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# Sluggish Hadean geodynamics: Evidence from coupled $^{146,147}\text{Sm}$ – $^{142,143}\text{Nd}$ systematics in Eoarchean supracrustal rocks of the Inukjuak domain (Québec)

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1 **Sluggish Hadean geodynamics: Evidence from coupled  $^{146,147}\text{Sm}$ -**  
2  **$^{142,143}\text{Nd}$  systematics in Eoarchean supracrustal rocks of the Inukjuak**  
3 **domain (Québec)**

4  
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## Abstract

1  
2 The discovery of deficits in  $^{142}\text{Nd}/^{144}\text{Nd}$  in mafic rocks of the Nuvvuagittuq Supracrustal Belt (NSB) has  
3 triggered a debate about the possible preservation of Hadean (pre-3.85 Ga) crustal remnants in the  
4 little-known but areally extensive Innuksuac complex (3.6-3.8 Ga, Inukjuak domain, Northeast  
5 Superior Province, Canada). Geochronological investigations in the NSB, however, are hampered by  
6 the poor preservation and highly disturbed isotopic record of various mafic (amphibolite) lithologies  
7 that host the  $^{142}\text{Nd}$  anomalies. Here we present  $^{146}\text{Sm}$ - $^{142}\text{Nd}$  and  $^{147}\text{Sm}$ - $^{143}\text{Nd}$  data for rocks of  
8 extrusive magmatic and sedimentary protoliths from the Ukaliq supracrustal belt, a newly discovered  
9 volcano-sedimentary enclave locked within granitoid gneisses of the Inukjuak domain. Our study also  
10 includes the first  $^{146}\text{Sm}$ - $^{142}\text{Nd}$  data for quartz-magnetite rocks (banded iron-formation; BIF) of the NSB  
11 and the Eoarchean Isua supracrustal belt (ISB) in southern West Greenland. We show that Ukaliq  
12 amphibolites carry variably negative  $^{142}\text{Nd}$  anomalies, ranging from 0 to -10 ppm, which are positively  
13 correlated with their Sm/Nd ratio. If considered as an isochron relationship, the  $^{146}\text{Sm}$ - $^{142}\text{Nd}$  array  
14 yields an apparent Hadean emplacement age of  $4215_{-76}^{+50}$  Ma. The negative  $^{142}\text{Nd}$  anomalies,  
15 however, appear to be mainly restricted to amphibolites with boninitic affinities, likely reflecting  
16 inheritance from an enriched mantle source. In contrast, tholeiitic and ultramafic lavas have normal  
17  $\mu^{142}\text{Nd}$  regardless of their Sm/Nd ratio. Furthermore, BIF from Ukaliq and Nuvvuagittuq lack the  
18 negative  $^{142}\text{Nd}$  anomalies that should have been produced by in situ decay of  $^{146}\text{Sm}$  had these  
19 sediments been deposited prior to ca. 4.1 Ga. Instead, they exhibit  $\mu^{142}\text{Nd}$  identical to that measured  
20 in Isua BIF. Collectively, our results suggest that the  $^{146}\text{Sm}$ - $^{142}\text{Nd}$  array characterizing mafic lithologies  
21 of Ukaliq and Nuvvuagittuq is an inherited signature with doubtful chronological significance. We  
22 interpret the volcanic protoliths of the Innuksuac complex to have been produced by metasomatically  
23 triggered melting of a variably enriched Eoarchean mantle, following addition of felsic melts and/or  
24 fluids derived from a foundering Hadean mafic crust. Application of coupled  $^{146,147}\text{Sm}$ - $^{142,143}\text{Nd}$   
25 chronometry to Ukaliq lavas yields a model age of differentiation of  $4.36_{-0.06}^{+0.05}$  Ga for this Hadean

1 precursor. This is similar to late-stage crystallization ages inferred for the lunar and terrestrial magma  
2 oceans. The long-term preservation of Earth's primordial crust points to subducted lithospheric  
3 recycling in the post-magma ocean Earth.

4

## 5 **1. Introduction**

6 In the absence of an actual rock record of the first 500 Myr of Earth's history – as opposed to detrital  
7 Hadean zircons separated from their parent rocks (e.g. Mojzsis et al., 2001) – direct constraints on  
8 the composition, dynamics, and ultimate fate of the primordial lithosphere remain out of reach.  
9 Alternatively, indirect studies of the daughter products of short-lived radioactive nuclides show that  
10 the silicate Earth experienced early (4.4-4.5 Ga) differentiation (Harper and Jacobsen, 1992; Bennett  
11 et al., 2007; Boyet, 2005; Boyet et al., 2003; Caro et al., 2003), most likely due to the crystallization of  
12 a deep magma ocean in the aftermath of the moon-forming giant impact. By analogy to the lunar  
13 magma ocean model, it has been suggested that Earth's primordial crust was produced via upward  
14 migration and crystallization of mafic/ultramafic residual liquids in the final stages of solidification of  
15 the uppermost mantle (Caro et al., 2005; Bourdon and Caro, 2007; Rizo et al., 2011). Whereas various  
16 chronological aspects of these early events continue to be refined, the fate of Earth's primordial  
17 silicate reservoirs and the extent to which magma ocean processes subsequently influenced the  
18 geodynamic evolution of our planet, is enigmatic. Geochemical and isotopic studies of Jack Hills  
19 zircons suggest that magma ocean crystallization was rapidly followed by the onset of crustal  
20 formation processes akin to those operating in the modern Earth (e.g. Harrison, 2009). Precious little  
21 is known beyond this, however, about the geodynamic processes by which the primordial lithosphere  
22 was returned to the mantle, or the timescale associated with it.

23 The question of the rise (and demise) of the terrestrial protocrust is intrinsically connected to that of  
24 the geodynamic regime prevailing in the Hadean. A common view, based mostly on petrological and  
25 structural arguments, is that subduction (*sensu stricto*) was inoperative until the late Archean (Shirey

1 and Richardson, 2011; Bédard et al., 2003) and that renewal of the Earth's crust before that time  
2 operated in a “vertical tectonic” regime (Robin and Bailey, 2009). This view is supported by thermal  
3 evolution models which predict that in the hot early Earth mantle melting would have taken place at  
4 greater depth than today, generating a thicker crust associated with a highly depleted lithospheric  
5 mantle (Johnson et al., 2013; Korenaga, 2006; Vlaar et al., 1994; Sleep and Windley, 1982).  
6 Consequently, the Hadean lithosphere was likely stiffer and more buoyant, inhibiting the  
7 development of subduction zones and favoring instead a sluggish tectonic style characterized by  
8 slower plate motion and an overall longer crustal residence time (Korenaga, 2006; Foley et al., 2014).  
9 Alternatively, hotter mantle temperatures may have pushed the young Earth into a stagnant-lid  
10 regime (O’Neill and Debaille, 2014), where the mantle is overlain by a mechanically strong and  
11 generally immobile lithosphere, and crustal recycling only takes place during episodic pulses of rapid  
12 subduction. Lastly, gravitational instabilities in the thickened Hadean crust may have caused  
13 catastrophic episodes of rapid foundering and rejuvenation of the entire lithosphere (van Thienen et  
14 al., 2004).

15 The main obstacle to distinguishing these very different scenarios is the paucity of reworked Hadean  
16 components in the Archean rock record. In this context, the presence of deficits in  $^{142}\text{Nd}/^{144}\text{Nd}$  in  
17 magmatic rocks of the Nuvvuagittuq supracrustal belt (NSB), within the Archean Innuksuac gneiss  
18 complex (Northeastern Superior province, Quebec), has major implications for our understanding of  
19 Hadean geodynamics (O’Neil et al., 2008; Roth et al., 2013). Due to the short half-life of  $^{146}\text{Sm}$   
20 ( $T_{1/2}=103$  Myr),  $^{142}\text{Nd}$  heterogeneities can only have been produced prior to about 4.1 Ga, and,  
21 therefore, are specifically related to mantle-crust differentiation in the Hadean (e.g. Caro, 2011). As  
22 Nd is more incompatible than Sm, enriched silicate reservoirs such as Earth’s Hadean crust would be  
23 characterized by relatively low Sm/Nd ratios, resulting in the development of negative  $^{142}\text{Nd}$   
24 anomalies (low  $^{142}\text{Nd}/^{144}\text{Nd}$ ), whereas the complementary depleted mantle would develop positive  
25  $^{142}\text{Nd}$  anomalies. The ubiquitous presence of negative  $^{142}\text{Nd}$  anomalies in mafic lithologies of the NSB  
26 has thus raised the question of whether actual Hadean volcano-sedimentary sequences are

1 preserved in the Inukjuak domain, or if this terrane instead inherited the geochemical fingerprint of a  
2 long vanished Hadean reservoir (O'Neil et al., 2008; Roth et al., 2013; Guitreau et al., 2014).

3 Innate negative  $^{142}\text{Nd}$  anomalies from reworked Hadean components have also been reported from  
4 granitoids and mafic rocks of the Acasta gneisses (3.96 Ga, Slave craton, Canada (Mojzsis et al., 2014;  
5 Roth et al., 2014), the Schapenburg komatiite (Puchtel et al., 2016) and some 3.4 Ga Ameralik dykes  
6 of Southwest Greenland (Rizo et al., 2012). Likewise, the negative  $^{142}\text{Nd}$  anomalies carried by  
7 Eoarchean tonalite-trondhjemite-granodiorite (TTG) rocks associated with the NSB (i.e. the Voizel  
8 suite) provide clear evidence for a variable degree of geochemical inheritance in plutonic rocks of the  
9 Innuksuac complex (O'Neil et al., 2008; Roth et al., 2013). At odds with this interpretation, O'Neil et  
10 al. (2008) proposed that the NSB still contains vestiges of the Hadean precursor in which the  $^{142}\text{Nd}$   
11 effect was produced, present as a heterogeneous package of highly altered mafic rocks  
12 (cummingtonite-rich amphibolite) colloquially termed by them the "Ujaraaluk unit" (O'Neil et al.,  
13 2011). This interpretation relies on the argument that NSB cummingtonite-amphibolites exhibit  
14  $^{142}\text{Nd}/^{144}\text{Nd}$  signatures that positively correlate with their Sm/Nd ratio (O'Neil et al., 2008). This  
15 characteristic was observed neither in the Acasta, Schapenburg, or Ameralik rocks cited above, and  
16 as such could be taken to represent a disturbed yet geochronologically significant isochron  
17 relationship. If the interpretation of O'Neil and co-workers is correct, then the volcano-sedimentary  
18 sequence of the NSB would represent the oldest preserved crust on Earth, and accordingly its  
19 geochemical record would have the potential to constrain the geodynamic and environmental state  
20 of our planet to within less than 300 Myr after the Moon-forming event.

21 Yet, the interpretation of the  $^{146}\text{Sm}$ - $^{142}\text{Nd}$  signal as a true isochron in the NSB rocks is not without  
22 caveats. First, the chronological constraints provided by the  $^{147}\text{Sm}$ - $^{143}\text{Nd}$  and  $^{146}\text{Sm}$ - $^{142}\text{Nd}$   
23 chronometers are in fact strongly discordant; the cummingtonite-amphibolites define a younger  
24  $^{147}\text{Sm}$ - $^{143}\text{Nd}$  errochron at ca. 3.6 Ga (O'Neil et al., 2012), and the apparent decoupling of the two Sm-  
25 Nd chronometers is not well understood (O'Neil et al., 2012; Roth et al., 2013). Second, quartz-biotite

1 schists and quartzites of probable detrital origin from the NSB show robust detrital zircon  
2 populations in a 3.65-3.78 Ga range, inconsistent with deposition in the Hadean (David et al., 2006;  
3 Cates and Mojzsis, 2007; Cates et al., 2013; Darling et al., 2013). Cates and Mojzsis (2007) also  
4 established a firm minimum age for the sequence at 3.75 Ga from a trondhjemitic sheet crosscutting  
5 amphibolites and BIF near the southern tip of the belt. The geochronological implications of these  
6 results depend on the nature of zircon-bearing protoliths, as well as their field relationship with the  
7 cummingtonite-amphibolite unit, the contentious nature of which has produced diverging  
8 interpretations of the zircon record (Augland and David, 2015; Darling et al., 2013). Nevertheless, the  
9 picture that emerges from conventional geochronological approaches points towards an Eoarchean  
10 age for the NSB, in contrast to the ca. 4.3 Ga date provided by the  $^{146}\text{Sm}$ - $^{142}\text{Nd}$  system. Hence, while  
11 the isotopic signal carried by Nuvvuagittuq rocks is exceptional – and may hold the key to a better  
12 understanding of the Hadean geological evolution – the fundamentals of both its chronological and  
13 geodynamic significance remain unclear.

14 The geochronological issue raised by the NSB  $^{146}\text{Sm}$ - $^{142}\text{Nd}$  record is further exacerbated by the poor  
15 preservation of the mafic lithologies carrying the  $^{142}\text{Nd}$  anomalies (O’Neil et al., 2011). This is due to  
16 hydrothermal and metamorphic processes (e.g. Cates and Mojzsis, 2009) which resulted in severe  
17 disturbance of their geochemical signatures and currently prevents reliable dating using conventional  
18 radiogenic isotope systems (Guitreau et al., 2013; O’Neil et al., 2012; Roth et al., 2013; Touboul et al.,  
19 2014). The Nuvvuagittuq belt, however, is not the singular occurrence of supracrustal rocks in the  
20 wider Innuksuac complex; regional mapping, aerial photographs and aeromagnetic surveys also show  
21 the presence of a dozen or so scattered supracrustal enclaves in the general area of the Inukjuak  
22 domain (Simard et al., 2003), none of which have previously been subject to any detailed field or  
23 geochronological investigation. Here, we present high-precision  $^{146,147}\text{Sm}$ - $^{142,143}\text{Nd}$  data for a mapped  
24 unit of magmatic and sedimentary rocks from the Ukaliq<sup>1</sup> supracrustal belt (USB), a newly discovered

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<sup>1</sup> Ukaliq (ᐃᑲᑲᑦ) is « Arctic hare » *Lepus arcticus* in the local *Inuktitut* language of Nunavik in northern Québec, and is used by us as an informal field name for this supracrustal enclave.

1 volcano-sedimentary enclave situated a few kilometers north of the NSB. Our results show that mafic  
2 lithologies of the USB define a rough positive correlation between  $^{142}\text{Nd}/^{144}\text{Nd}$  and Sm/Nd, which, if  
3 interpreted as an isochron, would yield a Hadean emplacement age similar to that reported for  
4 Nuvvuagittuq. Our observations, however, consistently point towards an inherited origin for the  
5  $^{142}\text{Nd}$  effects. We show how this vestigial signal in turn provides a means to better understand the  
6 geodynamic evolution of the young Earth, from the crystallization of the magma ocean to the genesis  
7 of the oldest continental nuclei.

8

## 9 **2. Geological setting**

10 The Ukaliq supracrustal belt (USB) belongs to one of several scattered enclaves of the Innuksuac  
11 complex, a group of plutonic and supracrustal rocks rafted within the predominantly Neoproterozoic  
12 Inukjuak domain (Minto block, Northeast Superior Province (NESP), Quebec). The geology of the  
13 region has been described in detail in several previous studies (e.g. Cates and Mojzsis, 2007, 2009,  
14 2013; Stevenson et al., 2006; O'Neil et al., 2007) and we only focus here on the newly discovered  
15 Ukaliq outcrops. The Ukaliq enclave (Fig. 1) is composed of interleaved rocks of volcanic and  
16 sedimentary protolith that are intruded by late leucogranitoids and surrounded by 3.45-3.65 Ga old  
17 tonalitic gneisses of the Voizel suite. Located approximately 5-10 km north of Nuvvuagittuq, the USB  
18 is an asymmetrical belt with a maximum thickness of 60 m and a NNW extent of several kilometers.  
19 Its southernmost exposure – the focus of this study – is within a low-strain window dominated by  
20 amphibolites (*Am*) and variably serpentinized ultramafic rocks (*Aum*), with minor sedimentary  
21 components including Iron formations (*BIF*), quartzite (*Aq*) and quartz-biotite shists (*Aqbc*) of  
22 probable detrital sedimentary origin. Although the Ukaliq enclave is intact, the sequence has been  
23 strongly deformed, transposed, and like the rest of the Inukjuak domain was metamorphosed to the  
24 upper amphibolite facies (Cates and Mojzsis, 2009). The ultramafic units show clear evidence at the  
25 outcrop for extensive alteration, and range from pure serpentinites on the eastern side of the



1 sequence to more pyroxene-rich compositions toward the West. We interpret this field relation to  
2 reflect a relict magmatic differentiation trend within a komatiitic flow. The presence of chemical  
3 sediments near to what we interpret to be the base of the sequence points to a predominantly  
4 volcanic or subvolcanic origin for the mafic/ultramafic rocks. It is noteworthy that unlike in the NSB,  
5 cummingtonite-rich amphibolites rarely occur in the USB. We interpret this to reflect the absence of  
6 the hydrothermally altered, low-Ca mafic lithologies that volumetrically dominate in the  
7 Nuvvuagittuq belt.

8 Our sample set was collected in the mapped exposures on the southern part of the USB during  
9 fieldwork in 2012 and 2014. The collection consists of 38 amphibolites and ultramafic rocks, 6  
10 chemical sediments, 13 granitoid gneisses (Voizel suite), and 2 Neoproterozoic granites (Boizard suite)  
11 sampled from the enclosing gneisses of the supracrustals. Sample locations are reported on the map  
12 (Fig. 1), and correlated GPS coordinates are provided in Appendix A1.

### 13 **3. Whole-rock geochemistry**

#### 14 ***3.1. Mafic and ultramafic rocks***

15 Whole-rock major and trace element analyses were performed on amphibolites and ultramafic rocks  
16 representative of the main lithological units of the USB (Appendix A1). Most Ukaliq ultramafic rocks  
17 are distinguished by high Al/Ti and low Gd/Yb ratios and, overall, are compositionally similar to Al-  
18 enriched komatiites (Appendix A1) (Arndt et al., 2008). Their high degree of serpentinization and  
19 metasomatism expected to occur during hydrothermal alteration renders these rocks poorly suited  
20 for  $^{147}\text{Sm}$ - $^{143}\text{Nd}$  studies. Thus, with the exception of one relatively well preserved pyroxenite, and two  
21 hornblendites sampled near the top of the main ultramafic body, this category of rock samples are  
22 not further considered in this study.

23 Mafic lithologies of the USB display a wide compositional range, with  $\text{SiO}_2=46\text{-}53$  wt%,  $\text{MgO}=7\text{-}12$   
24 wt% and  $\text{CaO}=4\text{-}12$  wt% (Fig. 2, Appendix A2). Most samples define a trend of decreasing

1 incompatible elements (e.g.  $\Sigma$ REE) with increasing  $\text{SiO}_2$  content (Fig. 2), which cannot be described as  
2 a magmatic differentiation trend and suggests the presence of distinct primary magma compositions.  
3 The major and trace element characteristics, in conjunction with petrographic examination of thin  
4 sections, contributes to distinguishing four subtypes of mafic rocks within this outcrop, hereafter  
5 referred to as *tholeiitic*, *transitional*, *boninitic* and *enriched*. The main characteristics of these four  
6 groups are illustrated in plots of Al/Ti versus selected major and trace elements in Fig. 2, and can be  
7 summarized as follows;

8 *Tholeiitic* lavas (N=9) have low  $\text{SiO}_2$  content (46-49 wt%) and  $\text{Al}_2\text{O}_3/\text{TiO}_2$  ratios ranging from 10 to 20.  
9 With the exception of one specimen with anomalously high  $\text{SiO}_2$ , this group is fairly homogeneous,  
10 with  $\text{CaO}\approx 10$  wt%,  $\text{MgO}\approx 8$  wt%,  $\text{Al}_2\text{O}_3\approx 15$  wt% and  $\text{Fe}_2\text{O}_3\approx 12$ -15 wt%. Despite low Silica contents,  
11 samples show the highest overall abundance of incompatible elements, with  $\Sigma$ REE=25-60 ppm and  
12  $\text{TiO}_2=0.7$ -1.3 wt%, consistent with derivation of their parent magma from a relatively fertile mantle  
13 source. Samples from this group have flat chondrite-normalized REE patterns (Appendix A2), exhibit  
14 a slight depletion in LILE and show little or no HFSE anomaly.

15 *Boninitic* lavas (N=5), in contrast, have markedly higher  $\text{SiO}_2$  content (50-53 wt%) and  $\text{Al}_2\text{O}_3/\text{TiO}_2$   
16 ratios (27-30) associated with low CaO (5 wt%) and high MgO (12 wt%) contents. This group has the  
17 lowest overall abundance of incompatible elements ( $\Sigma$ REE=20-30 ppm,  $\text{TiO}_2=0.5$  wt%), is markedly  
18 enriched in Cr (up to 800 ppm), and exhibits a concave upward trace element pattern with sub-  
19 chondritic  $(\text{Gd}/\text{Yb})_N$  and super-chondritic  $(\text{La}/\text{Sm})_N=1.5$ -1.9. Trace element patterns show pronounced  
20 negative Nb-Ta anomalies ( $(\text{Nb}/\text{Th})_N\approx 0.3$ ), and slight excesses of Zr compared to the adjacent REE.  
21 The major and trace element characteristics of this group are reminiscent of modern low-Ca  
22 boninites (Crawford et al., 1989), although only 2 out of 5 samples have  $\text{SiO}_2$  contents high enough to  
23 classify as *sensu stricto* boninites according to the IUGS nomenclature (Le Bas, 2000).

24 Intermediate between tholeiitic and boninitic lavas, the '*transitional*' group (N=5) is characterized by  
25  $\text{Al}_2\text{O}_3/\text{TiO}_2$  ratio typically ranging between 20 and 25, and  $\text{SiO}_2$  content between 48-50 wt%. Samples

1 from this group exhibit low Nb/Th and high Th/Yb ratios similar to the boninitic lavas, and their major  
2 element composition is essentially identical to the tholeiitic group, albeit with lower TiO<sub>2</sub> (and ΣREE)  
3 contents suggestive of a more refractory mantle source.

4 Lastly, a single specimen (IN12032), hereafter referred to as *enriched metabasalt*, is characterized by  
5 high SiO<sub>2</sub> (52 wt%), together with high REE content (ΣREE=52 ppm), and a marked enrichment in LILE  
6 ((Th/Yb)<sub>N</sub>=5.9). The sample displays negative Nb and Ti anomalies reminiscent of magmas from  
7 modern calc-alkaline series, although its FeO/MgO ratio of 1.6 does not place it unambiguously  
8 within the calc-alkaline field of the Miyashiro diagram. As will be discussed later (section 5), the  
9 major and trace element chemistry of this sample point either towards assimilation of a tonalitic  
10 contaminant at crustal level, or metasomatic enrichment of a depleted mantle source by tonalitic  
11 melts.

12 Overall, the geochemistry of Ukaliq amphibolites closely resembles that described for “metabasalts”  
13 in Nuvvuagittuq. Tholeiitic and transitional amphibolites from our outcrops would fall into what has  
14 been termed in the NSB as the “High-Ti” group, while the enriched and boninitic lavas are similar to  
15 the “enriched low-Ti” and “depleted low-Ti” groups, respectively (O’Neil et al., 2011). Ukaliq lavas,  
16 therefore, appear to bear some relation to the cummingtonite-amphibolites at Nuvvuagittuq. They  
17 nevertheless display less compositional heterogeneity, most likely reflecting a different alteration  
18 history, than their respective equivalents in the NSB. Specifically, the exposed lithologies show no  
19 evidence for secondary loss of Ca and Na (Fig. 2C), suggesting that the hydrothermal event proposed  
20 to have mobilized all but the most immobile elements in NSB mafic protoliths (Cates et al., 2013) did  
21 not affect the Ukaliq rocks. While our USB samples show local evidence for secondary silicification  
22 and metasomatism, they define coherent compositional fields, which we conclude are more likely  
23 than the highly altered NSB cummingtonite-amphibolites to reflect primary characteristics of their  
24 parent magmas.

25

### 1 **3.2. Chemical sediments (Quartzites and BIFs)**

2 Magnetite-bearing rocks of chemical sedimentary origin occur both on the Eastern side of the  
3 sequence, as a discontinuous Si-rich layer locally grading into cherty units, and on the Western side,  
4 as a nearly continuous 50 cm-1 m wide Fe-rich layer of probable BIF protolith interleaved with mafic  
5 rocks (Fig. 1). The specimen sampled on the Eastern side has high SiO<sub>2</sub> content (89 wt%) and low  
6 Fe<sub>2</sub>O<sub>3</sub> (8.5 wt%), with all other oxides below or equal to 1 wt%. BIFs sampled on the Western side  
7 have high Fe<sub>2</sub>O<sub>3</sub> contents (35-70 wt%), MgO=4-7 wt% and Al<sub>2</sub>O<sub>3</sub>=0.6-2 wt%. All samples display shale-  
8 normalized REE+Y patterns typical of Archean marine sediments, marked by a depletion of LREE  
9 compared to HREE, small positive Eu anomalies and elevated Y/Ho ratios (Fig. 3).

10

## 11 **4. Results**

12 <sup>146,147</sup>Sm-<sup>142,143</sup>Nd results for 21 amphibolites, 2 hornblendites, 1 pyroxenite, 14 granitoid gneisses  
13 and 11 chemical sediments of the Ukaliq belt and surrounding Innuksuac complex are summarized in  
14 Table 1 and Figure 4. Individual analyses for samples and standards, as well as analytical methods  
15 employed for <sup>147</sup>Sm-<sup>143</sup>Nd and <sup>142</sup>Nd analyses are provided in Appendix A3-4. Reproducibility of the  
16 JNdi standard during the course of this study was on average of ±3 ppm (2.S.D.) (Appendix A3).  
17 Variations of the <sup>142</sup>Nd/<sup>144</sup>Nd ratio, noted as μ<sup>142</sup>Nd, are expressed as relative deviations (in ppm)  
18 with regards to the JNdi standard. Variations of the <sup>143</sup>Nd/<sup>144</sup>Nd ratio are expressed using the  
19 conventional ε notation, after normalization to the CHUR value (Bouvier et al., 2008). Throughout the  
20 paper, <sup>146</sup>Sm-<sup>142</sup>Nd ages are calculated using an initial <sup>146</sup>Sm/<sup>144</sup>Sm ratio of 0.0082 and a half-life of  
21 103 Ma (Meissner et al., 1987; Marks et al., 2014). Alternative ages calculated using a half-life of 68  
22 Ma for <sup>146</sup>Sm (Kinoshita et al., 2012) are also provided in parenthesis, in which case the initial  
23 <sup>146</sup>Sm/<sup>144</sup>Sm ratio was adjusted to 0.0094. Unless stated otherwise, errors are provided as 2 S.D.

24

#### 1 **4.1. Amphibolites and ultramafic rocks**

2 As shown in Figure 4, each group of mafic/ultramafic rocks is characterized by a distinct and  
3 internally homogeneous  $^{142}\text{Nd}$  signature. Tholeiitic and ultramafic lavas have  $\mu^{142}\text{Nd}$  within error of  
4 the modern mantle value, at  $-1.3\pm 2.8$  ppm and  $-0.8\pm 0.4$  ppm, respectively. In contrast, the boninitic  
5 and transitional lavas exhibit similar negative effects at  $-4.1\pm 1.6$  ppm and  $-4.7\pm 2.8$  ppm. Lastly, the  
6 enriched amphibolite (IN12032) exhibits the lowest  $\mu^{142}\text{Nd}$  signature at  $-9.4\pm 3$  ppm. When plotted in  
7 a  $^{142}\text{Nd}/^{144}\text{Nd}$  vs Sm/Nd space (Fig. 5A), mafic rocks define a rough positive correlation which, if  
8 considered as an isochron relationship, yields an apparent emplacement age of  $4215_{-76}^{+50}$  Ma, (or  
9  $4321_{-50}^{+33}$  Ma using  $T_{1/2}=68$  Ma). This result is similar to that obtained from mafic samples of the NSB  
10 (O'Neil et al., 2008; Roth et al., 2013), confirming the close relationship between Ukaliq and  
11 Nuvvuagittuq.

12 The  $^{147}\text{Sm}$ - $^{143}\text{Nd}$  results obtained from Ukaliq lavas (Fig. 5B) show substantial excess scatter and,  
13 overall, provide an imprecise date of  $3903\pm 250$  Ma. Eliminating samples showing signs of secondary  
14 alteration, silicification or K-metasomatism results in a slightly older age estimate at  $3963\pm 250$  Ma.  
15 As for the  $^{146}\text{Sm}$ - $^{142}\text{Nd}$  array, the slope of the  $^{147}\text{Sm}$ - $^{143}\text{Nd}$  errorchron is largely controlled by the  
16 enriched amphibolite; disregarding this sample yields a younger age of  $3735\pm 320$  Ma that resembles  
17 U-Pb zircon geochronology for the oldest gneissic components of the NSB (Cates and Mojzsis, 2007).  
18 Regressions obtained by pooling together samples with identical  $\mu^{142}\text{Nd}$  yield imprecise but similar  
19 Eoarchean dates at  $3588\pm 410$  Ma (tholeiitic and ultramafics) and  $3677\pm 480$  Ma (transitional and  
20 boninitic). Hence, the  $^{147}\text{Sm}$ - $^{143}\text{Nd}$  systematics do not substantiate a Hadean emplacement age for  
21 Ukaliq lavas.

22

#### 23 **4.2. Plutonic rocks**

24 Tonalitic gneisses sampled in the vicinity of Ukaliq have zircon U-Pb ages ranging from 3.45 Ga to  
25 3.65 Ga, and  $^{147}\text{Sm}$ - $^{143}\text{Nd}$  model ages ( $T_{\text{dm}}$ ) ranging from 3.3 to 3.9 Ga. With the exception of IN12014,

1 all TTG gneisses have negative  $\epsilon^{143}\text{Nd}_i$  ranging from 0 to -3  $\epsilon$ -units, and all but one sample have  
2 negative  $\mu^{142}\text{Nd}$  averaging  $-5.6\pm 3.2$  ppm. On the other hand, Neoproterozoic granites have  $\mu^{142}\text{Nd}$  within  
3 error of the modern terrestrial value, despite negative  $\epsilon^{143}\text{Nd}_i$  indicative of a crustal precursor. These  
4 results confirm the presence of an inherited Hadean component in the Voisei suite, as previously  
5 reported by O'Neil et al. (2008) and Roth et al. (2013). This Hadean component, however, does not  
6 appear to have been involved in later magmatic events in the area.

7

### 8 *4.3. Rocks of chemical sedimentary origin*

9 New  $^{146,147}\text{Sm}$ - $^{142,143}\text{Nd}$  analyses for magnetite-bearing rocks of probable BIF protolith from the  
10 Nuvvuagittuq, Ukaliq and Isua supracrustal belts are summarized in Figure 4. Nuvvuagittuq BIFs  
11 define an imprecise date of  $2719\pm 610$  Ma, similar to a two-point isochron age, suggesting at least  
12 partial isotopic equilibration on a whole-rock scale during metamorphism associated with assembly  
13 of NESP terranes in the Neoproterozoic (Cates and Mojzsis, 2009). Disturbance of the  $^{147}\text{Sm}$ - $^{143}\text{Nd}$   
14 chronometer in NSB samples with low Nd contents is also evidenced by highly scattered model ages  
15 (Fig. 6) which prevents determination of a deposition age using this method. From another  
16 standpoint, four USB samples with markedly higher Nd contents yield homogeneous model ages at  
17 3.78-4.07 Ga, similar to the  $^{147}\text{Sm}$ - $^{143}\text{Nd}$  age derived from mafic/ultramafic samples. Despite variably  
18 disturbed  $^{147}\text{Sm}$ - $^{143}\text{Nd}$  systematics, all samples from Ukaliq and Nuvvuagittuq present identical  $\mu^{142}\text{Nd}$   
19 within errors of the terrestrial value, at  $-1.9\pm 2.1$  and  $-2.7\pm 1.3$  ppm, respectively. As shown in Figure  
20 5A, BIFs from Ukaliq and Nuvvuagittuq do not plot on the  $^{146}\text{Sm}$ - $^{142}\text{Nd}$  array defined by volcanic rocks.  
21 Their  $\mu^{142}\text{Nd}$  is constant, irrespective of their Sm/Nd ratio, and identical to that inferred for the  
22 Neoproterozoic ocean from our analyses of Isua BIFs ( $\mu^{142}\text{Nd} = -2.4\pm 3$  ppm). Thus, despite their  
23 stratigraphic relationships with mafic lavas carrying the  $^{142}\text{Nd}$  anomalies, chemical sediments in the  
24 Ukaliq/Nuvvuagittuq belts show no evidence for in situ decay of  $^{146}\text{Sm}$  that would be expected from a  
25 Hadean deposition age.

1

## 2 5. Discussion

### 3 5.1. Radiogenic vs. inherited $^{142}\text{Nd}$ anomalies

4 The apparent  $^{146}\text{Sm}$ - $^{142}\text{Nd}$  and  $^{147}\text{Sm}$ - $^{143}\text{Nd}$  ages derived from magmatic rocks of the USB, while  
5 somewhat less discordant than those obtained for Nuvvuagittuq, remain subject to the same  
6 ambiguities raised by previous investigations of the NSB. Since magmas derived from sources with  
7 different  $\mu^{142}\text{Nd}$  would also have distinct initial  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios, all  $^{147}\text{Sm}$ - $^{143}\text{Nd}$  ages obtained from  
8 Ukaliq and Nuvvuagittuq lavas are inherently problematic. Contamination of Eoarchean magmas by a  
9 Hadean enriched component would, in fact, generate mixing lines with positive slopes in both the  
10  $^{146}\text{Sm}$ - $^{142}\text{Nd}$  and  $^{147}\text{Sm}$ - $^{143}\text{Nd}$  isochron plots. Therefore, even the near-concordant Hadean dates  
11 derived from filtered subsets of mafic rocks by O'Neil et al. (2012) are ambiguous, consistent either  
12 with a Hadean emplacement age or the presence of an inherited component within younger lavas.  
13 The geochronological significance of any Sm-Nd results for these rocks is further obscured by the fact  
14 that the major and trace element variability observed in mafic lavas, and therefore most of the  
15 observed spread in Sm/Nd, is not primarily controlled by magmatic differentiation but most likely by  
16 source heterogeneities (Section 5.3). These observations preclude a straightforward age  
17 determination from either the  $^{146}\text{Sm}$ - $^{142}\text{Nd}$  or  $^{147}\text{Sm}$ - $^{143}\text{Nd}$  chronometers. Examination of the fine  
18 structure of the  $^{142,143}\text{Nd}$  signal, however, reveals several key features that consistently point towards  
19 an inherited origin for the negative anomalies in Ukaliq lavas. First,  $^{147}\text{Sm}$ - $^{143}\text{Nd}$  regressions obtained  
20 by pooling samples with identical  $^{142}\text{Nd}/^{144}\text{Nd}$  (and, arguably, identical initial  $^{143}\text{Nd}/^{144}\text{Nd}$ ), yield  
21 imprecise but clearly *younger* ages than that obtained from the  $^{146}\text{Sm}$ - $^{142}\text{Nd}$  array (Section 4.1.).  
22 Second, the presence of  $^{142}\text{Nd}$  anomalies appears to be mainly restricted to lavas with boninitic  
23 affinities, suggesting derivation from a metasomatically enriched mantle source (section 5.3.). In  
24 contrast, tholeiitic and ultramafic rocks have constant  $\mu^{142}\text{Nd}$  irrespective of their Sm/Nd ratio (Fig.  
25 5A). Lastly, our results on chemical sediments of the USB and NSB are difficult to reconcile with a

1 Hadean emplacement age. BIFs have low Sm/Nd ratios that reflect on the predominantly crustal  
2 origin of REE in seawater (e.g. Mloszewska et al., 2013), so that deposition before 4.1 Gyr ago is  
3 expected to have resulted in the production of significant  $^{142}\text{Nd}$  anomalies (typically -10 ppm for a  
4 4.25 Ga deposition age). The BIFs of the USB and NSB, however, show no statistically resolvable  
5 effect. Their  $\mu^{142}\text{Nd}$  is indistinguishable from the signature of Eoarchean seawater, as inferred from  
6 the Isua BIFs analyses. We conclude that this observation is inconsistent with deposition of BIF  
7 protoliths at a time when  $^{146}\text{Sm}$  was still extant.

8 The lack of  $^{142}\text{Nd}$  anomalies in chemical sediments of the Ukaliq/Nuvvuagittuq belts has profound  
9 implications for the geochronology of supracrustal enclaves in the Innuksuac complex. Chemical  
10 sediments in both belts are stratigraphically interleaved with mafic lavas carrying variable  $^{142}\text{Nd}$   
11 anomalies (Mloszewska et al., 2012; O'Neil et al., 2011). Further, field observations revealed no  
12 evidence for tectonic intercalation of the BIFs within the associated mafic/ultramafic sequences.  
13 Hence, the lack of unradiogenic effects despite low Sm/Nd ratios characterizing these lithologies  
14 cannot be explained by late sedimentation on a pre-existing Hadean mafic crust. While samples with  
15 low Nd content show evidence for late disturbance of the  $^{147}\text{Sm}$ - $^{143}\text{Nd}$  system, the Ukaliq BIFs with  
16 high Nd content yield Eoarchean model ages consistent with U-Pb zircon geochronology, and show  
17 no compelling evidence for isotopic resetting during Neoproterozoic metamorphism. Thus, while it is  
18 difficult to entirely disprove the possibility of open system behavior of the  $^{146}\text{Sm}$ - $^{142}\text{Nd}$  system in BIFs,  
19 we believe that the similarity between Isua, Ukaliq and Nuvvuagittuq samples is more than mere  
20 coincidence. The most plausible interpretation is that chemical sediments that are found interleaved  
21 within the Ukaliq/Nuvvuagittuq sequences deposited at a time when  $^{146}\text{Sm}$  was extinct, from an  
22 Eoarchean ocean isotopically identical to, or possibly slightly less radiogenic than the modern mantle.  
23 Given their stratigraphic relationship with the surrounding mafic lava flows, the lack of unradiogenic  
24 effects in BIFs strengthens the case for an inherited origin of the  $^{142}\text{Nd}$  anomalies in volcanic rocks of  
25 the Innuksuac complex.



1

## 2 *5.2. Age of the Hadean enriched reservoir*

3 Due to the short lifetime of  $^{146}\text{Sm}$ , the presence of  $^{142}\text{Nd}$  heterogeneities in Ukaliq/Nuvvuagittuq  
4 lavas constitutes straightforward evidence that Hadean material was involved in the genesis of the  
5 oldest components of the Innujuak domain. More quantitative age constraints cannot be derived  
6 from the slope of the  $^{146}\text{Sm}$ - $^{142}\text{Nd}$  array, as the latter reflects a mixture of Hadean and Eoarchean  
7 components and is therefore chronologically meaningless. Nevertheless, a model age of  
8 differentiation can be derived for the Hadean enriched precursor, using a combination of the  $^{146}\text{Sm}$ -  
9  $^{142}\text{Nd}$  and  $^{147}\text{Sm}$ - $^{143}\text{Nd}$  chronometers (e.g. Caro, 2011). Model age calculations using the coupled  
10  $^{146,147}\text{Sm}$ - $^{142,143}\text{Nd}$  system have the advantage of being solely based on the isotopic composition of the  
11 rocks and do not rely on their Sm/Nd ratios. Using a simple set of chronometric equations,  $^{146,147}\text{Sm}$ -  
12  $^{142,143}\text{Nd}$  systematics can provide a model age of differentiation ( $T_d$ ) and an estimate of the time-  
13 integrated  $^{147}\text{Sm}/^{144}\text{Nd}$  ratio of the reservoir in which the  $^{142}\text{Nd}$  anomaly was initially produced.

14 Following previous  $^{146,147}\text{Sm}$ - $^{142,143}\text{Nd}$  studies, we make the simplifying assumption that the Hadean  
15 reservoir carrying the  $^{142}\text{Nd}$  anomaly was generated at time  $T_d$  from an initially primitive mantle, and  
16 subsequently evolved as closed system until it was sampled in the Eoarchean, when  $^{146}\text{Sm}$  was no  
17 longer extant. We consider an eruption age of 3.75 Ga for Ukaliq lavas, as inferred from previous U-  
18 Pb zircon studies in the NSB (Augland and David, 2015; Cates and Mojzsis, 2007; Cates et al., 2013;  
19 David et al., 2006), and use the composition of IN12032 ( $\mu^{142}\text{Nd}=-9.8$  ppm and  $\varepsilon^{143}\text{Nd}_i=-2$ ) as the  
20 closest approximation of the Hadean component. With these input parameters, the model age of  
21 differentiation for the Ukaliq enriched source is estimated to be  $4.36_{-0.06}^{+0.05}$  Ga (or  $4.44_{-0.04}^{+0.03}$  Ga using a  
22 68 Ma half-life for  $^{146}\text{Sm}$ ). By comparison, the Isua mantle source is estimated to have differentiated  
23  $4.42_{-0.06}^{+0.05}$  Ga ago (Caro et al., 2006; Rizo et al 2011), which is only marginally older than the estimated  
24 age of crystallization of the lunar magma ocean, at  $4.39_{-0.014}^{+0.016}$  Ga (McLeod et al., 2014). As shown in  
25 Figure 7, a regression including the  $^{142,143}\text{Nd}$  data for Ukaliq and Isua supracrustal belts yields an age

1 of  $4.39_{-0.035}^{+0.04}$  Ga, which is similar to the model age derived from IN12032 and virtually identical to the  
2 estimated age of differentiation of the lunar mantle.

3 It is important to recognize that the chronological information derived from  $^{146,147}\text{Sm}$ - $^{142,143}\text{Nd}$   
4 systematics is a model age and, as such, depends on the compositional model assumed for the Bulk  
5 Silicate Earth (BSE). The ages provided above were calculated assuming that the BSE has a chondritic  
6 Sm/Nd ratio ( $^{147}\text{Sm}/^{144}\text{Nd}=0.1960$ , Bouvier et al., 2008) and a  $^{142}\text{Nd}/^{144}\text{Nd}$  ratio identical to that of the  
7 modern mantle (i.e.  $\mu^{142}\text{Nd}_{\text{BSE}}=0$ ). However, alternative models involving slightly superchondritic  
8 Sm/Nd compositions have been proposed based on the meteoritic  $^{142}\text{Nd}$  record (e.g. Boyet and  
9 Gannoun, 2013; Caro et al., 2008; Jackson and Jellinek, 2013; O'Neill and Palme, 2008; Qin et al.,  
10 2011; Caro, 2015). As shown in Figure 7B, a superchondritic Sm/Nd ratio for the BSE would tend to  
11 generate older model ages for the Isua depleted source, and younger ages for the Ukalik enriched  
12 source. Therefore, the apparent synchronous differentiation of Ukalik and Isua parent reservoirs  
13 remains, to a certain extent, model dependent. Solving this issue requires precise assessment of the  
14 role of nucleosynthetic vs. radiogenic processes in generating the chondritic  $^{142}\text{Nd}$  signal, which is  
15 analytically challenging due to the small magnitude of the measured anomalies. However, recent  
16 studies suggest that the offset between the terrestrial and chondritic  $^{142}\text{Nd}/^{144}\text{Nd}$  ratios may be  
17 entirely accounted for by nucleosynthetic processes (Fukai and Yokoyama, 2016; Burckhardt et al.,  
18 2016), in which case the chronological results shown in Figure 7 would apply. A single, large-scale  
19 differentiation event ca. 4.4 Gyr ago would then best account for the  $^{142,143}\text{Nd}$  signatures recorded in  
20 both the Ukalik/Nuvvuagittuq and Isua rocks.

21 The presence of positive  $^{142}\text{Nd}$  anomalies in the Eoarchean mantle is generally viewed as reflecting  
22 magma ocean crystallization in the aftermath of the Moon-forming giant impact (e.g. Caro, 2011;  
23 Caro et al., 2005; Debaille et al., 2013; Bennett et al., 2007; Boyet et al., 2003). This interpretation  
24 relies on the estimated age of differentiation, which fits independently derived constraints on the  
25 timescale of terrestrial accretion, as well as the apparent decoupling of the Lu-Hf and Sm-Nd systems

1 in the Isua mantle source; an expected outcome of Mg-perovskite crystallization in a deep magma  
2 ocean (Caro et al., 2005; Rizo et al., 2011). A synchronous differentiation of the Ukaliq and Isua  
3 sources would thus imply contamination of former's lavas by material derived from Earth's  
4 primordial crust, more than 600 Myr after solidification of the magma ocean. The emplacement of  
5 such long-lived, compositionally buoyant lithosphere has been theorized based on parameterized  
6 and numerical convection models (Korenaga, 2006; O'Neill et al., 2013; van Hunen and van den Berg,  
7 2008). Due to the sparsity of Hadean components in the geological record, however, its prior  
8 existence has proved difficult to substantiate. The chronological constraints derived from  $^{146,147}\text{Sm}$ -  
9  $^{142,143}\text{Nd}$  systematics suggest that Hadean plates stabilized early, and could be preserved from  
10 recycling for a period of time much longer than modern oceanic plates. From a geodynamic  
11 viewpoint, this would be consistent with a regime of either stagnant-lid (O'Neill and Debaille, 2014)  
12 or sluggish plate tectonics (Foley et al., 2014; Korenaga, 2006), but is seemingly at odds with the  
13 occurrence of global resurfacing events, or any mechanism involving rapid rejuvenation of the  
14 Hadean surface. Overall, our results suggest that hotter mantle temperatures in the Hadean induced  
15 a relatively quiescent tectonic regime, characterized by inefficient lithospheric recycling and a long  
16 crustal residence time. This quiescent regime, in turn, allowed remnants of Earth's primordial crust to  
17 contribute to the genesis of continental terranes in the Eoarchean.

18

### 19 *5.3. Composition of the Hadean enriched reservoir*

20 We now turn from the chronological to the petrogenetic implications of our results, focusing on the  
21 nature of the Hadean protolith. Of potential importance to this issue is the observation that  $\mu^{142}\text{Nd}$  in  
22 Ukaliq lavas show a high degree of covariation with Th/La (Fig. 8A), a trace element ratio usually  
23 exhibiting limited variability in mafic lithologies, with the notable exception of arc magmas (Plank,  
24 2005). As Th and La are both highly incompatible, they exhibit similar behavior during partial melting  
25 and only experience fractionation during crustal differentiation processes. As a result, the upper

1 crust is characterized by high Th/La (0.25-0.4), whereas MORBs and most OIBs have Th/La<0.1  
2 (Condie, 1993; Plank, 2005; Taylor and McLennan, 1985). Examination of the Th/La-Sm/La  
3 relationships of Figure 8B shows that tholeiitic lavas have low Th/La irrespective of their Sm/La, as  
4 observed in modern MORBs. In contrast, lavas exhibiting  $^{142}\text{Nd}$  anomalies show a trend of increasing  
5 Th/La with decreasing Sm/La, likely reflecting a mixing relationship between the prevalent Eoarchean  
6 mantle (or its melting products) and an enriched end-member similar to the average Archean crust.  
7 Thus, Ukaliq lavas must have inherited their  $^{142}\text{Nd}$  signature from a felsic contaminant, which would  
8 be consistent with the reworking of Hadean crustal material in the Innuksuac complex.

9 By 3.75 Gyr ago, a 4.36 Ga old felsic crust with  $^{147}\text{Sm}/^{144}\text{Nd}=0.08-0.12$  would have developed a  
10 negative  $\mu^{142}\text{Nd}$  of -20 to -30 ppm (Fig. 7A, model A). As shown in Figures 8A-9, assimilation of such  
11 unradiogenic material could readily explain the compositional range of Ukaliq amphibolites. Based on  
12 these relationships, the trace element composition of IN12032 can be consistently reproduced by ca.  
13 20 wt% assimilation of a TTG contaminant with  $\mu^{142}\text{Nd} = -20$  to -30 ppm (Fig. 9B-C). Hence, much of  
14 the compositional variability observed in Ukaliq lavas could be accounted for by crustal  
15 contamination. It is also well established that such mechanism can generate apparent  $^{147}\text{Sm}-^{143}\text{Nd}$   
16 dates (and, therefore,  $^{146}\text{Sm}-^{142}\text{Nd}$  dates) well in excess of true emplacement ages, as illustrated by  
17 several case studies of Archean mafic and ultramafic suites (Chauvel et al., 1985; Juteau et al., 1988).

18 The crustal assimilation model, however, faces several difficulties. First, despite the seemingly simple  
19 relationships of Figure 9, neither the boninitic nor the transitional lavas can be generated by crustal  
20 contamination starting from the most primitive tholeiitic composition. This is most evident for  
21 boninitic lavas, which exhibits Mg contents higher than tholeiitic lavas, as well as lower abundances  
22 of incompatible elements despite higher  $\text{SiO}_2$  contents. Second, the crustal assimilation model  
23 requires a contaminant with highly negative  $\mu^{142}\text{Nd}$ . Felsic plutonic rocks currently exposed in the  
24 vicinity of the Ukaliq belt, however, average  $-5.6\pm 3.2$  ppm and do not represent plausible  
25 contaminants, as is evident in a plot of Th/Yb vs.  $\mu^{142}\text{Nd}$  (Fig. 9B). Lastly, the negative  $^{142}\text{Nd}$  effects

1 observed in Voizel TTGs would imply that their parent magmas assimilated pre-existing Hadean felsic  
2 crust in proportions ranging from 15 to 25 wt%. The reworking of older continental crust into  
3 younger generations of granitoids is not uncommon, but in the present case appears difficult to  
4 reconcile with the striking absence of inherited Hadean zircons in these heavily contaminated rocks  
5 (David et al., 2006; Cates and Mojzsis, 2007).

6 An alternative scenario, more consistent with the above observations, is that Ukaliq lavas inherited  
7 their signature from an Eoarchean felsic component derived from a pre-existing Hadean mafic crust.  
8 In this case, the  $^{142,143}\text{Nd}$  signature of Ukaliq lavas would reflect that of the Hadean precursor, but  
9 their high Th/La values would represent a compositional characteristic of the felsic derivatives  
10 carrying the negative  $^{142}\text{Nd}$  effects. A mafic precursor would be generally consistent with the  
11 compositional constraints derived from coupled Sm-Nd systematics (Fig. 7A); using the  $^{142,143}\text{Nd}$   
12 signature of the most contaminated sample, the maximum  $(^{147}\text{Sm}/^{144}\text{Nd})_{\text{srce}}$  ratio of the Hadean  
13 source is estimated to be 0.17, which falls within the compositional range of mafic/ultramafic rocks  
14 (0.15-0.20) (Condie, 1993). As shown in Figure 8D, a 4.36 Ga old mafic crust with  $^{147}\text{Sm}/^{144}\text{Nd}=0.15-$   
15  $0.17$  would have developed by 3.75 Ga a  $\mu^{142}\text{Nd}$  of -10 to -15 ppm (model B), and its felsic derivatives  
16 would plot on the  $\mu^{142}\text{Nd}$ -Th/La array defined by Ukaliq lavas (model C, Fig 8C). This scenario would  
17 thus satisfy trace element constraints, which require a predominantly felsic contaminant, while  
18 circumventing the issues associated with the crustal assimilation model.

19 The scenarios mentioned above are expected to generate identical effects with regards to trace  
20 elements. However, they differ in that a Hadean mafic precursor (and its felsic derivatives (model C))  
21 would have less negative  $\mu^{142}\text{Nd}$  than a felsic crust of the same age (model A). Consequently, a  
22 crustal contamination scenario using model C as enriched end-member would require larger amount  
23 (>40 wt%) of assimilation to account for the signature of IN12032. The  $\mu^{142}\text{Nd}$ -Th/La systematics of  
24 Ukaliq rocks, alternatively, could result from metasomatic enrichment of a depleted or primitive  
25 mantle reservoir, prior to extraction of their parent magmas. The isotopic signature of Ukaliq lavas

1 would then require adding 2-10 wt% of a tonalitic contaminant with  $\mu^{142}\text{Nd}=-15$  ppm to a mantle  
2 with initially primitive abundances of REE.

3 A key observation in support of a metasomatically enriched mantle source is the widespread  
4 occurrence of lavas with boninitic affinities in the Nuvvuagittuq/Ukaliq belts. Boninites are  
5 subduction-related volcanic rocks characterized by high  $\text{SiO}_2$  (>52 wt%), high MgO (>8 wt%) and low  
6  $\text{TiO}_2$  (<0.5 wt%) contents (Crawford et al., 1989; Hickey and Frey, 1982). Their characteristic U-shaped  
7 REE patterns and overall low abundances of incompatible elements are taken to reflect addition of  
8 subduction fluids/melts to a highly refractory mantle, the formation of which is generally attributed  
9 to prior extraction of tholeiitic melts during asthenospheric uplift associated with trench retreat or  
10 back-arc spreading (König et al., 2010; Bedard, 1999; Hickey and Frey, 1982). The presence of lavas  
11 sharing the geochemical characteristics of modern boninite/tholeiite associations in the NSB has  
12 been emphasized in several previous studies (O'Neil et al., 2011; Turner et al., 2014), but the  
13 implication of this result for Sm-Nd systematics has received surprisingly little attention. Of central  
14 importance is the long recognized observation that most boninite suites define positive correlations  
15 in a  $^{143}\text{Nd}/^{144}\text{Nd}$  vs. Sm/Nd plot (Cameron et al., 1983; Hickey and Frey, 1982; König et al., 2010).  
16 These covariations arise from the fact that slab-derived components often contribute >50% of the  
17 LREE budget of modern boninites (Cameron et al., 1983; König et al., 2010). A consequence,  
18 illustrated in Figure 10C, is that while tholeiitic magmas in fore arcs or subduction-related ophiolites  
19 have  $\epsilon^{143}\text{Nd}$  similar to their coeval mantle, boninites, when present, have variable but always less  
20 radiogenic  $\epsilon^{143}\text{Nd}$  largely inherited from the subducting plate.

21 It is unclear whether the geochemical features illustrated in Figure 10 must imply the existence of  
22 modern-type subduction processes in the Eoarchean, or could have been generated in drip-like  
23 downwellings. Nevertheless, in the absence of plausible contaminants in the Innuksuac complex, the  
24 isotopic and geochemical characteristics of Ukaliq lavas point towards metasomatic enrichment of a  
25 variably depleted Eoarchean mantle as the most plausible scenario for explaining the Innuksuac

1  $^{146}\text{Sm}$ - $^{142}\text{Nd}$  array. This inherited signature, in turn, establishes a clear genetic relationship between  
2 the foundering of Earth's primordial crust and the emplacement of both plutonic and volcanic rocks  
3 in the Innuksuac complex.

4

## 5 **6. Conclusions**

6 An intense debate has surrounded the  $^{146}\text{Sm}$ - $^{142}\text{Nd}$  signature characterizing volcanic rocks of the  
7 Nuvvuagittuq supracrustal belt, following O'Neil et al.'s proposal to assign a Hadean emplacement  
8 age to the sequence. The highly altered nature of the mafic lithologies carrying the  $^{142}\text{Nd}$  anomalies,  
9 however, has been an obstacle to geochronological investigations in the NSB, and has led to  
10 diverging interpretations of their isotopic record. In this study, we investigated the  $^{146,147}\text{Sm}$ - $^{142,143}\text{Nd}$   
11 systematics of volcanic and sedimentary rocks from the Ukaliq supracrustal belt, a newly discovered  
12 volcano-sedimentary enclave of the Innuksuac complex. Mafic lavas of the USB lack evidence of the  
13 hydrothermal alteration that massively modified the chemistry of Nuvvuagittuq rocks and, overall,  
14 are in a better state of preservation. They nevertheless display a similar geochemical "flavor",  
15 characterized by the association of arc-type volcanic rocks with variably negative  $^{142}\text{Nd}$  anomalies.  
16 Despite a rough correlation between the  $^{142}\text{Nd}/^{144}\text{Nd}$  and Sm/Nd ratios, the fine structure of the  
17  $^{146}\text{Sm}$ - $^{142}\text{Nd}$  signal in Ukaliq rocks is inconsistent with a Hadean emplacement age.  $^{142}\text{Nd}$  anomalies  
18 are primarily carried by boninitic lavas, likely signaling metasomatic enrichment at mantle depth,  
19 whereas the associated tholeiitic and ultramafic rocks have normal  $^{142}\text{Nd}/^{144}\text{Nd}$  regardless of their  
20 Sm/Nd ratio. More importantly, chemical sediments interleaved in the Nuvvuagittuq and Ukaliq  
21 sequences lack the negative anomalies that, given their low Sm/Nd ratio, would be expected had  
22 these sediments deposited in the Hadean.

23 Coupled  $^{146,147}\text{Sm}$ - $^{142,143}\text{Nd}$  chronometry indicates that the Ukaliq/Nuvvuagittuq Hadean source was  
24 extracted from the mantle ca. 4.4 Gyr ago, possibly as a result of magma ocean crystallization, and  
25 had a predominantly mafic composition. We propose that foundering of this primordial crust after a

1 long period of quiescence at the surface produced felsic melts and/or fluids carrying unradiogenic  
2  $^{142,143}\text{Nd}$  which imprinted the overlying mantle with a chemically and isotopically enriched signature.  
3 Metasomatically triggered melting of this modified mantle then generated a variety of boninitic and  
4 tholeiitic magmas, the combination of which resulted in the  $^{146}\text{Sm}$ - $^{142}\text{Nd}$  pseudo-isochrons observed  
5 in Ukaliq and Nuvvuagittuq lavas. Beyond their chronological implications, our results provide clear  
6 observational evidence for the emplacement of a long-lived lithosphere following solidification of the  
7 terrestrial magma ocean. This observation suggests that hotter internal temperatures did not impede  
8 the stabilization of Hadean plates. Rather, they reduced the efficiency of lithospheric recycling and  
9 favored a more sluggish tectonic style in the post-magma ocean Earth.

10

11

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## Figure Captions

**Figure 1: (A)** Geographical location and geological map of the southern part of the Ukaliq Supracrustal belt showing the main lithological units and sampling sites. GPS coordinates for samples analyzed in this study are provided in the electronic supplement. **(B)** Lithological sections and magnetic susceptibility profiles across the Ukalik belt.

**Figure 2:**  $\text{Al}_2\text{O}_3/\text{TiO}_2$  vs selected major and trace element in mafic lavas of the Ukaliq and Nuvvuagittuq Supracrustal Belts. Data for the Ukaliq belt are available in electronic supplement. Nuvvuagittuq data are compiled from the literature (Cates and Mojzsis, 2007; Cates et al., 2013; O'Neil et al., 2011, 2008, 2007).

**Figure 3:** Shale-normalized REE+Y patterns for Ukaliq and Nuvvuagittuq BIFs analyzed in this study. PAAS: Post-Archean Australian Shale.

**Figure 4:** Summary of  $^{142}\text{Nd}$  results for volcanic rocks, plutonic rocks and chemical sediments analyzed in this study. Errors for individual analyses (or individual samples) are given as 2 S.E. Grey fields represent 2 S.D. errors on averages obtained for each lithologic type or location.

**Figure 5: (A)**  $^{146}\text{Sm}$ - $^{142}\text{Nd}$  results for volcanic and sedimentary rocks of the Ukaliq and Nuvvuagittuq belts, plotted in a conventional isochron diagram. The grey field represents the 2.S.D error envelope

1 for the regression on mafic lavas (Sample IN14002 is excluded from regression). **(B)**  $^{147}\text{Sm}$ - $^{143}\text{Nd}$   
2 errorchron obtained on volcanic rocks of the Ukaliq belt. Both regressions are calculated using  
3 Isoplot (Ludwig, 1991).

4

5 **Figure 6:** Depleted Mantle model ages ( $T_{\text{DM}}$ ) for BIFs of the Ukaliq and Nuvvuagittuq belts. Note that  
6 most samples show a trend of decreasing model ages with decreasing Nd content, consistent with  
7 open system behavior during late metamorphic events. Samples with high Nd abundances from the  
8 Ukaliq belt define a narrower age range, consistent with closed-system behavior since 3.8-4 Ga.

9

10 **Figure 7: (A)** Coupled  $^{146,147}\text{Sm}$ - $^{142,143}\text{Nd}$  systematics for magmatic rocks of the Ukaliq belt and  
11 surrounding TTGs of the Voizel suite. The  $^{142,143}\text{Nd}$  systematics of Isua supracrustal belt (3.7-3.8 Ga;  
12 Caro et al. (2006)) are shown for comparison. The dashed curves represent loci of constant  
13  $(^{147}\text{Sm}/^{144}\text{Nd})_{\text{source}}$  ratios, ranging from 0.13 to 0.24, in the Hadean source. Solid lines are loci of  
14 constant model ages, ranging from 4.1 Ga to 4.567 Ga. The thick black line represents a linear  
15 regression including Isua and Ukaliq data. **(B)** Dependence of the calculated model ages for Isua and  
16 Ukaliq sources on the BSE Sm/Nd ratio. All ages are calculated using a half-life of 103 Ma for  $^{146}\text{Sm}$ .  
17 Ages calculated using a half-life of 68 Ma are provided in the text.

18

19 **Figure 8: (A)**  $\mu^{142}\text{Nd}$  vs. Th/La in amphibolites of the Ukaliq belt. The grey field represents the 2 S.D.  
20 error envelope for the linear regression obtained from mafic lavas (one datapoint excluded from  
21 regression). The pink curve represents a mixing relationship between the most primitive tholeiitic  
22 composition and a crustal end-member with  $\mu^{142}\text{Nd} = -30$  ppm and a Th/La ratio of 0.26,  
23 corresponding to the average Archean crust (Condie, 1993; Taylor and McLennan, 1985). Numbers in  
24 italic represent the mass fraction of assimilated felsic crust. **(B)** Th/La versus Sm/La in Ukaliq mafic

1 lavas. The compositional fields for modern MORBS and OIBs (Plank, 2005), as well as the Archean and  
2 modern upper continental crust (Condie, 1993; Taylor and McLennan, 1985) are shown for  
3 comparison. A linear regression through boninitic and enriched lavas intersects the average  
4 composition of the Archean crust, suggesting that the carrier of the negative  $^{142}\text{Nd}$  anomalies was a  
5 LREE-enriched felsic component. **(C)** Location of the possible enriched end-members in a  $\mu^{142}\text{Nd}$ -  
6  $\varepsilon^{143}\text{Nd}$  plot. Model A shows the expected composition of 4.36 Ga old felsic crust with  
7  $^{147}\text{Sm}/^{144}\text{Nd}=0.08-0.12$  (Condie, 1993; Taylor and McLennan, 1985). Model B represents the  
8 composition of a 4.36 Ga mafic crust with  $^{147}\text{Sm}/^{144}\text{Nd}=0.15-0.17$ . **(D)** Location of proposed Hadean  
9 end-members in a  $\mu^{142}\text{Nd}$  vs Th/La diagram. Model C shows the expected composition of felsic  
10 products derived from a 4.36 Ga mafic crust, after extinction of  $^{146}\text{Sm}$ .

11

12 **Figure 9: (A)** Th/Yb vs Nb/Th, **(B)**  $\mu^{142}\text{Nd}$  vs Th/Yb and **(C)**  $\mu^{142}\text{Nd}$  vs  $\text{SiO}_2$  in mafic lithologies of the  
13 Ukaliq belt. The solid pink curves represent mixing relationships between the most primitive tholeiitic  
14 composition and a crustal component defined by the average our analyses of Voizel TTGs. The grey  
15 fields in panel (B) and (C) represent the compositional range for tholeiitic magmas contaminated by a  
16 4.36 Ga tonalitic crust with  $\mu^{142}\text{Nd}$  ranging from -20 ppm (upper dashed curve) to -30 ppm (lower  
17 dashed curve). Numbers in *italic* represent the mass fraction of assimilated felsic material.

18

19 **Figure 10:** Trace element and isotopic systematics of boninites and tholeiitic basalts in the Marianna  
20 fore-arc **(A-C)**, compared to those of the boninitic and tholeiitic groups in the Ukaliq belt **(C-D)**. Data  
21 for the Marianna fore arc lavas are from Reagan et al. (2010). Similar relationships were also  
22 reported from several boninite suites worldwide (Cameron et al., 1983; Hickey and Frey, 1982; König  
23 et al., 2010).

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**Appendix A: Supplementary material**

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A1: GPS coordinates and major and trace element data for samples analyzed in this study (Tables SM1-4).

A2: Major and trace element plots for mafic lithologies of the Ukalik belt (Figures SM1-2).

A3: Analytical methods for  $^{147}\text{Sm}$ - $^{143}\text{Nd}$  and  $^{142}\text{Nd}$  analyses

A4:  $^{142}\text{Nd}$  analyses for samples and standards (Tables SM6-7)

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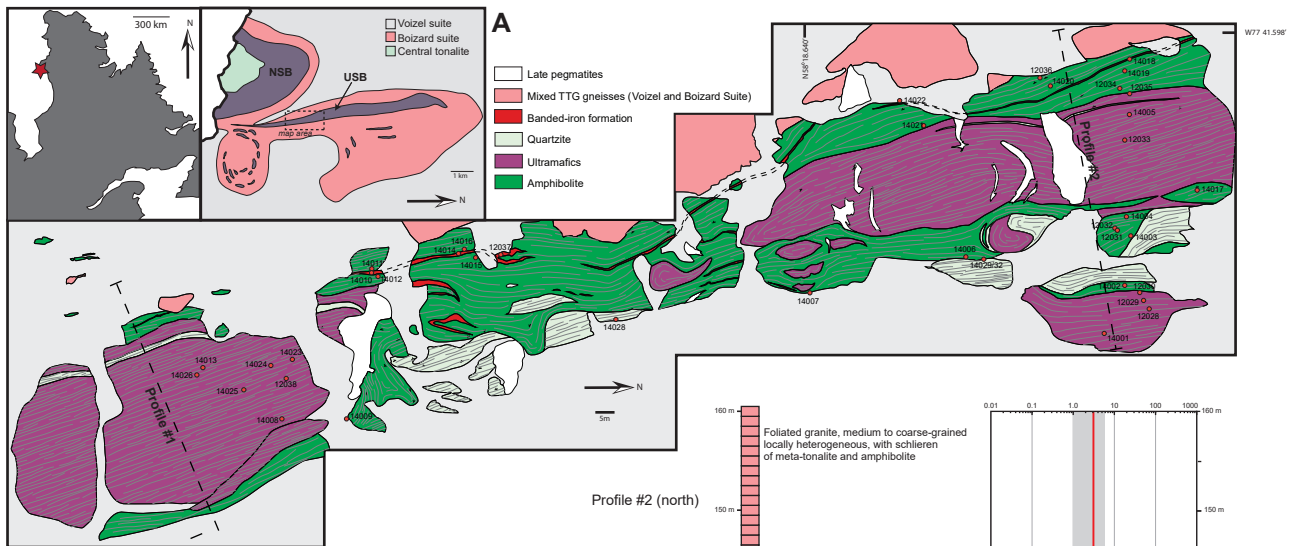
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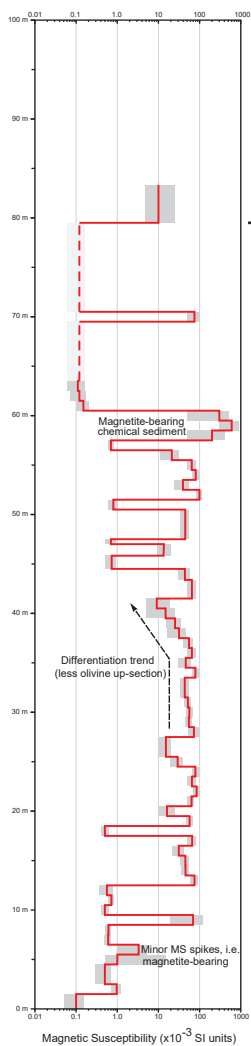
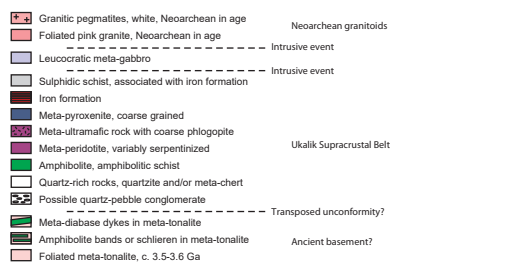


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**B**



Profile #1 (south)

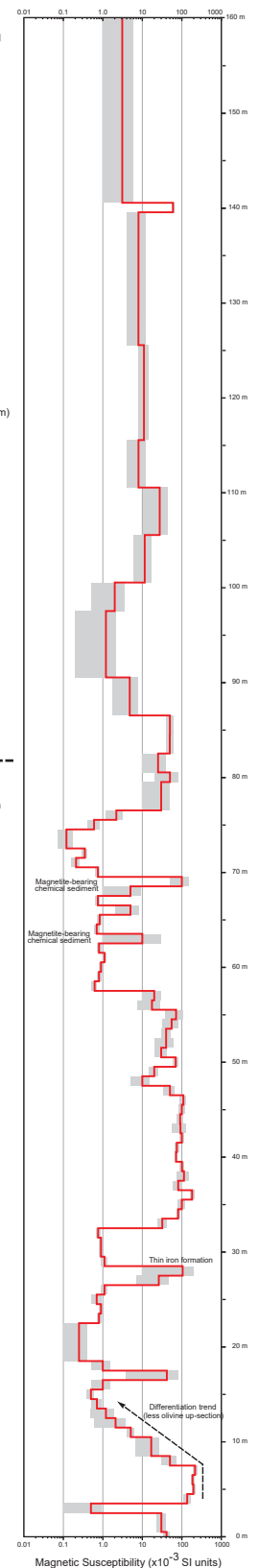


FIGURE 2

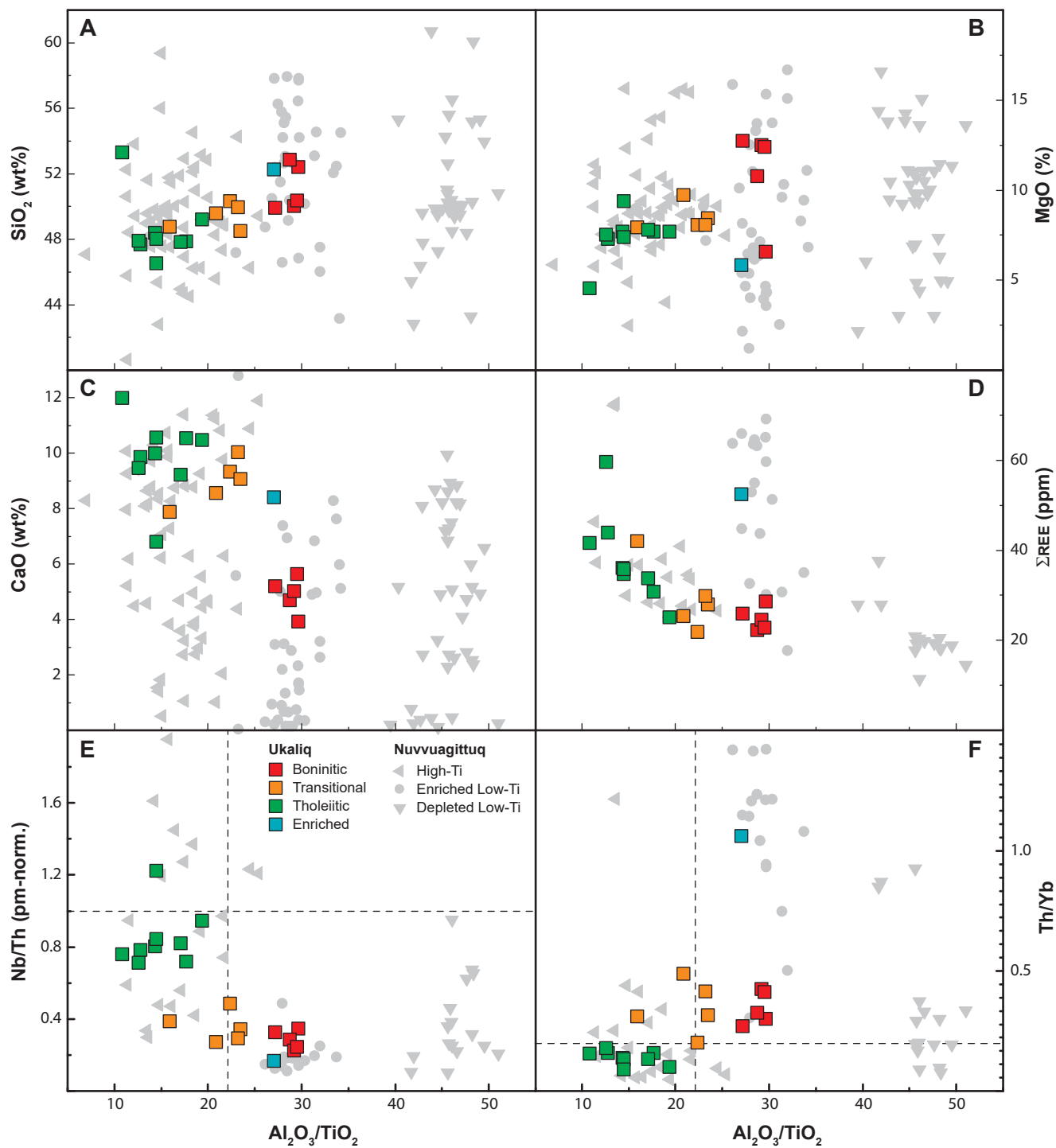


FIGURE 3

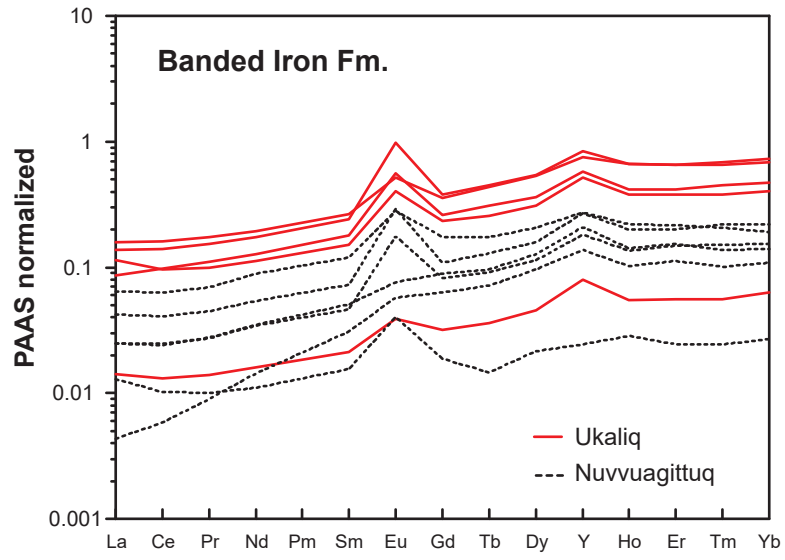


FIGURE 4

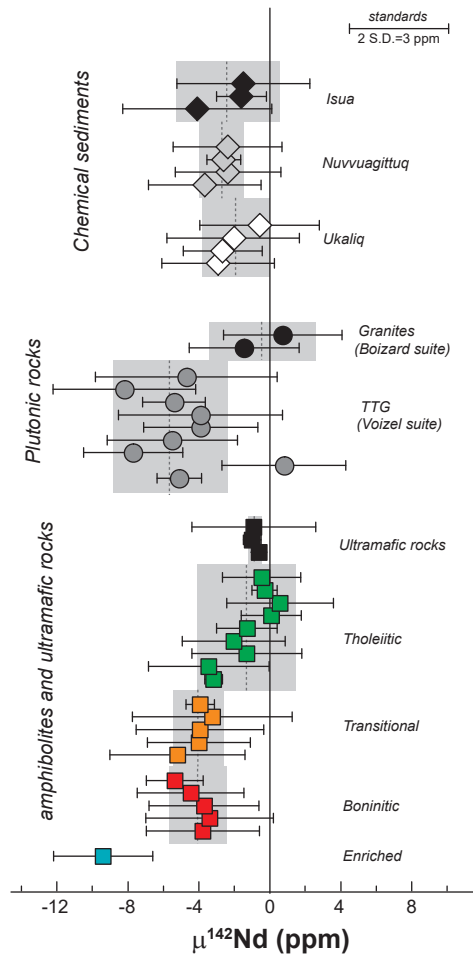


FIGURE 5

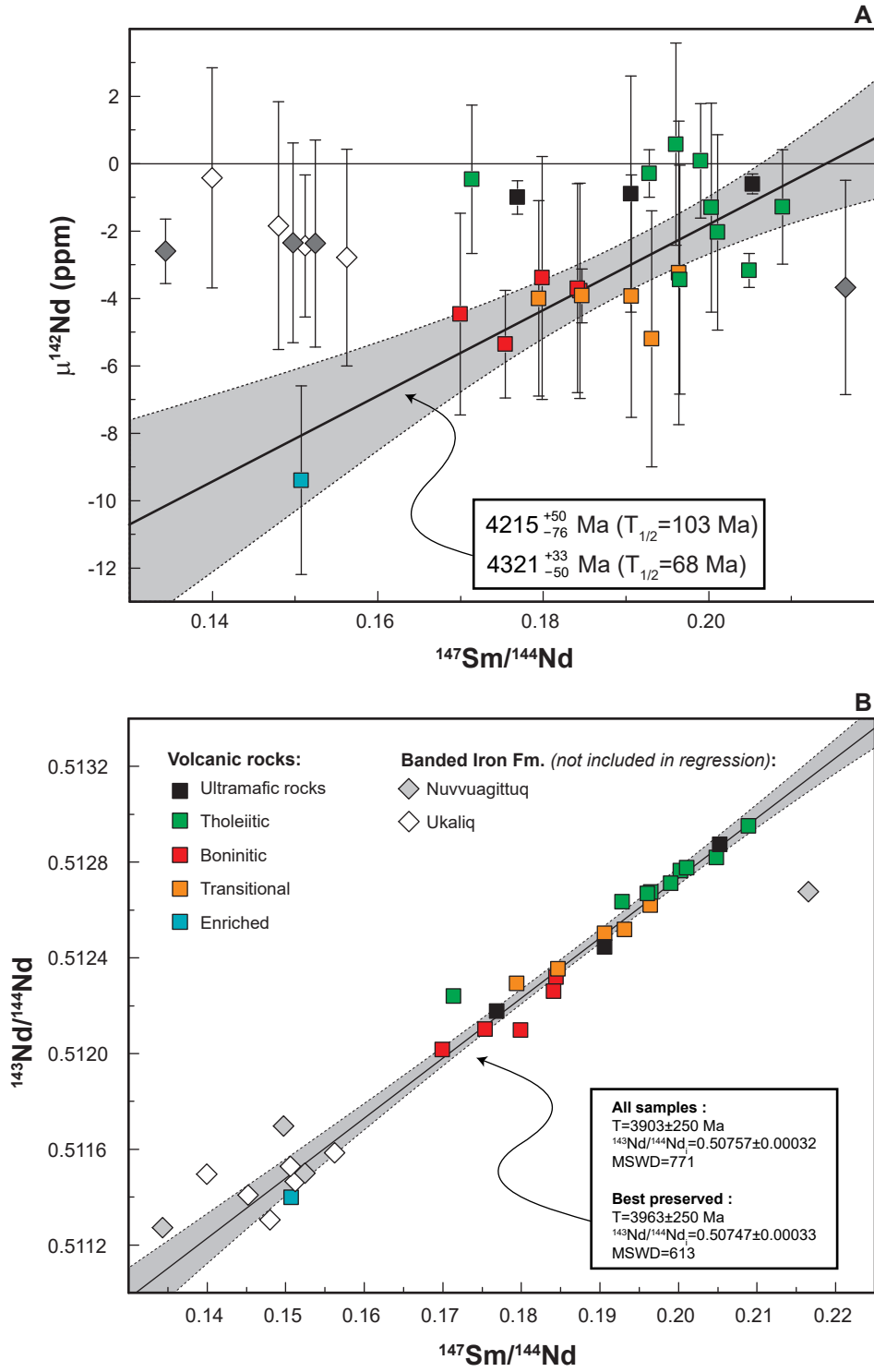


FIGURE 6

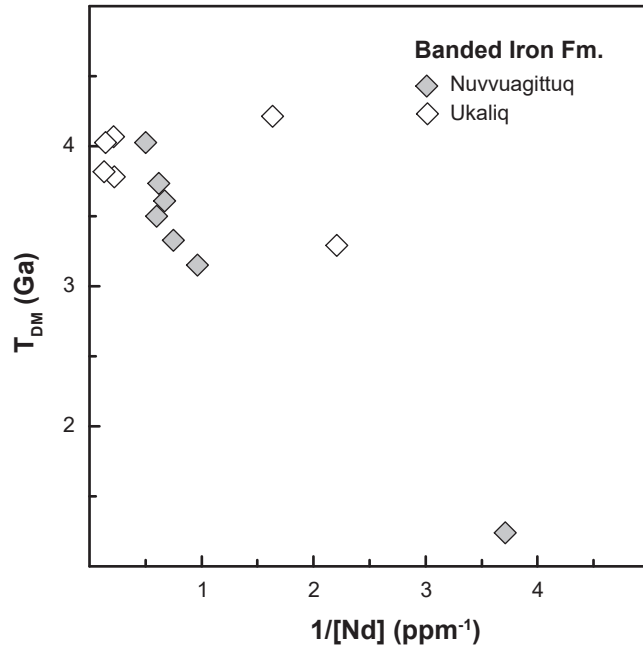




FIGURE 7

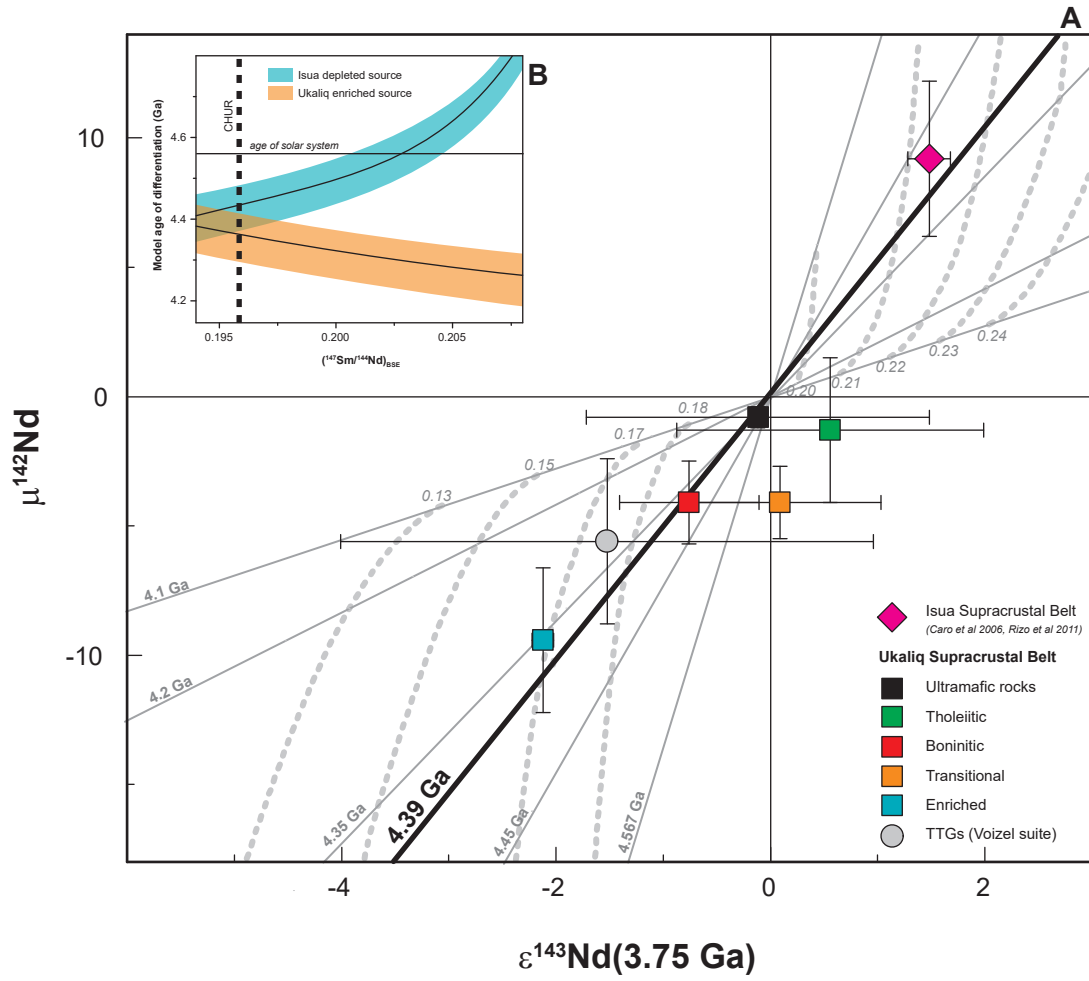


FIGURE 8

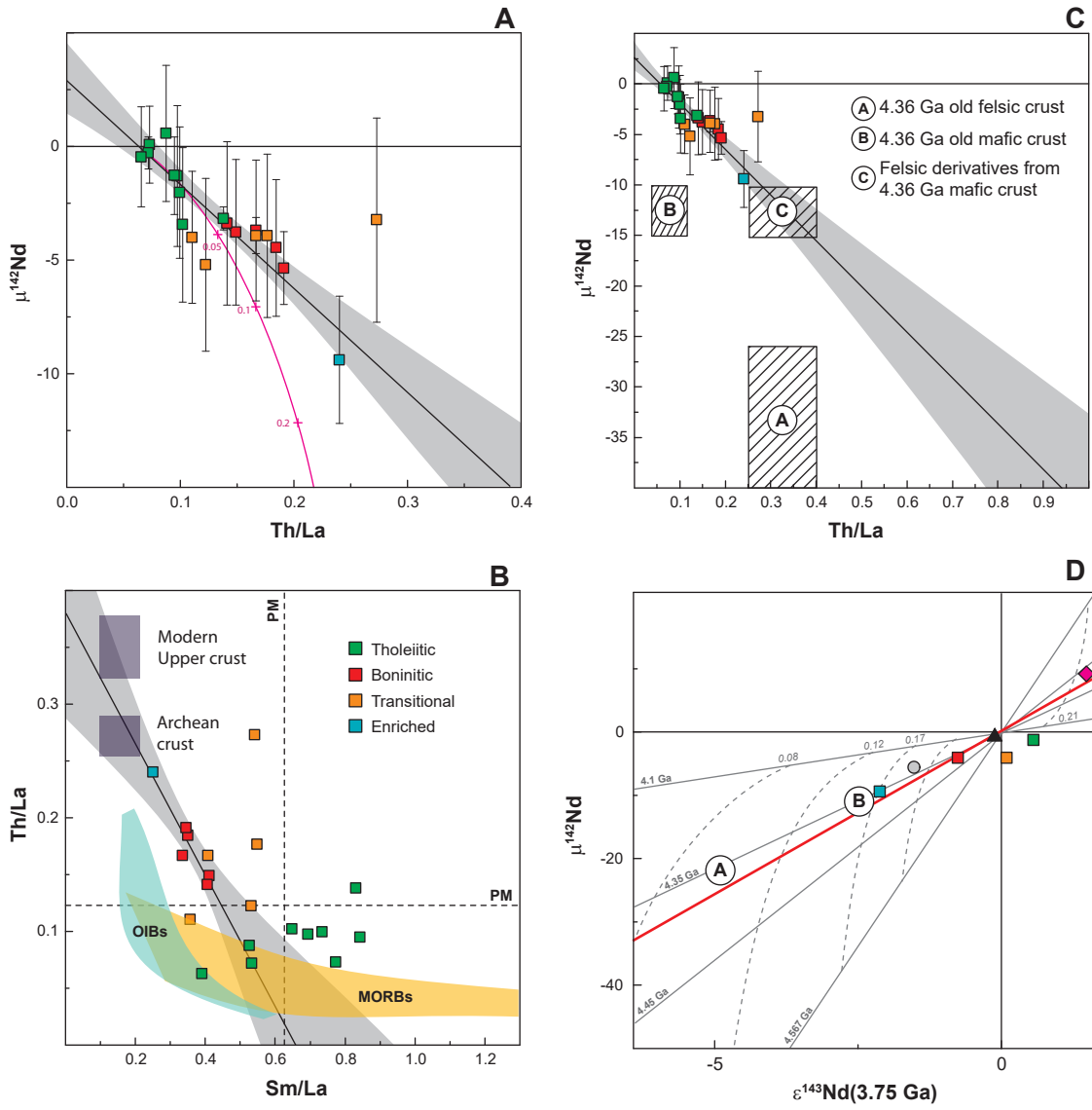


FIGURE 9

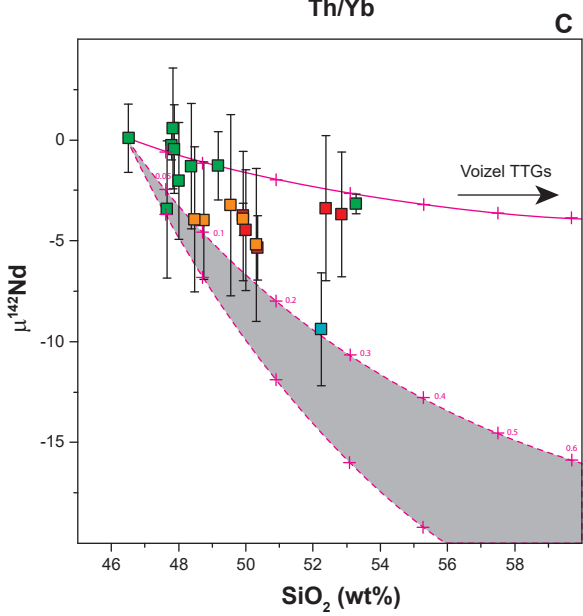
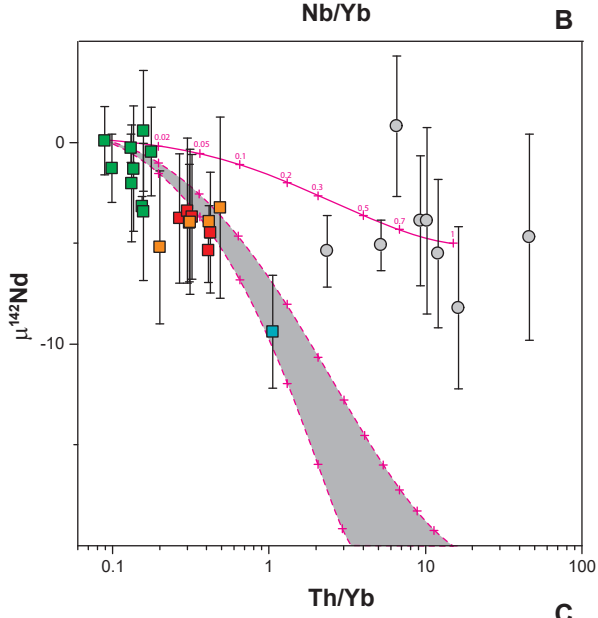
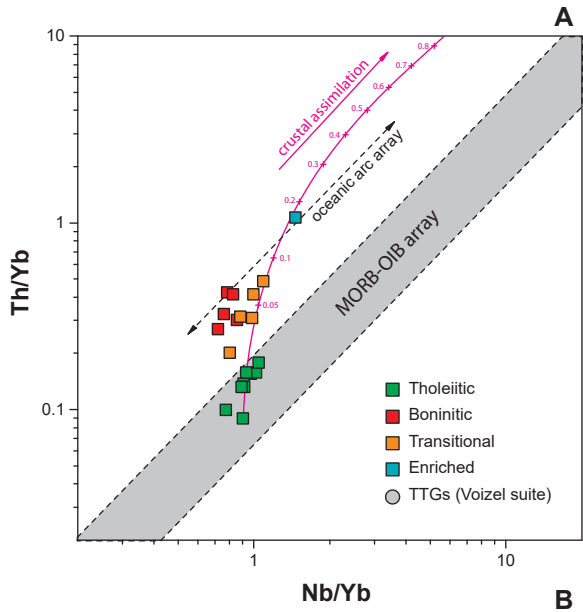


FIGURE 10

