Neodymium-142 Evidence for Hadean Mafic Crust

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Neodymium-142 data for rocks from the Nuvvuagittuq greenstone belt in northern Quebec, Canada, show that some rock types have lower 142Nd/144Nd ratios than the terrestrial standard (ε142Nd = −0.07 to −0.15). Within a mafic amphibolite unit, 142Nd/144Nd ratios correlate positively with Sm/Nd ratios and produce a 146Sm/142Nd isochron with an age of 4280 ± 53 million years. These rocks thus sample incompatible-element-enriched material formed shortly after Earth formation and may represent the oldest preserved crustal section on Earth.

The short-lived 146Sm–142Nd isotopic system [half life (T1/2) = 103 million years (Myr)] has proven useful for investigating the early differentiation of the silicate portion of Earth. Recent measurements of the 146Sm–142Nd system in Eoarchean (4.0 to 3.6 Ga) rocks, primarily from Greenland, show excesses in 142Nd/144Nd ratios of 10 to 20 parts per million (ppm) compared to modern terrestrial standards testifying to Earth differentiation events within a few tens of million years of Earth formation (3–7). The high 142Nd/144Nd measured

for these rocks indicate that the Eoarchean crustal rocks were sourced in a mantle with high Sm/Nd ratio. We describe evidence from the Nuvvuagittuq greenstone belt that a complimentary, low Sm/Nd ratio, reservoir is also found in the terrestrial rock record and that these rocks may be the oldest yet discovered on Earth.

The recent discovery of the Nuvvuagittuq greenstone belt in Ungava, Québec, provides a new suite of Eoarchean rocks with which to further our understanding of the early crust-mantle system. The Nuvvuagittuq belt exposes volcanic and metasedimentary rocks in an isochron synform refolded into a more open south-plunging synform (Fig. 1) (8) and is surrounded by a 3.66-billion-

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year (Gy) tonalite (9, 10). Geochronological constraints for the belt come mainly from rare felsic bands (0.5 to 1 m in width) composed of plagioclase, biotite, and quartz that have yielded a discordant zircon age of 3817 ± 16 My (9). A minimum age of 3750 My has also been obtained from U-Pb ion microprobe analyses of zircons. A minimum age of 3750 My has also been obtained from U-Pb ion microprobe analyses of zircons found in a similar lithology (11). Although no clear crosscutting relationship has been found, the felsic bands are commonly found within gabbroic sills that may suggest an intrusive nature for these rocks. A minimum age of 3750 My has also been obtained from U-Pb ion microprobe analyses of zircons. The dominant lithology of the belt is a cummingtonite-amphibolite referred to as “faux-amphibolite” because of its unusual mineralogical composition in which the dominant amphibole is cummingtonite, in contrast to the hornblende-dominated amphibolites usually found in the Superior Province. The faux-amphibolite is composed of variable amounts of cummingtonite, plagioclase, biotite, and quartz plus or minus garnet (8), commonly with compositional layering defined by the alternation of biotite-rich and cummingtonite-rich lamina-tions. These rocks are very heterogeneous and can be almost entirely composed of cummingtonite, giving them a light gray color, whereas some are reddish brown in color and mainly consist of biotite and garnet, with minor amounts of cummingtonite.

The faux-amphibolite is intruded in the western limb of the synform by ultramafic and gabbroic sills. Compared with these relatively undeformed gabbros, two larger gabbroic sills toward the center of the belt display pronounced gneissic textures, suggesting that they may be older than the less-deformed gabbroic sills. The faux-amphibolite in the western limb rarely contains garnet, whereas toward the center of the belt it has abundant garnet and commonly higher Al2O3 contents (8). The faux-amphibolite was originally interpreted to be a paragneiss (10) because of the abundance of garnet and compositional layering. These rocks, however, are more mafic than typical Archean shales and have a basaltic major element composition similar to those of the gabbroic sills but with lower CaO, slightly lower TiO2, and commonly higher Al2O3 contents. These features suggested that they could be highly altered mafic pyroclastites comagmatic with the gabbro sills (8). The faux-amphibolite, however, is enriched in light rare earth elements (LREEs), which argues against a direct cognetic relationship with the gabbros that intrude it, all of which have flat REE patterns (table S1).

Seven samples of the faux-amphibolite yielded low 143Sm/144Nd ratios (0.143 to 0.179) with correspondingly low measured 142Nd/144Nd (ε142Nd from −27.4 to −9.7, where ε143Nd = ([143Nd/144Nd]sample/[143Nd/144Nd]CHUR − 1) × 104 and CHUR is chondritic uniform reservoir) and 142Nd/144Nd ratios (ε142Nd = −0.07 to −0.15, where ε142Nd = ([142Nd/144Nd]sample/[142Nd/144Nd]standard) − 1) × 104 relative to the terrestrial standard [Fig. 2, table S2, and supporting online material (SOM) text]. Two tona-
Sm/Nd ratios as low as those measured in the faux-amphibolite and felsic bands would not produce 142Nd/144Nd ratios outside of measurement uncertainty from the terrestrial standard if this parent/daughter fractionation occurred later than \(-4.1\) to \(4.2\) Ga. Thus, even if the faux-amphibolite has crystallization ages of 3.8 Gy, the steepness of the 142Nd/144Nd-Sm/Nd co-variation requires that they sample a LREE-enriched material that is at least 4.28 Gy old. This LREE-enriched component could be either older crust that contaminated parental melts like the gabbrros or a LREE-enriched mantle source that melted to produce the faux-amphibolite. Regardless of the nature of the LREE-enriched component, its low Sm/Nd ratio must have formed while 146Sm was still extant, and the 4.28-Gy-old isochron provides the best indication of the age of this end member.

An alternate interpretation is that the 4.28-Gy-old isochron indeed dates the formation age of the faux-amphibolite, but this possibility is not supported by the 3.8-Gy-old 147Sm-143Nd age of this unit. For an isochron that passes through the terrestrial mantle point, however, a reduction in Sm/Nd ratio of the faux-amphibolite with the lowest Sm/Nd ratios by only 4.4% caused by metamorphism at 3.8 Ga would rotate a 145Sm-143Nd isochron of 4.28 Gy to 3.8 Gy. Increasing the Sm/Nd ratio of the low–Sm/Nd ratio faux-amphibolite by 4.4% would increase the 146Sm-142Nd isochron age by only 25 My, well within the uncertainty of the data, illustrating the potential of the 146Sm-142Nd system to see through later metamorphic events.

Obviously, other corroborative data would help resolve whether the 4.28-Gy age dates the rocks themselves or an older component involved in their genesis. In spite of attempts to do so, zircons have not yet been found in the faux-amphibolite. Whole-rock Pb isotope data for the faux-amphibolite (table S1) do not define a valid isochron. The best fit line through the 206Pb/204Pb–207Pb/204Pb data corresponds to an age of 2.4 ± 0.4 Gy, indicative of a late disturbance of the U-Pb system at the whole-rock scale. The faux-amphibolite is crosscut by the gabbro sills and therefore must be older than the gabbrros. Although the undeformed gabbrros give a 147Sm-143Nd isochron age of 3.84 Gy (Fig. 4A), an isochron constructed from nine samples of the more gneissic, presumably older, gabbrros gives an age of 4023 ± 110 My (MSWD = 0.78) with initial ε143Nd = +1.7 (Fig. 4B). All samples of the faux-amphibolite, except PC-129, yield negative ε143Nd(3.8 Gy) values ranging from −3.2 to −1.0, compared with the mostly positive ε143Nd(3.8 Ga) (−0.2 to +3.1) for the gabbro and ultramafic sills (table S2). When the ε143Nd values for the faux-amphibolite, except PC-129, are calculated for an age of 4.28 Gy, they range from −0.3 to +2.3 with an average value of 0.6. This average initial ε143Nd value is consistent with the mantle value at 4.28 Ga predicted by various depleted mantle evolution models (5, 15, 16), but

**Fig. 2.** The 142Nd/144Nd ratios for the Nuvvuagittuq rocks normalized to the La Jolla standard. Gray solid bar corresponds to the external (6 ppm) error obtained on the terrestrial standard. Error bars for individual samples correspond to either the 2σ-mean internal precision of the mass spectrometer analysis or the 2σ-mean of repeat analysis of the sample on the same mass spectrometer filament load. Solid circle indicates ultramafic sill; open circles, gabbro; diamonds, faux-amphibolite (alternating open and solid diamonds show data for replicate analyses of single samples); squares, tonalite; and triangles (alternating open and solid triangles show data for replicate analyses of single samples), felsic band.

**Fig. 3.** 142Nd/144Nd versus 147Sm/144Nd isochron diagram. Symbols as described for Fig. 2. Only the average value of replicate analyses is plotted on this figure. The horizontal gray band shows the ±6 ppm external precision obtained on the terrestrial standard. Error bars on individual samples correspond to either the 2σ-mean of multiple analyses or the 2σ-mean of the individual mass spectrometer run for samples run only once. The best fit line through the faux-amphibolite and gabbro data corresponding to an age of 4.28 Ga is shown, as are 3.8- and 4.0-Gy isochrons for reference. The gray circle shows the average value measured for ordinary and enstatite chondrites (12).
perhaps not as depleted as suggested by the Greenland data (7, 17, 19). As a result, the calculated $^{143}$Nd-depleted-mantle model ages ($T_{DM}$) for the faux-amphibolite, except PC-129, range from 4.1 to 4.4 Ga, consistent with the age suggested by $^{142}$Nd systematics and in contrast to the 3.2 to 3.6 Ga $T_{DM}$ values of the gabbros and sample PC-129 (table S2).

Whether or not the faux-amphibolite is 4.28 Gy old, its compositional characteristics may provide clues to the process of crust formation in the Hadean (~4.0 Ga). The basaltic major and compatible (e.g., Ni) trace element composition of the faux-amphibolite is consistent with derivation from a peridotitic mantle. Compared to the gabbros and to modern mid-ocean ridge basalts, the most unusual compositional characteristic of the faux-amphibolite is its low Ca content, high K and Rb contents, and LREE enrichment. Because elements like K and Rb are easily affected by alteration, however, it is unclear whether these are magmatic features of the faux-amphibolite. The LREE enrichment could reflect relatively low degrees of mantle melting, but this explanation is not supported by the relatively low concentration of elements such as Ti and Nb in the faux-amphibolite. The high LREE to Nb ratios of the faux amphibolite, however, is similar to that of modern calc-alkaline melts produced in convergent settings. Whether or not the faux-amphibolite is 4.28 Gy old, its compositional characteristics may provide clues to the process of crust formation in the Hadean (~4.0 Ga).

References and Notes

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Supporting Online Material

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Materials and Methods

Table S1 to S6
Fig. S1 and S2
References

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Infants’ Persuasive Search Errors Are Induced by Pragmatic Misinterpretation

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Having repeatedly retrieved an object from a location, human infants tend to search the same place even when they observe the object being hidden at another location. This persuasive search error is usually explained by infants’ inability to inhibit a previously rewarded search response or to recall the new location. We show that the tendency to commit this error is substantially reduced (from 81 to 41%) when the object is hidden in front of 10-month-old infants without the experimenter using the communicative cues that normally accompany object hiding in this task. We suggest that this improvement is due to an interpretive bias that normally helps infants learn from demonstrations but misleads them in the context of a hiding game. Our finding provides an alternative theoretical perspective on the nature of infants’ persuasive search errors.

Human infants’ abilities for understanding the physical world are often tested in hide-and-search tasks. First demonstrated by Piaget (1), the persuasive search error (sometimes called the A-not-B error) is a well-known and robust mistake that infants close to 1 year of age normally commit. In the standard A-not-B task, a demonstrator repeatedly places an object