as high as +23 ppm have been reported for supracrustal rocks from Greenland and Québec (Willbold et al., 2011; Touboul et al., 2014; Dale et al., 2017), as well as from the Northwest Territories (Willbold et al., 2015) and Fennoscandia (Puchtel et al., 2016b).

The apparent disappearance of ^{142}Nd anomalies during the Archean was initially interpreted as evidence for re-homogenization of early-formed silicate reservoirs within the mantle on the timescale of at least one billion years (Caro et al., 2006; Bennett et al., 2007; Carlson and Boyet, 2008). The presence of sizeable ^{182}W isotopic anomalies in late Archean and younger rocks, however, indicates that mantle mixing did not completely eliminate primordial anomalies early in Earth history. The ~15 ppm positive ^{182}W anomalies found in the 2.82 Ga Kostomuksha komatiites were interpreted to indicate that early-formed domains in the mantle survived for at least 1.7 Ga (Touboul et al., 2012), while ^{182}W isotopic heterogeneities in the Phanerozoic, including young rocks from Baffin Bay, Ontong Java, Hawaii, and Samoa, suggest that primordial domains are still present in the mantle (Rizo et al., 2016a; Mundl et al., 2017).

Some of the inefficient mixing evidenced by the longevity of primordial domains in the mantle could be due to early Earth tectonic regimes differing from those of modern-style plate tectonics (O'Neill and Debaille, 2014). For example, the survival of a ^{142}Nd anomaly of +7 ± 3 ppm in 2.72 Ga tholeiites from the Abitibi greenstone belt (AGB), but a near complete absence of ^{142}Nd anomalies in the post-Archean geological record has been interpreted to indicate a global-scale transition from a stagnant-lid tectonic regime prior to 2.5 Ga to mobile-lid post-Archean plate tectonics (Debaille et al., 2013).

Osmium isotope and highly siderophile element (HSE) abundance systematics provide additional information about early Earth processes. For example, the observation that the HSE occur in roughly chondritic relative proportions in the Bulk Silicate Earth (BSE), and that absolute abundances of at least some of the HSE are higher than would be expected from metal-silicate equilibration, have led to the concept of late accretion. Late accretion is commonly envisioned as a process whereby at least 0.5% of Earth's mass was added to the mantle through the continued accretion of planetesimals subsequent to the cessation of core formation (Chou et al., 1983; Morgan, 1985). Issues related to late accretion are much debated, including the composition of the late accreted materials and the time frame within which they were delivered to Earth and homogenized within the mantle (*e.g.,* Maier et al., 2009; Walker, 2014). Some of the uncertainties stem from the fact that the absolute HSE abundances in the early Earth's mantle are not well constrained and that the causes of their abundance variations are only poorly understood. One example of an attempt to interpret these data is that of Maier et al. (2009) who, on the basis of measured Pt contents in Archean komatiites, argued for a gradual increase in HSE abundances in their presumed deep mantle sources between ~3.5 and ~2.9 Ga due to slow downward mixing of a "late veneer" of chondritic materials.

In this study, we report combined ^{182}Hf-^{182}W, ^{146,147}Sm-^{142,143}Nd, ^{176}Lu-^{176}Hf, ^{187}Re-^{187}Os, and HSE and lithophile trace element abundance data for 2.72 Ga komatiitic basalts from Boston Creek Township in the AGB. We use the data to (1) constrain the long-term evolution of the mantle domain beneath the Superior Craton that gave rise to the BCF parental magmas, (2) evaluate the degree of late Archean mantle heterogeneity in terms of absolute and relative HSE abundances based on our previously published and new Os isotopic and HSE abundance data, and (3) provide new constraints on the timing of late accretionary processes and mixing times of the Earth's mantle.

2. GEOLOGICAL BACKGROUND, SAMPLES, AND PREVIOUS STUDIES

The geology, petrology, and geochemistry of the Boston Creek Flow (BCF) are described in detail by Stone et al. (1987, 1995a, 1995b) and Walker and Stone (2001). The BCF is located in the Ontario portion of the AGB, ~16 km south of Kirkland Lake (Supplementary Fig. A1). Lavas of the AGB are interpreted to have been formed during three volcanic cycles (Cycles I through III: Jensen and Pyke, 1982). A complete volcanic cycle consisted of a basal komatiite sequence, overlain by a tholeiitic sequence, followed by a calc-alkaline sequence, and capped by an alkaline felsic sequence. The BCF belongs to Cycle II, which is