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Half a billion years of reworking of Hadean mafic crust to produce the Nuvvuagittuq Eoarchean felsic crust

Jonathan O'Neil [a,b,*], Maud Boyet [b], Richard W. Carlson [c], Jean-Louis Paquette [b]

[a] Department of Earth Sciences, University of Ottawa, 140 Louis Pasteur, Ottawa, K1N 6N5, Canada
[b] Clermont Université, Université Blaise Pascal, Laboratoire Magmas et Volcans, CNRS UMR 6524, BP 10448, F-63000 Clermont-Ferrand, France
[c] Department of Terrestrial Magnetism, Carnegie Institution of Washington, 5241 Broad Branch Rd. NW, Washington, DC, 20015, USA

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ABSTRACT

The Nuvvuagittuq greenstone belt is dominated by mafic rocks, called the Ujaraaluk unit, that are mostly composed of cummingtonite–plagioclase–biotite with variable amounts of garnet. While the oldest zircons contained in thin intrusive trondhjemitic bands are ∼3.8 Ga, ^{146}Sm–^{142}Nd systematics suggest that the Ujaraaluk unit is as old as 4.4 Ga. The Nuvvuagittuq greenstone belt is surrounded by Eoarchean TTGs that have geochemical and isotopic compositions consistent with their derivation by partial melting of a source similar in composition and age to the Ujaraaluk unit. New zircon dates reported here show the Nuvvuagittuq TTGs to consist at least of four distinct age units of 3.76 Ga, 3.66 Ga, 3.5–3.4 Ga and 3.35 Ga. The Hf isotopic compositions of zircons from the TTG are consistent with derivation from Hadean mafic crust. The 3.66 Ga to 3.35 Ga TTGs appear to have been formed primarily from melting of a source compositionally similar to the 4.4 Ga Ujaraaluk unit, whereas the more radiogenic Hf of the zircons from the 3.76 Ga TTGs may suggest derivation from melting of a source compositionally similar to 4.1 Ga intrusive gabbros. Alternatively, the distinct rare earth element patterns of the 3.76 Ga and 3.66 Ga TTGs suggest their derivation from sources with variable amounts of residual garnet and hence formation at different depths. The composition of the older TTGs is indicative of a deeper source that may have involved a greater interaction between the melt and the mantle to explain the more radiogenic Hf isotopic compositions of their zircons. Sources compositionally similar to the Ujaraaluk unit and intrusive gabbros appear to be the most likely candidates for the Hadean precursor of the Nuvvuagittuq TTGs.

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1. Introduction

Investigation of Earth's primitive crust, its formation mechanism and its evolution though time is unfortunately limited by the scarcity of Eoarchean/Hadean terranes. Most of the oldest Archean terranes are dominated by felsic rocks from the Tonalite–Trondhjemite–Granodiorite (TTG) series. These felsic rocks, however, cannot be directly produced by melting of peridotitic mantle, but must instead have been derived from the melting of an older mafic precursor. The Nuvvuagittuq greenstone belt (NGB) located in Northeastern Canada is mainly composed of mafic/ultramafic rocks with a minimum age of 3.75 Ga (Cates and Mojzsis, 2007; David et al., 2009). Such an early mafic precursor may represent a remnant of Earth's primordial crust. The dominant lithology of the NGB, called the Ujaraaluk unit, is interpreted to be a metamorphosed hydrothermally altered mafic volcanic sequence (O'Neil et al., 2007, 2011) formed in the Hadean, between 4.3 and 4.4 Ga (O'Neil et al., 2008, 2012). Obtaining accurate ages on old terrestrial mafic rocks, however, is challenging. Because Zr-poor mafic magmas do not crystallize zircon, geochronological constraints on Archean mafic rocks commonly come from long-lived radiogenic isotope systems that are susceptible to partial or total resetting by younger metamorphic/metasomatic events. The short-lived ^{146}Sm–^{142}Nd isotope system that yields the Hadean age for the NGB is less susceptible to partial resetting (O'Neil et al., 2012) because ^{146}Sm became extinct before ∼4 Ga. The Hadean age of the NGB mafic rocks however has been questioned in part because the oldest U–Pb ages obtained on zircons in meta-igneous rocks from the NGB range from 3758^{+51}_{-47} Ma to 3817 ± 16 Ma (Cates and Mojzsis, 2007; David et al., 2009). These ∼3.8 Ga rocks, however are intrusive trondhjemitic bands and thus provide only a minimum age for the mafic rocks. In order to better constrain the geological relationship between the mafic and felsic rocks and the evolution of the NGB through time, we present whole-rock Lu–Hf data for the Nuvvuagittuq rocks as well as coupled U–Pb and Hf isotopic analyses in zircons from a series of surrounding and intrusive TTGs.

* Corresponding author at: Department of Earth Sciences, University of Ottawa, 140 Louis Pasteur, Ottawa, K1N 6N5, Canada.
E-mail address: jonathan.oneil@uottawa.ca (J. O'Neil).

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2. Geological setting

2.1. Geologic summary

The NGB is a ∼10 km^2 volcano-sedimentary belt located in Northeastern Canada (Fig. 1) mainly composed of a mappable unit called the Ujaraaluk unit consisting of a mafic cummingtonite–plagioclase–biotite ± garnet amphibolite (O'Neil et al., 2011). The Ujaraaluk unit is divided into distinct chemostratigraphic units with a high-Ti and a low-Ti geochemical group. The low-Ti Ujaraaluk is further subdivided into two subgroups based on their respective abundances of incompatible trace elements with a depleted low-Ti group and an enriched low-Ti group (O'Neil et al., 2011). The map pattern of the Ujaraaluk unit suggests that the different groups follow a chemical stratigraphy within the NGB subsequently deformed into a kilometer-scale refolded fold (Fig. 1). The NGB also contains 3 chemical groups of ultramafic bodies interpreted to be co-genetic cumulates to the mafic Ujaraaluk and following the same map pattern as their respective Ujaraaluk mafic groups (O'Neil et al., 2011).

The NGB is bordered by Eoarchean TTGs dated at 3661 ± 4 Ma (David et al., 2009), further surrounded by younger 2750 ± 16 Ma heterogeneous tonalities (Simard et al., 2003). Predominantly along the western margin of the NGB, the Eoarchean TTG intrudes the NGB mafic lithologies. Despite the fact that they were produced after the extinction of ^{146}Sm, the TTGs yield a similar range in ^{142}Nd/^{144}Nd ratios compared to the Ujaraaluk unit, but with lower Sm/Nd ratios and no correlation between their ^{142}Nd/^{144}Nd and Sm/Nd ratios (O'Neil et al., 2012) as is also observed in new ^{142}Nd analyses reported in this study (Table 2 supplementary data, Fig. 6 supplementary data). The ^{142}Nd anomalies for the NGB TTGs are consistent with their derivation from melting of a Hadean precursor (i.e. formed before the extinction of ^{146}Sm) that is compositionally similar to the Ujaraaluk unit. Remelting of a Hadean Ujaraaluk-like basement to produce the NGB TTGs is also supported by experimental data showing that partial melting of rocks compositionally similar to the Ujaraaluk produces melts similar to the NGB Eoarchean TTG (Adam et al., 2012). Other felsic lithologies include a plagioclase–quartz–biotite schist dated at 3366 ± 3 Ma (David et al., 2009) and fine-grained trondhjemites locally intruding the NGB as thin 30–50 cm bands dated at ⩾3751 ± 10 Ma (Cates and Mojzsis, 2007) and 3817 ± 16 Ma (David et al., 2009) establishing a minimum age for the NGB.

2.2. Geochronological debate

Rocks from the Ujaraaluk unit and co-genetic ultramafic rocks yield a wide range of ^{142}Nd/^{144}Nd ratios, from samples with excesses in ^{142}Nd (up to +8 ppm) to samples with deficits in ^{142}Nd (down to −18 ppm) compared to terrestrial Nd standards (O'Neil et al., 2012). The variability in ^{142}Nd can only have been created in the Hadean as ^{146}Sm was extinct by the beginning of the Archean. Samples from the Ujaraaluk unit show a statistically significant correlation between their ^{142}Nd/^{144}Nd and Sm/Nd ratios in all Ujaraaluk groups taken together or individually by chemical group (O'Neil et al., 2012). The overall correlation provides a slope that corresponds to an age of 4388^{+15}_{-17} Ma (MSWD = 5.8, $n = 50$), or 4406^{+14}_{-17} Ma (MSWD = 1.0, $n = 9$) when considering only the samples with the least disturbed Sm–Nd. The Ujaraaluk unit has been affected by Neoarchean metamorphism as shown by the crystallization of garnet around 2.7 Ga (O'Neil et al., 2012). This thermal event has affected the ^{147}Sm–^{143}Nd systematics of the Ujaraaluk unit causing all chemical groups combined to define a scattered ^{147}Sm/^{144}Nd vs. ^{143}Nd/^{144}Nd correlation corresponding to an age of 3598 ± 200 Ma (MSWD = 134) with the individual chemical groups defining ^{147}Sm–^{143}Nd correlations that range in age from 2517 to 3257 Ma. The least disturbed Ujaraaluk samples however yield a ^{147}Sm–^{143}Nd isochron age of 4321 ± 160 Ma (MSWD = 6.3, $n = 9$, O'Neil et al., 2012). Massive gabbro sills intruding the Ujaraaluk unit give a ^{147}Sm–^{143}Nd isochron age of 4115 ± 100 Ma (MSWD = 4.8, $n = 13$) interpreted by O'Neil et al. (2012) as a minimum age for the Ujaraaluk, consistent with their Hadean age.

The Hadean age of the Ujaraaluk unit has been challenged. The ^{142}Nd anomalies in the Ujaraaluk unit have been confirmed by Roth et al. (2013), but they attributed the ^{142}Nd variation to be an inherited feature caused by mixing, at 3.8 Ga, with a hypothesized Hadean enriched source reservoir. We note that their hypothesized enriched Hadean end member has Sm/Nd and ^{143}Nd/^{144}Nd ratios essentially identical to the lowest Sm/Nd sample from the Ujaraaluk unit thus allowing the Ujaraaluk to be their hypothesized enriched Hadean crust. Consequently, this model does not rule out the simpler model proposed by O'Neil et al. (2012) that the ^{142}Nd isotopic variation in the Ujaraaluk unit is due to their formation while ^{146}Sm was still actively decaying.

Guitreau et al. (2013) proposed an age of 3864 ± 70 Ma for the NGB based on a Lu–Hf isochron that includes rock types ranging from mafic amphibolite to TTG to quartzites and includes separated zircons. As their sample set includes data for only two Ujaraaluk samples, and given that our much more extensive Lu–Hf dataset for the Ujaraaluk, presented in this paper, provides Lu–Hf "isochron" slopes ranging from 2537 to about 4400 Ma depending on sample lithology, we consider the limited Lu–Hf data from Guitreau et al. (2013) to provide little or no constraint on the age of the Ujaraaluk. Cates et al. (2013) proposed a maximum age of 3780 Ma for the NGB based on the oldest ^{207}Pb/^{206}Pb age on zircon from a putative detrital fuchsitic quartzite. However, the ^{207}Pb/^{206}Pb ages believed to be non-metamorphic are as low as 3718 Ma and the U–Pb Concordia age of these zircons suggest they derive from a single source with an age of 3742 ± 14 Ma. This age is indistinguishable from the 3758^{+51}_{-47} Ma to 3817 ± 16 Ma trondhjemites intruding the NGB that provide a minimum age of emplacement for the NGB mafic rocks. The single age population and its agreement with the age of intruding trondhjemites calls into question the interpretation of this sample as a "detrital" quartzite. Darling et al. (in press) have rather suggested that these fuchsitic quartzites are metasomatically-altered orthogneiss intrusive bands.

3. Sample description and analytical procedures

A series of mafic and felsic samples were selected and analyzed for their whole-rock Lu–Hf isotopic compositions (Table 1). Mafic samples comprise 24 Ujaraaluk samples including all three distinct geochemical groups, one ultramafic sample and 6 gabbro samples. Felsic samples comprise 9 TTGs, one pegmatite and the 3366 Ma plagioclase–quartz–biotite schist from David et al. (2009) called felsic schist in this study. The TTGs have compositions ranging from trondhjemites to granodiorites (Fig. 1 supplementary data). They comprise coarse grained rocks exhibiting a strong foliation found to the West of the NGB or inside the major NGB fold (Fig. 1), and thin finer grained bands intruding the NGB to the Southwest. For this study, we call the ∼3.8 Ga intrusive bands, the trondhjemitic bands, and the coarser-grained felsic rocks on both sides of the NGB, the TTGs. Of these felsic samples, zircon separates from 3 TTGs (PC-284, PC-285, PC-286), one trondhjemitic band (PC-287), and the felsic schist (PC-134) also were analyzed for Lu–Hf and U–Pb systematics (Tables 2, 3 supplementary data). Four TTG samples have been analyzed for their ^{146}Sm–^{142}Nd and ^{147}Sm–^{143}Nd isotope systematics (Table 2 supplementary data). Sample locations are shown on Fig. 1. All Hf isotopic compositions were determined using the Nu-Plasma ICP-MS at the Department of Terrestrial Magnetism (DTM) in Washington DC while the whole-rock Sm–Nd data

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