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Tungsten isotope composition of the Acasta Gneiss Complex

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ABSTRACT

High-precision tungsten ($^{182}W/^{184}W$) isotope measurements on well-characterised mafic and felsic samples of the ca. 3960 Ma Acasta Gneiss Complex (AGC; Northwest Territories, Canada) show radiogenic $\varepsilon^{182}W$ values between +0.06 to +0.15. Two ca. 3600 Ma felsic samples from this terrane have $\varepsilon^{182}W \sim 0$ and are the oldest samples so far documented to have a W isotopic composition indistinguishable from that of the modern mantle. The $\varepsilon^{182}W$ data are correlated with $\varepsilon^{142}Nd$ (Roth et al., 2014) and we attribute this variability to incomplete metamorphic homogenisation of the 3960 Ma protolith with more recent material in a 3370 Ma tectono-thermal event. Notably, the value of the positive $\varepsilon^{182}W$ anomalies seen in the 3960 Ma AGC samples that are least affected by metamorphic homogenisation is comparable to that observed in other early Archean rocks (Isua Supracrustal Belt, Greenland; Nuvvuagittuq Supracrustal Belt, Canada) and the late Archean Kostomuksha komatiites (Karelia). This demonstrates a globally constant signature. We infer that the presence of a pre-late veneer mantle represents the most straightforward interpretation of a uniform distribution of $\varepsilon^{182}W \sim +0.15$ value in Archean rocks of different ages. We show that such a notion is compatible with independent constraints from highly siderophile element abundances in mafic and ultra-mafic Archean mantle-derived rocks. The absence of anomalous $\varepsilon^{182}W$ and $\varepsilon^{142}Nd$ so far measured in samples younger than ca. 2800 Ma suggests progressive convective homogenisation of silicate reservoirs. The downward mixing of an upper mantle rich in late-delivered meteoritic material might account for these combined observations.

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1. Introduction

Seismic tomography and geochemical constraints provide us with a detailed picture of the physical and dynamic state of the present-day mantle (Coltice and Schmalzl, 2006; Kellogg and Turcotte, 1990; van der Hilst, 1999; van Keken and Zhong, 1999). Valuable information on the geodynamic regimes prevalent on the early Earth can be obtained by numerical simulations and analogue experiments (e.g. Davaille, 1999; Gonnermann et al., 2002; Samuel and Farnetani, 2003). Yet, uncertainties about physical parameters that characterised the Earth's initial planetary conditions make it difficult to quantitatively assess the early Earth's convective regimes. Observational evidence to constrain the dynamics of the terrestrial Archean mantle has been scant, but high-precision determinations of differences in $^{142}Nd/^{144}Nd$ resulting from decay of short-lived ^{146}Sm have recently opened a new window into the evolution of Hadean-early Archean rocks (e.g. Bennett et al., 2007; Boyet et al., 2003; Caro et al., 2003; Debaille et al., 2013; O'Neil et al., 2008; Rizo et al., 2011; Roth et al., 2013). Investigating how early-formed reservoirs with discrete $^{146}Sm/^{144}Nd$ were dispersed and homogenised within the Earth over geological time-scales yields important information on the physical structure of the early terrestrial mantle (Bennett et al., 2007; Caro et al., 2003, 2005; Debaille et al., 2013; Harper and Jacobsen, 1992; Rizo et al., 2013).

The short-lived ^{182}Hf–^{182}W system offers a further powerful means to probe Earth's formation and early evolution. With a half-life of 8.9 Myr (Vockenhuber et al., 2004) variations in $^{182}W/^{184}W$ can only have been produced during the first ca. 50 million years

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of solar system history. The siderophile character of W compared to the lithophile behaviour of its parent Hf (Goldschmidt, 1930) means that significant amounts of Earth's W were sequestered into the core. That the Earth's mantle has a $^{182}W/^{184}W \sim 200$ ppm higher than chondritic meteorites implies this process occurred while ^{182}Hf was still extant (Kleine et al., 2002; Schoenberg et al., 2002; Yin et al., 2002). This pervasive planetary process dominates the terrestrial W isotopic composition. More recently, well-resolved ∼15 ppm enrichments in $^{182}W/^{184}W$ relative to the present-day mantle value were discovered in ca. 3800 Ma early Archean rocks from the Isua Supracrustal Belt in southern West Greenland (Willbold et al., 2011). The authors postulated that the magnitude of positive $^{182}W/^{184}W$ anomalies observed in the Isua Supracrustal Belt is consistent with the estimated W isotopic composition of a Hadean mantle prior to the addition of a chondritic 'late veneer' (Chou, 1978; Morgan, 1985). In the model favoured by Willbold et al. (2011), the discrepancy between the W isotope budget of Hadean and the present-day mantle is therefore reconciled by externally augmenting the Earth with chondritic material sometime between the giant Moon-forming impact and the purported "Late Heavy Bombardment" (Tera et al., 1974). If this interpretation is correct, high-precision W isotope data may be used to trace how this chondritic material mixed into the Hadean/Archean mantle and thus provide useful insights into the geodynamic framework of the early terrestrial mantle.

In contrast, others (Touboul et al., 2014, 2012) have attributed terrestrial $\varepsilon^{182}W$ anomalies to very early silicate differentiation processes or continued silicate-metal fractionation after core formation ($\varepsilon^{182}W$ is the part-per-ten thousand deviation of the measured $^{182}W/^{184}W$ in a sample relative to that of the standard, i.e. the modern mantle value). In the case of the Touboul et al. (2012) model, the higher incompatibilities of W and Nd relative to Hf and Sm for most silicate solids might predict elevated $\varepsilon^{142}Nd$ to be associated with positive $\varepsilon^{182}W$. This is indeed the case for the Isua Supracrustal Belt, although Willbold et al. (2011) showed that the magnitudes of the two anomalies were inconsistent with the simplest model scenarios. It is thus of significant interest to examine early Archean samples with negative $\varepsilon^{142}Nd$, where a negative $\varepsilon^{182}W$ might be expected as a corollary of early silicate differentiation as suggested by Touboul et al. (2012).

Touboul et al. (2014) have recently investigated samples with negative $\varepsilon^{142}Nd$ from the early Archean Nuvvuagittuq Supracrustal Belt (NSB) in northern Québec (Canada), but these samples show a positive $\varepsilon^{182}W \sim +0.15$ anomaly similar to the samples from the Isua Supracrustal Belt (Willbold et al., 2011). To account for these differences, in conjunction with the samples' siderophile element abundances, Touboul et al. (2014) argue for a decoupling of $\varepsilon^{182}W$ from $\varepsilon^{142}Nd$ as a result of the preferential mobility of W in subduction related fluids. Here, we examine further the relationship between $\varepsilon^{142}Nd$ and $\varepsilon^{182}W$ values, with high-precision W isotope analyses of 3600 to 3960 Ma (Mojzsis et al., 2014) Archean rocks from the Acasta Gneiss Complex (AGC), Northwest Territories (Canada). Our study includes samples with negative $\varepsilon^{142}Nd$, suggestive of a Hadean silicate differentiation event (Roth et al., 2014).

2. Geological background, previous data and sample selection

Details of the geological setting for all samples analysed in this study are reported in Mojzsis et al. (2014), Guitreau et al. (2014) and Roth et al. (2014) and in the Supplementary Material. Only a brief overview is provided here summarising information relevant for the interpretation of our data. Detailed field studies (Iizuka et al., 2006, 2009, 2007) have identified four dominant lithologies within the AGC (mafic, felsic, layered and foliated series). Samples of this study belong to two of these groups: (i) the mafic series comprising gabbroic, quartz dioritic and dioritic gneisses and (ii) the felsic series consisting of tonalitic, trondhjemitic, granodioritic and granitic gneisses. Although much older, ca. 4200 Ma zircon xenocrysts were previously identified in felsic gneisses (Iizuka et al., 2006), the dominant age of magmatic zircons in felsic gneisses that are in chemical equilibrium with their host rock are of ca. 3960 Ma age (Mojzsis et al., 2014). The latter age most likely represents the time of the emplacement of the AGC (Mojzsis et al., 2014). Younger, ca. 3600 Ma concordant ages from felsic gneiss samples were attributed to zircon growth in amphibolite grade metamorphic events as well as crust addition to the AGC (Bowring and Housh, 1995; Guitreau et al., 2012; Iizuka et al., 2007; Mojzsis et al., 2014).

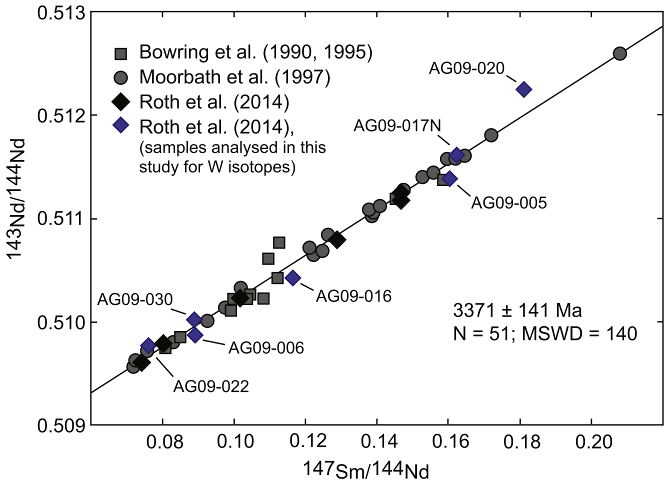

Fig. 1. $^{143}Nd/^{144}Nd$–$^{147}Sm/^{144}Nd$ errorchron for Acasta Gneiss Complex samples (Bowring and Housh, 1995; Bowring et al., 1990; Moorbath et al., 1997; Roth et al., 2014). Samples analysed for $^{182}W/^{184}W$ isotopes in this study are shown in blue and are labelled. The data has been interpreted as the result of partial re-equilibration of the ^{147}Sm–^{143}Nd isotope system at ca. 3370 Ma (Roth et al., 2014) due to a pervasive metamorphic event as documented by secondary zircon growth (Mojzsis et al., 2014; Moorbath et al., 1997; Roth et al., 2014; Whitehouse et al., 2001).

Roth et al. (2014) and Guitreau et al. (2014) reported combined $^{142}Nd/^{144}Nd$, $^{143}Nd/^{144}Nd$ and $^{176}Hf/^{177}Hf$ data for AGC samples reported in Mojzsis et al. (2014). Most samples show a deficit in $^{142}Nd/^{144}Nd$ of up to −14 ppm relative to present-day mantle, in line with the formation and isolation of an early enriched reservoir in the Hadean and a late Hadean/early Archean emplacement age for these rocks (Roth et al., 2014). Combined ^{147}Sm–^{143}Nd data for these samples, however, define a 3370 Ma Mesoarchean errorchron (Fig. 1) similar to previous findings (Mojzsis et al., 2014; Moorbath et al., 1997; Whitehouse et al., 2001). This discrepancy was attributed to partial resetting of the ^{147}Sm–^{143}Nd and ^{146}Sm–^{142}Nd systems during a 3370 Ma metamorphic event (Roth et al., 2014). Based on combined whole-rock $^{176}Hf/^{177}Hf$, U–Pb zircon and trace element data, Guitreau et al. (2014) concluded that gneisses belonging to the 3960 Ma age group were derived from mantle melts with only limited contributions from pre-existing crustal material. Notably, the same samples also display well-resolved deficits in $^{142}Nd/^{144}Nd$ (Roth et al., 2014). Felsic gneisses of the 3600 Ma U–Pb zircon age group show modern terrestrial $^{142}Nd/^{144}Nd$ values (Roth et al., 2014) and crustal $^{176}Hf/^{177}Hf$ ratios (Guitreau et al., 2014) indicating that these samples derived, at least in part, from crust with a $^{142}Nd/^{144}Nd$ similar to that of modern bulk silicate Earth.

For this study, samples were earmarked for W isotope analysis (Fig. 1) based on a desire to cover a wide range of Nd and Hf isotope compositions (Guitreau et al., 2014; Roth et al., 2014) as well as simple age spectra (Guitreau et al., 2012; Mojzsis et al., 2014). Thus, we analysed four felsic gneisses that belong to the 3960 Ma

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