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Formation age and metamorphic history of the Nuvvuagittuq Greenstone Belt

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ABSTRACT

The Nuvvuagittuq Greenstone Belt (NGB) in Northern Quebec, Canada, is dominated by mafic and ultramafic rocks metamorphosed to at least upper amphibolite facies. Rare felsic intrusive rocks provide zircon ages of up to ~3.8 Ga (David et al., 2009; Cates and Mojzsis, 2007) establishing the minimum formation age of the NGB as Eoarchean. Primary U-rich minerals that may provide reliable formation ages for the dominant mafic lithology, called the Ujaraaluk unit, have yet to be found. Metamorphic zircons, rutiles and monazites are present in the unit and give variably discordant results with ^{207}Pb/^{206}Pb ages ranging from 2.8 Ga to 2.5 Ga. The younger ages overlap 2686 ± 4 Ma zircon ages for intruding pegmatites (David et al., 2009) and Sm–Nd ages for garnet formation in the Ujaraaluk rocks suggesting this era as the time of peak metamorphism and metasomatism in the NGB, coeval with regional metamorphism of the Superior craton. Sm–Nd data for Ujaraaluk whole rocks scatter about a Sm/Nd vs. ^{143}Nd/^{144}Nd correlation (MSWD = 134) whose slope would correspond to 3.6 ± 0.2 Ga if interpreted as an isochron. This "isochron" is seen to consist of a series of younger ~3.2–2.5 Ga slopes for the different geochemical groups within the Ujaraaluk, emanating from a baseline distribution older than 4 Ga. The ^{146}Sm–^{142}Nd chronometer is less affected by metamorphism at 2.7 Ga because of ^{146}Sm extinction prior to ~4 Ga. Expansion of the ^{142}Nd dataset for the Ujaraaluk and associated ultramafic rocks continues to show a good correlation between Sm/Nd ratio and ^{142}Nd/^{144}Nd that corresponds to an age of 4388^{+15}_{-17} Ma. The dataset now includes samples with superchondritic Sm/Nd ratios that extend the correlation to ^{142}Nd excesses of up to 8 ppm compared to the terrestrial standard with a total range in ^{142}Nd/^{144}Nd of 26 ppm. The upper Sm/Nd ratio end of the Ujaraaluk correlation is defined by rocks that are interpreted to be cumulates to compositionally related extrusive rocks indicating that this crystal fractionation had to occur while ^{146}Sm decay was active, i.e. well before 4 Ga. Intruding gabbros give ^{143}Nd and ^{142}Nd isochron ages of respectively 4115 ± 100 Ma and 4313^{+41}_{-69} Ma, also supporting an Hadean age for the gabbros and providing a minimum age for the intruded Ujaraaluk unit. 3.6 Ga tonalites surrounding the NGB, 3.8 Ga trondhjemitic intrusive veins, and a 2.7 Ga pegmatite show a deficit in ^{142}Nd compared to the terrestrial standard. These felsic rocks plot to the low Sm/Nd ratio side of the Ujaraaluk isochron and do not show a correlation between their Sm/Nd and ^{142}Nd/^{144}Nd ratios, which can be explained if they are melts of ancient LREE-enriched mafic rocks, such as the Ujaraaluk, with the melting occurring after ^{146}Sm was extinct. A subset of least disturbed Ujaraaluk samples has coherent isotopic compositions for both short-lived and long-lived Nd isotopic systems giving ^{143}Nd and ^{142}Nd isochron ages overlapping within error of 4321 ± 160 Ma (MSWD = 6.3) and 4406^{+14}_{-17} Ma (MSWD = 1.0), respectively. This age represents our best age estimate for the Ujaraaluk unit. The NGB thus preserves over 1.6 billion years of early Earth history including an expanse of mafic crust formed in the Hadean.

1. Introduction

The first billion years of Earth history is poorly presented in the rock record with most early terrains being Eoarchean in age, leaving the Hadean Eon almost devoid of available samples. Until recently, the only available samples older than 4.1 billion years old (Ga) were detrital zircons from the Jack Hills conglomerate (~4.4 Ga; Wilde et al., 2001). Although these zircons provide invaluable information about the early Earth, their host rocks

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have been destroyed, leaving no direct samples of Earth's primordial crust. As a result, the nature of Earth's early crust and the processes responsible for its formation are largely conjecture. Other than these detrital zircons, rare occurrences of Eoarchean crust provide the only compositional constraints on the nature of Earth's early crust. These terrains include the Acasta Gneiss, Canada (4.03 Ga; Bowring and Williams, 1999), the Itsaq Gneiss Complex, Greenland (3.85–3.60 Ga; Nutman et al., 1996; Nutman and Friend, 2009), the Napier complex, Antarctica (3.95–3.8 Ga; Williams et al., 1986; Simon and Nigel, 2007), the Saglek-Hebron block, Labrador (3.78–3.73 Ga; Collerson, 1983; Schiotte et al., 1989), and the Anshan area, China (3.8 Ga; Song et al., 1996; Liu et al., 2008; Wu et al., 2008, 2009; Nutman et al., 2009). Earth's primitive crust is most likely to have been derived from the partial melting of the mantle to produce an early mafic crust. This is consistent with the Lu–Hf isotopic compositions of the Jack Hills zircons that suggest that their host rock was tonalite-trondhjemite-granodiorite (TTG) derived from the melting of a basaltic Hadean precursor (Blichert-Toft and Albarede, 2008; Kemp et al., 2010).

Investigation of Earth's primitive crust and the timing of its formation have largely focused on felsic rocks because they are the most likely host rocks for the zircons that provide robust geochronological constraints. These felsic rocks, however, cannot have been directly produced by melting of mantle peridotite. Instead, they likely were produced by melting of an older mafic precursor. Using zircon ages from felsic rocks to provide geochronological constraints on suites of mafic rocks requires a very accurate understanding of the geologic relationships between the different lithologies. Stratigraphic relationships between felsic and mafic units are rarely unequivocal in early Archean terrains that generally have been affected by multiple phases of intense deformation and metamorphism. This emphasizes the need to focus on the mafic component in Eoarchean/Hadean terrains in order to constrain the composition and the timing of formation of Earth's earliest crust. Unfortunately, obtaining accurate ages on old terrestrial mafic rocks is difficult due to their lack of zircon, the common recrystallization of their original igneous mineralogy during later metamorphic events, and their generally low concentrations of the incompatible-element-based radiometric systems used for dating. While long-lived isotopic systems such as ^{147}Sm–^{143}Nd, ^{176}Lu–^{176}Hf and ^{187}Re–^{187}Os are powerful tools to study the evolution of the crust–mantle system through time, Eoarchean/Hadean terrains usually have suffered extensive metamorphism and deformation that can affect these geochronometers through metamorphic/metasomatic redistribution of parent and/or daughter element any time after rock formation. On the other hand, the short-lived ^{146}Sm–^{142}Nd isotopic system (half life = 68 Ma; Kinoshita et al., 2012) is not as susceptible to partial resetting because ^{146}Sm became extinct prior to ~4 Ga. Thus the ^{146}Sm–^{142}Nd system is an ideal tool to probe any potential Hadean terrain. ^{142}Nd deficits recently have been identified in the Nuvvuagittuq Greenstone Belt (NGB) mafic rocks (O'Neil et al., 2008) suggesting an age of nearly 4.3 Ga, which would make it the only known remnant of Hadean crust preserved on Earth. However, the oldest U–Pb age obtained in zircon from rare intrusive felsic rocks in the NGB is 3817 ± 16 Ma (David et al., 2009). Nevertheless, the NGB offers a unique opportunity to constrain the composition of Earth's early crust and the processes responsible for the formation of crust in the Eoarchean/Hadean.

In this paper, we present an isotopic study combining both Nd long-lived and short-lived systems (^{147}Sm–^{143}Nd, $T_{1/2}$ = 106 Ga and ^{146}Sm–^{142}Nd, $T_{1/2}$ = 68 Ma) focusing on the mafic and ultramafic rocks of the NGB to put as many geochronological constraints as possible on the formation and evolution of the main lithology in the belt.

2. Geologic setting

The Nuvvuagittuq Greenstone Belt is located in Northern Quebec, Canada within the Hudson Bay terrane of the Northeastern Superior Province (Fig. 1). The Hudson Bay terrane is a TTG-greenstone terrain subdivided into different domains (Tikkerutuk, Bienville, Goudalie, La Grande, southern Douglas Harbour domains) and characterized by Nd model ages generally older than 3.0 Ga (Boily et al., 2009). The old rocks of the terrane are intruded by a series of younger TTG (~2.7 Ga) with low initial ^{143}Nd/^{144}Nd suggesting recycling of older crust (Boily et al., 2009). The Hudson Bay terrane is interpreted to represent a cratonic nucleus of the Northeast Superior Province onto which the more juvenile rocks of the Rivière Arnaud terrane were juxtaposed. The NGB is a ~10 km^2 volcano-sedimentary sequence preserved on the East shore of Hudson Bay approximately 35 km south of the Inuit municipality of Inukjuak. The NGB is dominantly composed of mafic to ultramafic rocks with chemical sedimentary rocks and minor felsic components, all highly deformed and metamorphosed. The map pattern of the NGB (Fig. 1) is dominated by a large-scale North-closing synform plunging moderately to the South. The West limb of this open fold consists of a tight isoclinal South-closing synform with a steeply E-plunging fold axis. The NGB has been metamorphosed to at least upper amphibolite facies. Cates and Mojzsis (2009) proposed that the NGB experienced at least two significant metamorphic episodes around 3.6 Ga and 2.7 Ga based on overgrowth of zircons, with the Neoarchean event reaching 640 °C.

The NGB is dominated by mafic rocks. The most abundant lithology is a heterogeneous, but generally basaltic, group of rocks mainly composed of variable proportions of cummingtonite–biotite–plagioclase–garnet. Due to its important variation in mineralogy, we refer to this lithological unit as the Ujaraaluk unit (formerly called the faux-amphibolite; O'Neil et al., 2007, 2008) that comprises facies that include both cummingtonite-rich rocks and rocks that are dominated by a garnet–biotite paragenesis. Despite this wide range in mineralogical proportions, the different parageneses of the Ujaraaluk unit show a relatively small range of major element composition from basaltic to basaltic andesite (O'Neil et al., 2011a) reinforcing their grouping as a lithological unit. The Ujaraaluk unit can be subdivided into three distinct geochemical groups mainly based on Al/Ti ratios and trace element profiles. These geochemical groups follow a chemical stratigraphy within the NGB with a high-Ti group that has relatively flat normalized incompatible trace element profiles at the base of the tight synform followed by a low-Ti group stratigraphically above. Chemical sediments lie at the transition between the high-Ti and the low-Ti Ujaraaluk groups. The low-Ti Ujaraaluk unit is further subdivided into two subgroups with distinct Al/Ti ratios and trace element profiles referred as the depleted low-Ti group and the enriched low-Ti group based on their relative concentration of incompatible trace elements (O'Neil et al., 2011a). Rocks from the low-Ti Ujaraaluk unit directly above the chemical sediments have lower concentrations of incompatible trace elements and distinct U-shaped rare earth element (REE) profiles, whereas the rocks from the low-Ti Ujaraaluk at the top of the sequence have the most enriched REE profiles (O'Neil et al., 2011a). The Ujaraaluk unit as a whole is interpreted by O'Neil et al. (2011a) to represent hydrothermally altered mafic volcanic crust transitioning from rocks with tholeitic affinitities to rocks with boninitic and calc-alkaline affinities deposited in a submarine volcanic environment. This is supported by the presence of deformed, but well-preserved pillows within the Ujaraaluk unit. The SW corner of the NGB contains massive aphanitic basaltic greenstones mainly composed of chlorite–epidote–quartz–plagioclase–actinolite (O'Neil et al., 2007). These greenstones can be divided into the same three compositional groups seen in the Ujaraaluk unit with the same