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Nd isotopic evidence for transient, highly depleted mantle reservoirs in the early history of the Earth

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ABSTRACT

3870 Ma to 3760 Ma metadiorites and tonalites, and older mafic inclusions contained within these rocks from southern West Greenland, have a range of initial ϵ_{Nd} values from +4.5 to -4.5. The extremely positive initial values determined for nine of the fourteen early Archean samples demonstrate that they were derived from a LREE depleted mantle reservoir which had an ϵ_{Nd} value of $\approx +4$ prior to 3800 Ma. These rocks provide the best constrained evidence for the existence of highly LREE fractionated mantle reservoirs in the early Earth. In contrast, previous studies of younger 3700 and 3730 Ma tonalites from the same region show that the latter have lower initial ϵ_{Nd} values ranging from -4.6 to +2.0. The highest initial ϵ_{Nd} values determined for 3450 Ma komatiites from western Australia and southern Africa are +2 to +4, and for worldwide ca. 2700 Ma greenstone belts are +2 to +5. These values are well below the values for $\epsilon_{Nd}(3450 \text{ Ma}) (> +8)$ and $\epsilon_{Nd}(2700 \text{ Ma}) (> +15)$ that would be expected for the continued evolution of a highly depleted reservoir with Sm/Nd similar to that which produced the ca. 3.8 Ga Greenland metadiorites and tonalites. Thus, if the source region for the oldest Greenland gneisses was the prevalent upper mantle composition, it must have been an ephemeral feature later modified either by mixing with less-depleted mantle or with recycled LREE enriched, negative ϵ_{Nd} crust. The generation of highly positive ϵ_{Nd} values by 3.8 Ga requires differentiation of an extremely LREE fractionated reservoir very early in Earth's history. The Archean Nd isotope data may record the isolation, depletion by crustal extraction and subsequent partial rehomogenization of *limited* portions of the upper mantle, or alternatively may reflect transient large-scale differentiation processes unrelated to crustal extraction such as might occur in a terrestrial magma ocean.

1. Introduction

Initial Nd isotopic compositions determined for Archean rocks provide some of the strongest constraints on the processes of chemical evolution in the early Earth. Several lines of evidence argue that the bulk Earth has abundances of Sm and Nd and initial $^{143}\text{Nd}/^{144}\text{Nd}$ isotopic composition equal to that of chondritic meteorites [e.g., 1] and can thus be expected to have evolved along a chondritic evolution line. However, measurements of early Archean gneisses (3.4–4.0 Ga) with initial $^{143}\text{Nd}/^{144}\text{Nd}$ ratios which are substantially higher than chondritic compositions (positive epsilon Nd values) are increasingly common [e.g., 2,3,4]. As a consequence of the long half-life of the parent ^{147}Sm isotope (106 b.y.), long-term fractionation of Sm from Nd with the formation of LREE enriched (low Sm/Nd) regions and

complementary LREE depleted (high Sm/Nd) regions, as compared to the chondritic Sm/Nd ratio, is necessary to generate significant deviations in $^{143}\text{Nd}/^{144}\text{Nd}$ isotopic compositions from chondritic evolution. For early Archean rocks this requires chemical differentiation of their source regions very early in Earth's history. Although it is now generally agreed that LREE enriched and depleted chemical domains existed, the processes responsible for the formation, maintenance and destruction of different chemical reservoirs within the early Earth remain elusive. Suggested mechanisms for early Earth differentiation include extraction of the oldest felsic continental crust [e.g., 5,2,6,7], formation and protracted 'storage' of mafic and/or ultramafic crust [e.g., 8–11] and differentiation of a terrestrial magma ocean [e.g., 12, and papers therein].

This paper presents new Nd isotopic data from

carefully selected and precisely dated ≥ 3730 Ma rocks from West Greenland which document the existence of a strongly LREE depleted mantle reservoir in the early Archean. We use these new data combined with Nd isotopic data from the literature for other time periods to place constraints on the age of the highly depleted reservoir and its duration, and to re-evaluate models for fractionation in the early Earth.

The Greenland area, the focus of this paper, is the most extensive, best exposed and best studied of the early Archean terranes. The lithostratigraphic units of this region are summarized in Table 1. The early Archean complex in West Greenland consists of the quartzofeldspathic *Amîtsoq gneisses*, which were originally distinguished from other gneisses in the region because they contain abundant, locally discordant, tabular bodies of homogeneous amphibolite derived from a swarm of basic dykes, called the *Ameralik dykes* [13,14]. Scattered throughout the *Amîtsoq gneisses* are bodies (normally < 1 km wide) of diverse early Archean metabasic and sedimentary rocks. Apart from the largest body of all, the *Isua supracrustal belt*, these are known collectively as the *Akilia (supracrustal) association* [15] (Fig. 1).

The *Amîtsoq gneisses* display considerable diversity, and consist of TTG (tonalite, trond-

hjemite, granodiorite, diorite) suites, granites and quartz-monzonites. Conventional bulk U-Pb zircon and whole rock Sm-Nd and Rb-Sr geochemistry on the least reworked *Amîtsoq gneisses* in the Isukasia area, and reconnaissance SHRIMP U-Pb zircon geochronology on *Amîtsoq gneisses* south of Ameralik fjord, indicate that the protoliths of the *Amîtsoq gneisses* have an age range of 200 Ma or more [16,17], suggesting they could be the products of several unrelated events. This has recently been confirmed by extensive SHRIMP U-Pb geochronology [18]. A primary objective of this study is to empirically define mantle Nd compositions in the early Archean. Therefore, in recognition of the complexities of early Archean terranes we emphasize Nd data from a limited number of well-characterized samples.

2. Determination of precise initial $^{143}\text{Nd}/^{144}\text{Nd}$ ratios using U-Pb zircon age constraints

In many cases in the literature the initial ϵ_{Nd} values for Archean rocks have been determined from multisample suites by regression of whole-rock data to produce an isochron and an initial $^{143}\text{Nd}/^{144}\text{Nd}$ ratio. The problem with this approach is that it is generally difficult within

TABLE 1

Summary of early Archean lithostratigraphic units of the Nuuk district and SHRIMP zircon geochronological results. The chosen source references are not the first places where the lithostratigraphic names appeared in print, but where they are first discussed in publications readily available to the general reader. SHRIMP zircon results have been rounded to the nearest 5 Ma and are the unpublished data of Nutman, apart from ^a Kinny [17] and ^b Compston et al. [36]. This table is based on age determinations of more than thirty samples

Lithostratigraphic unit	Source	Description	SHRIMP ages (Ma)
<i>Orthogneisses</i>			
<i>Amîtsoq gneisses</i>	[14]	Any orthogneiss cut by abundant metabasic dykes known as the Ameralik dykes. The <i>Amîtsoq gneisses</i> include several groups of unrelated rocks. Most are tonalitic or granodioritic in composition, but granites, diorites and quartz monzonites also occur.	3870, 3820 ^a , 3810, 3760, 3730, 3700, 3650, 3625, 3510, 3380
<i>Supracrustal and mafic rocks</i>			
<i>Isua supracrustal belt</i>	[55,56]	A 35 km long belt which disappears under the inland ice at Isukasia. It consists of basic, intermediate and felsic metavolcanic rocks, banded iron formations and cherts, with associated gabbros and ultramafic rocks.	3805 ^b , 3700
<i>Akilia association</i>	[15]	All bodies of supracrustal rocks, metagabbros and ultramafic rocks, apart from the <i>Isua supracrustal belt</i> , that are intruded by components of the <i>Amîtsoq gneisses</i>	≥ 3870 , ≥ 3760 , 3650–3625

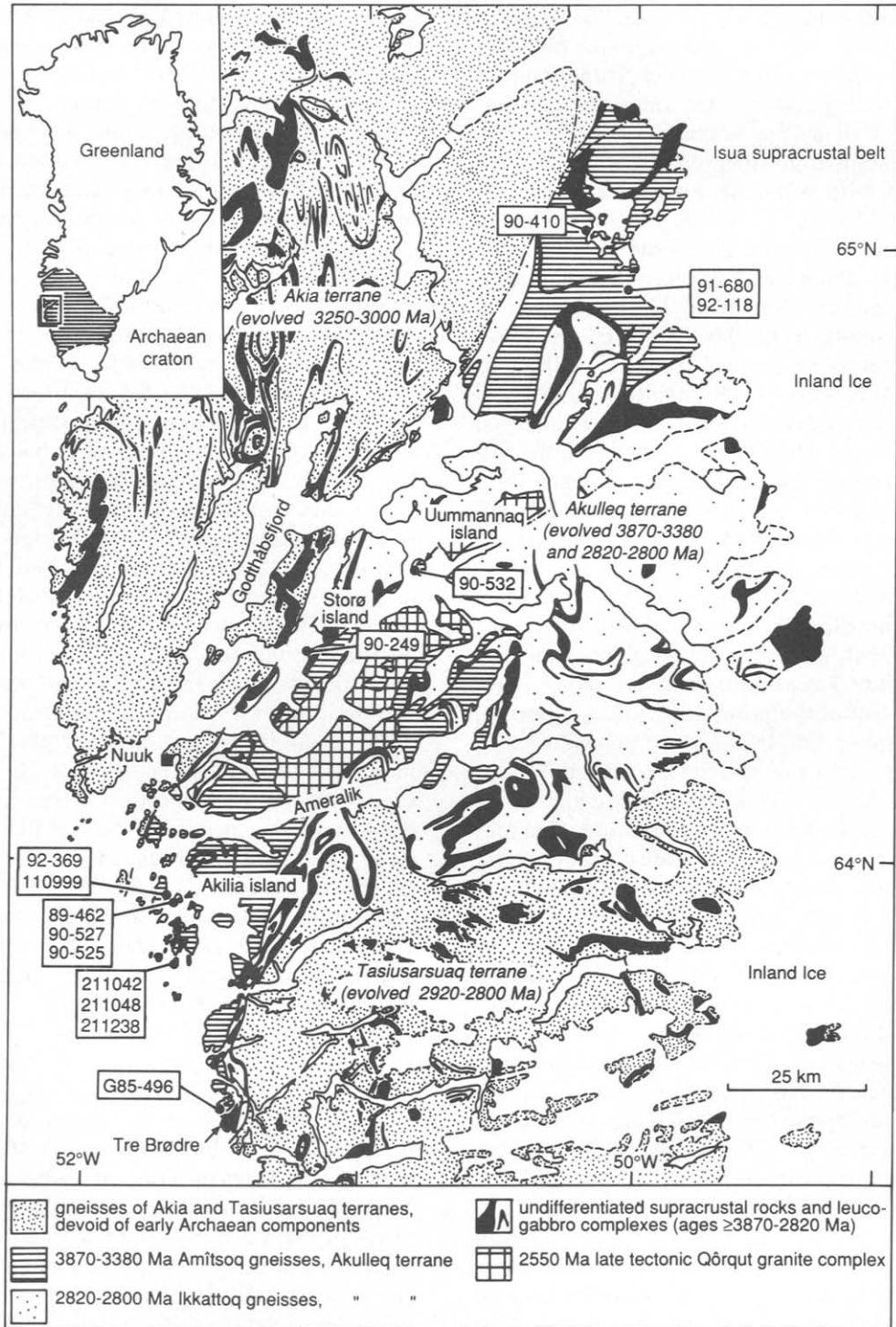


Fig. 1. Simplified geological map of southwest Greenland showing sample localities. Summary of terrane amalgamation in the late Archean is given by McGregor et al. [59].

Archean terranes to demonstrate that samples are consanguineous, owing to complex field relationships, often limited exposure, and the need to include a wide range of rock types to obtain a sufficient spread in Sm/Nd ratios. If the samples are not consanguineous, the data may be too scattered to fit a true isochron, or will form a mixing line (apparent isochron) for which the age and initial ratio will have no geological significance [e.g., 19,20]. To avoid the difficulties of assessing the age of the gneiss samples from the Sm-Nd data alone, we have included only samples with ages constrained by U-Pb within-grain dating of zircons using the SHRIMP ion microprobe. Zircon U-Pb characteristics, in addition to providing the precise (uncertainties ≤ 10 m.y.) crystallization age of the sample, were also used as indicators of possible disturbance of the Nd isotopic system. During high grade metamorphism, partial melt patches or metamorphic segregations can develop in the gneisses, causing small-scale fractionation of Sm and Nd. If the sample is not sufficiently large, this small-scale fractionation can lead to measurement of a Sm/Nd ratio that is biased by local fractionation incurred during reworking, and therefore is not representative of the protolith. By the proportion of 'new' zircons and overgrowths encountered in each sample and the severity of ancient Pb-loss events, the degree of reworking during high grade tectonothermal events may be assessed. Gneisses whose zircon systematics indicate that they have been severely reworked, or represent migmatites derived from two igneous protoliths were not used for the whole-rock Nd isotopic study. In order to provide an indication of this 'sample filter', concordia plots for three samples are presented in Fig. 2. Gneiss sample 90-527 (kindly provided by V.R. McGregor) is a migmatite, and has a complex zircon population, with ancient Pb-loss superimposed on ~ 3760 and ~ 3700 Ma igneous components. Due to this complexity, Nd results from this sample are not presented here. Sample G85-496, with an age of 3760 ± 6 Ma, has undergone ancient Pb-loss and some zircon growth at 3660–3650 Ma (Fig. 2b). This sample is from a homogeneous unit and definitely derived from a single igneous protolith. This is one of the most 'disturbed' samples that has been used for our Nd isotopic study. Sample 90-410 is a homo-

geneous dioritic gneiss with a protolith age of 3811 ± 4 Ma, which shows no younger zircon growth, and only limited ancient Pb loss (Fig. 2c). This is one of the most 'pristine' samples used for our Nd isotopic study. By filtering our samples in this way, we have tried to ensure that the calculated initial Nd isotopic ratios are representative of the protolith and are not modified as a result of Sm-Nd fractionation processes occurring a significant time after the protolith formed.

Dating of Archean mafic rocks is notoriously difficult, with good 'isochrons' (with a large spread in Sm/Nd values) often turning out to be mixing lines of no geological significance. Perhaps the best documented case of this is the Kambalda greenstones, whose Sm-Nd isochron age is 500 Ma too old [19]. These chronological problems call into doubt the accuracy of initial ϵ_{Nd} values for many suites of Archean mafic rocks, and hence their reliability as accurate indicators of mantle chemical evolution. Mafic rocks metamorphosed under granulite or amphibolite facies conditions commonly contain zircons. However, detailed SHRIMP studies of zircons from Akilia association mafic rocks [e.g., 21,22] indicate that these zircons rarely reflect the true protolith age, but have grown during subsequent metamorphism or are inherited from wallrocks. Therefore, in most cases zircon geochronology cannot be used with any confidence to derive *direct* protolith ages for *metamorphosed* mafic rocks. Instead we have undertaken SHRIMP zircon geochronology on the *oldest* orthogneisses intruding the mafic rocks used in the Nd isotopic studies. The accurate zircon ages derived from these samples thus provide a confident minimum age for the mafic rocks themselves.

2.1 Analytical techniques

Fresh, interior parts (> 1 kg) of the same samples as used for U-Pb zircon studies were broken and coarsely crushed using a hydraulic press. The crushed sample was split and then finely powdered using either a tungsten carbide swing mill, or in the case of the mafic samples, an agate swing mill. The final powders were carefully split to minimize bias due to powder heterogeneity. Aliquots of ca. 200 mg were spiked with a mixed $^{147}\text{Sm}/^{150}\text{Nd}$ spike, and dissolved using

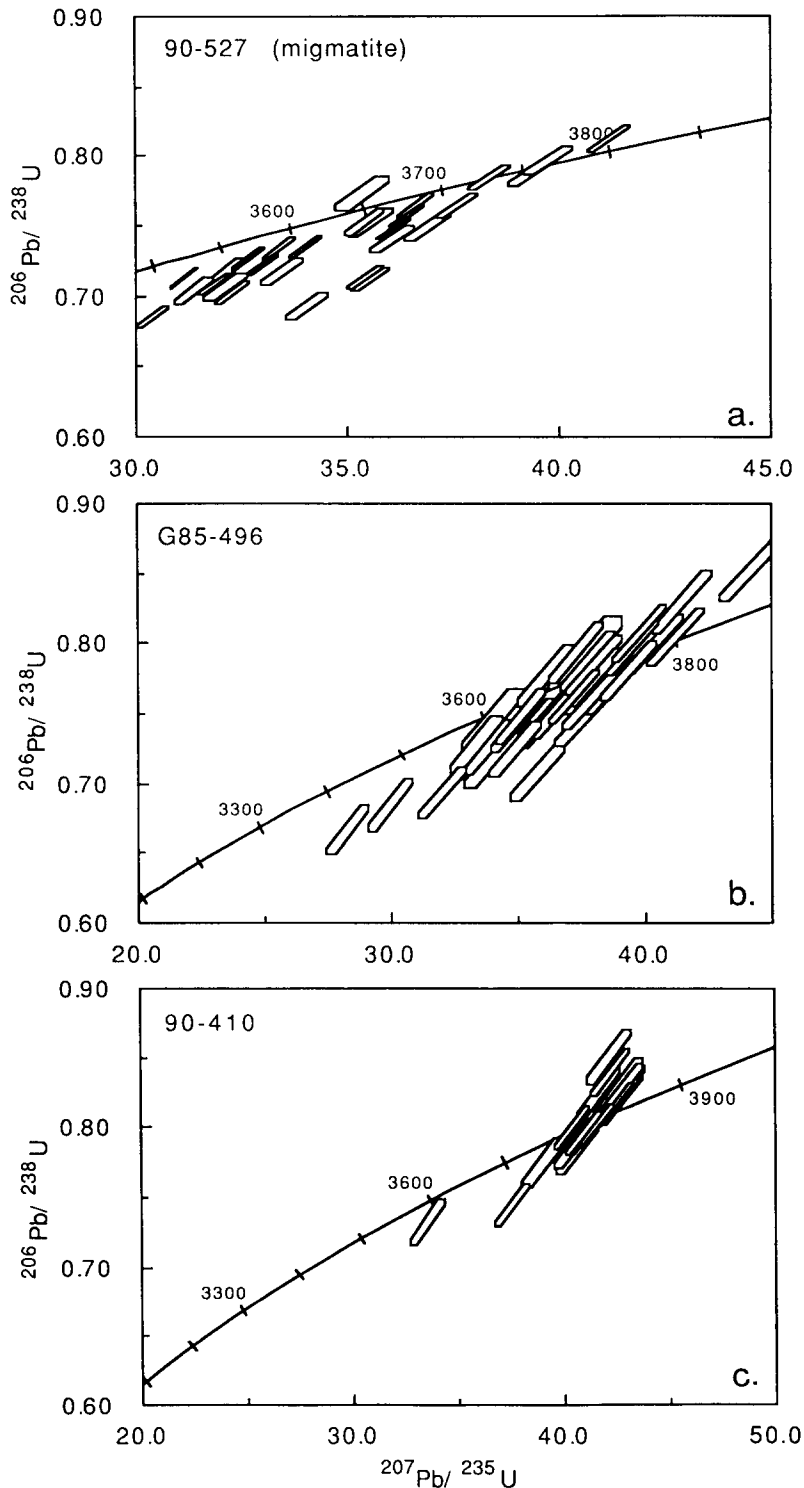


Fig. 2. Examples of zircon U-Pb concordia diagrams. (a) Amitsoq gneiss sample exhibiting a complex zircon population with ancient Pb-loss superimposed on ≈ 3760 Ma and ≈ 3700 Ma igneous components. Owing to this complexity, this sample was *not* used for the Nd isotopic studies. (b) Sample G85-496 with an age of 3760 ± 6 Ma. Some new zircon growth at 3660-3650 Ma is evident. (c) Sample 90-410 with an age of 3811 ± 4 Ma has a very simple zircon population with no younger zircon growth.

TABLE 2

Sm and Nd data for early Archean rocks

Sample	T (Ma)	Nd(ppm)	Sm(ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	$f_{(\text{Sm}/\text{Nd})}$	$^{143}\text{Nd}/^{144}\text{Nd}(0)$	$\epsilon_{\text{Nd}}(T)$	T_{DM} (Ma)
Amîtsoq gneisses								
89-462	3872 ±10	15.551	3.472	0.1350	-0.3139	0.511095 ±9	+0.3	3980
110999 ¹	3822 ±10	13.07	2.500	0.1157	-0.4120	0.510593 ±8	+0.1	3970
90-410	3812 ±4	43.100	8.533	0.1197	-0.3917	0.510920 ±8	+4.0	3620
"	"	47.395	8.876	0.1132	-0.4245	0.510782 ±10	+4.5	3590
"	"	58.888	11.626	0.1193	-0.3934	0.510922 ±8	+4.2	3610
91-680	3811 ±5	7.915	1.129	0.0862	-0.5617	0.510051 ±9	+3.5	3700
91-249	3762 ±7	18.443	2.978	0.0976	-0.5039	0.510153 ±8	-0.8	3930
G85-496	3760 ±6	4.293	0.733	0.1032	-0.4754	0.510558 ±7	+4.4	3580
"	"	4.509	0.775	0.1034	-0.4744	0.510566 ±7	+4.5	3570
90-527	3754 ±6	27.146	4.078	0.0908	-0.5384	0.510218 ±8	+3.7	3630
90-532	3729 ±3	5.444	1.105	0.1226	-0.3765	0.510597 ±7	-4.6	4270
"	"	5.693	1.158	0.1229	-0.3752	0.510630 ±7	-4.2	4220
92-369	3858 ±10	10.702	1.708	0.0961	-0.5115	0.510238 ±8	+2.9	3770
"	"	15.501	1.511	0.0972	-0.5058	0.510244 ±8	+2.4	3790
Akilia gabbros and leucogabbros								
90-525	≥3872 ±10	4.922	1.800	0.2211	+0.1240	0.513369 ±5	≤+1.8	3990
92-118	≥3811 ±5	12.538	2.759	0.1330	-0.3239	0.511232 ±7	≥+3.6	3630
"	"	9.925	2.1327	0.1299	-0.3397	0.511165 ±8	≥+3.7	3620
"	"	9.810	2.149	0.1324	-0.3267	0.511210 ±9	≥+3.3	3650
211042 ⁴	≥3784±22	17.006	4.147	0.1472	-0.2516	0.511560 ±12	≥+3.0	3650
211048	" "	3.996	0.903	0.1365	-0.3060	0.511295 ±9	≥+2.7	3680
211238	" "	34.448	5.677	0.0996	-0.4937	0.510409 ±9	≥+3.5	3660
Narryer Gneiss Complex, Western Australia²								
88-173	3730 ±5	52.312	7.889	0.0911	-0.5367	0.510132 ±16	+1.8	3760
88-28 ³	3731 ±4	38.53	6.83	0.1071	-0.4555	0.510512 ±11	+1.7	3710
89-456	3626 ±10	10.685	1.744	0.0986	-0.4985	0.510401 ±11	+2.3	3610
88-191	3597 ±7	77.084	12.330	0.0967	-0.5085	0.510356 ±8	+1.8	3610

Normalized to $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$. $\epsilon_{\text{Nd}}(T)$ calculated using a value of $^{143}\text{Nd}/^{144}\text{Nd} = 0.512665$ for CHUR to compensate for interlaboratory bias based on La Jolla standard measurements. $^{147}\text{Sm}/^{144}\text{Nd}_{\text{CHUR}} = 0.1967$. Duplicates are from repeat dissolutions of separate powder aliquots over several months. Reproducibility of initial ratios based on duplicate samples is better than 0.5 ϵ units.

$$T_{\text{DM}} = 1/\lambda_{\text{Sm}} \ln$$

$$\left[1 + \frac{(^{143}\text{Nd}/^{144}\text{Nd}_{\text{sample}} - ^{143}\text{Nd}/^{144}\text{Nd}_{\text{DM}})}{(^{147}\text{Sm}/^{144}\text{Nd}_{\text{sample}} - ^{147}\text{Sm}/^{144}\text{Nd}_{\text{DM}})} \right]$$

Additional Nd and zircon data from ¹ [33], ² [29], ³ [57] and ⁴ [58].

HF, HNO₃ and HCl acids in steel-jacketed teflon digestion vessels. To ensure complete digestion and equilibration of all minerals in these early Archean samples a two-step process was used. Acids were added to the sample-spike mixture in a teflon bomb, sealed, and placed on a hot plate at 150°C for at least 12 h. The top was removed and the sample taken to dryness to remove SiF₄. Fresh acids were then added, and the bomb and jacket assembled and placed in an oven at 200°C for at least 3 days. Nd and Sm were isolated using cation-resin ion-exchange columns and HDEHP-coated teflon bead columns. Approximately 100 ng of Nd was loaded onto a Re filament. A Finnigan Mat 261 was used for the isotopic measurements, with both Nd and Sm analyzed as the metal. Isotopic compositions and Sm and Nd concentrations were determined from the same spiked solution. Total procedural blanks averaged 70 pg for Nd, and for all samples is negligible.

During this study calibration of the Sm-Nd mixed solution was checked against a California Institute of Technology normal solution [23]. The reproducibility of the Sm/Nd ratio and Sm and Nd concentrations of the standard was better than 0.03%. La Jolla and Nd-1 (an in-house standard made from an Ames metal) measurements were interspersed with sample runs. The ANU averages for the last 2 years are La Jolla ¹⁴³Nd/¹⁴⁴Nd = 0.511888 ± 19 (*n* = 28) and Nd-1 ¹⁴³Nd/¹⁴⁴Nd = 0.512183 ± 17 (*n* = 136). The errors cited reflect external reproducibility at the 95% confidence level (2σ) rather than in-run precision. The calculated initial ε_{Nd} values reported in Table 2 have been modified (lowered) to take into account the laboratory bias as indicated by measurements of La Jolla; the reported measured ¹⁴³Nd/¹⁴⁴Nd ratios are unmodified.

To assess the reproducibility of our data we have repeated samples several months apart starting with new powder aliquots. As can be seen in Table 2 there is some variability in both the Sm and Nd concentrations and in the measured Nd isotopic compositions, but as these variations are correlated they translate to only slight differences in the calculated initial isotopic compositions. These variations result from powder inhomogeneity of the gneiss samples, and this is a problem commonly seen in granitoids. The repli-

cated samples provide an empirical measure of the reproducibility of the calculated initial Nd ratios taking into account all effects, and show it to be < ±0.5 ε units.

2.2 Results

The samples used in this study were selected for Nd isotopic analysis on the basis of age, rock type, zircon characteristics and field relationships. Localities are shown on the map of Fig. 1 and brief descriptions of the samples and their geological context are given in Appendix 1. An attempt was made to include samples that represent the more homogeneous and relatively undeformed parts of the polyphase Amîtsoq gneiss complex as well as samples of the older Akilia amphibolites which had well-constrained minimum ages.

The ¹⁴⁷Sm/¹⁴⁴Nd ratios (Table 2) are also listed in *f* notation [24] to readily indicate depletion with respect to a chondritic source (*f* = [¹⁴⁷Sm/¹⁴⁴Nd(sample)]/[¹⁴⁷Sm/¹⁴⁴Nd(chondrite)] - 1). Samples with positive *f* values will evolve to positive ε_{Nd} values, those with negative *f* values to negative ε_{Nd} values. We first discuss the data from the older Akilia supracrustal suite and then the results from the Amîtsoq gneiss samples.

Five samples of the Akilia gabbro-leucogabbro suite were analyzed. In each case the samples were collected from areas where the field relationships between the supracrustal and intrusive rocks were well defined and no field evidence for contamination of the supracrustal enclaves by the gneisses was present. The ages for each sample (from ≥ 3784 to ≥ 3872 Ma) listed in Table 2 are minimum ages constrained by U-Pb zircon ages of the intrusive Amîtsoq gneisses. ¹⁴⁷Sm/¹⁴⁴Nd ratios for the amphibolites vary from 0.2211 to 0.0996 (*f* = +0.1240 to -0.4937). The sample with the oldest minimum age, amphibolite 90-525, is constrained by its host Amîtsoq gneiss (89-462) to be older than 3872 Ma. This sample is LREE depleted (*f* = +0.1240) and with a *maximum* initial ε_{Nd} value of +1.8. In comparison, the initial ε_{Nd} value for the enclosing gneiss is +0.5. The other four Akilia gabbros are LREE enriched, and thus the initial values calculated based on

their minimum crystallization ages will themselves be minima. For example, 211042 has a calculated initial value of $\epsilon_{\text{Nd}}(3784\text{Ma}) = +3.0$. It is quite possible that this sample, as well as 211048 and 211238, are 100 Ma or more older than their host gneiss, corresponding to a ϵ_{Nd} value at 3884 Ma of +3.6. Samples 211042 and 211238 have minimum ϵ_{Nd} values of $\approx +3.0$ and +3.5 based on an age of 3784 Ma.

Sample 92-118 is from an enclave within the gneiss represented by sample 91-680, and thus is older than 3811 Ma. The $\epsilon_{\text{Nd}}(3811\text{Ma}) = +3.6$ value for the gabbro is identical to the value for the host gneiss at the same locality ($\epsilon_{\text{Nd}}(3811\text{Ma}) = +3.7$), suggesting these two rocks were derived from a similar parental source at approximately the same time.

The nine samples of granodioritic and tonalitic Amîtsoq gneisses in this study have U-Pb zircon ages spanning only 140 m.y., from 3872 to 3729 Ma, but with a very large range of initial ϵ_{Nd} values (from -4.6 to $+4.5$). All of these samples are LREE enriched, with $^{147}\text{Sm}/^{144}\text{Nd}$ ratios varying from 0.1350 to 0.0862 ($f = -0.3139$ to -0.5617), similar to the values measured in post-Archean granitoids. The Nd contents of these samples range from 4.293 to 43.100 mg/g, with an average of 15.5 mg/g. Three samples, including the oldest gneiss (89-462), have $\epsilon_{\text{Nd}}(t) = 0 \pm 0.5$, and five have values between $+2.7$ and $+4.5$. The most positive $\epsilon_{\text{Nd}}(t)$ value ($+4.5$) is from a 3760 Ma tonalite (G85-496). The youngest sample included in this study is a 3729 Ma tonalite (90-532) characterized by $\epsilon_{\text{Nd}}(3729) = -4.5$ and with a CHUR model age of 4240 Ma, requiring derivation from a long-term LREE enriched reservoir. This sample is from a homogeneous gneiss unit; we find no evidence, either petrographically or from the U-Pb zircon characteristics, for post-crystallization fractionation. Inherited zircons, which could yield the crystallization age of older components, have not been found using SHRIMP. Sample 90-532 adds to the small but expanding body of evidence, which includes rare ≈ 4200 Ma zircons [25], that some enriched continental crust was present on the early Earth, complementing a LREE depleted reservoir.

Because we are emphasizing differences in the initial Nd isotopic compositions in early Archean

rocks as compared with bulk Earth values, the Nd data are referenced to an evolving chondritic composition reservoir through the use of epsilon notation. The values used for the Earth's initial isotopic composition and for the Sm/Nd ratio are the accepted values as determined from a suite of chondritic meteorites [1]. We note here that some recent measurements of chondrites [26] suggest that the chondritic Nd isotopic composition at 4.556 Ga might be 0.3–0.5 ϵ units higher than the typically used values; other studies suggest it may be 0.5 units lower (cf. discussion in [11]). The effect on the data presented in Table 2 of higher CHUR values would be to lower our calculated initial Nd values by an amount approximately equal to the error. All other published datasets would be shifted as well, and therefore the arguments presented here would not be altered. Conversely, a lower value for CHUR would result in higher calculated epsilon values for our samples.

A potential problem that must be considered in all gneisses, Archean gneisses in particular, is that these rocks have experienced one or more tectonothermal events which may have resulted in fractionation of Sm from Nd. The effect of the modification of the Sm/Nd ratio on the calculated initial value will be proportional to the degree of Sm/Nd fractionation and the time span between fractionation and crystallization [cf. 27]. Because of the potentially severe effects of late-stage fractionation on the calculated initial ratios as already described, extreme care was used in sample selection, with the criteria including U-Pb zircon characteristics, field relationships and petrographic examination. Even with all these precautions, it cannot be demonstrated *a priori* that the rocks are not modified. We note, however, that these samples along with other early Archean samples with highly positive initial ϵ_{Nd} samples from the literature represent a wide range of bulk chemical compositions and would not be expected to respond similarly during alteration events. Additional evidence against the high ϵ_{Nd} values being an artifact of alteration is that slightly younger (3600–3730 Ma) Amîtsoq gneisses from the same areas as the > 3730 Ma gneisses, with similar bulk compositions and with almost identical post-crystallization histories, do not have exceptionally high ϵ_{Nd} values.

3. Origin of highly depleted reservoirs in the early Earth

3.1 Isotopic constraints

The published early Archean Nd database, with the exception of a few determinations from 3730 Ma rocks from the Narryer Gneiss Complex, Western Australia [28,29], the 3960 Ma Acasta gneisses of Canada [6], and the 3930 Ma gneiss from the Napier Complex, Antarctica [30] is derived solely from rocks in southern West Greenland and northern Labrador [31,16,3,32,33,34,2]. In previous studies, the ages and initial ϵ_{Nd} values of these samples were derived mainly from whole-rock isochrons, or the initial ϵ_{Nd} values were deduced using U-Pb zircon ages obtained on *similar* samples. There has been uncertainty in how to interpret this data, because of doubt whether the age of samples is known accurately, whether all samples in an isochron are consanguineous, and whether low Sm-Nd abundance mafic rocks have maintained closed isotopic systems throughout their history [cf. 34,35]. Interpretation of the early Archean Nd database has also been influenced by scepticism over the reality of early Archaean ϵ_{Nd} values of $\geq +4$ and by misinterpretation of the geological evolution of the complex to which the rocks belong.

Data from several previous studies have suggested that some early Archean rocks may have very high ϵ_{Nd} values. Jacobsen and Dymek [2], in a study of Isua supracrustal belt felsic volcanosedimentary rocks, calculated initial ϵ_{Nd} values of 0 to +4 at 3810 Ma, but they also quoted ϵ_{Nd} values of -1 to +3 at 3640 Ma because they expressed some doubt as to the validity of the +4 values, and hence considered the possibility that these rocks are somewhat younger. Regardless of uncertainty over the depositional age of the rocks, Jacobsen and Dymek concluded that the observed spread of 4 ϵ units reflects real variation in these rocks at their time of deposition, and that they contain several detrital components, including a depleted mantle source and an enriched sialic crust component with an age of 4100 Ma or more. SHRIMP zircon work [36,37] on the two main felsic volcanosedimentary units used by Jacobsen and Dymek [2] has demonstrated that these rocks contain unimodal zircon age popula-

tions with the *maximum* weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ ages of 3808 ± 4 Ma (2σ). Because of the apparently mixed provenance of these rocks, they are not the ideal suite for assessing the validity of the most positive ϵ_{Nd} values determined.

A collection of fourteen diverse Akilia association mafic rocks from several localities in West Greenland yielded a scatter bounded by reference lines equivalent to ages of ≈ 3600 Ma [34]. A subset of nine samples, mostly gabbros and leucogabbros from one igneous body, yielded an apparent Sm-Nd isochron age of 3887 ± 65 Ma with an initial ϵ_{Nd} of $+4.2 \pm 0.4$. This result was treated with considerable caution because of the implications for terrestrial evolution if the very high initial ϵ_{Nd} value is real, and because the age was almost 100 Ma greater than the *then* oldest-known rocks in the region. However, subsequent SHRIMP zircon U-Pb dating of an orthogneiss that intrudes mafic Akilia association rocks at the type locality on Akilia island yields a protolith age of 3872 ± 10 Ma [38]. This age, which must be the minimum age of some components of the Akilia association, corresponds closely to that obtained on Akilia gabbros by Gruau et al. [34] and the initial ϵ_{Nd} value is similar to the results of this study.

A thorough study of Nulliak assemblage mafic and ultramafic rocks in Labrador was presented by Collerson et al. [3]. Rocks interpreted to be a residual mantle suite yielded a Sm-Nd isochron age of 3815 ± 121 Ma, with an initial ϵ_{Nd} value of $+3.0 \pm 0.6$. Despite the potentially significant effects of metasomatism in these generally LREE-poor rocks during subsequent high grade tectonometamorphic events, Collerson et al. [3] argued that the results are significant, with the 'residual mantle' suite pointing towards a strongly depleted mantle reservoir ($\approx +3$ at 3800 Ma).

The results given in this paper provide the best constrained evidence to date that some early Archean tonalites, diorites and mafic rocks from West Greenland formed with minimum initial ϵ_{Nd} values of $\approx +4$ at 3811 Ma. We emphasize that these must be absolute *minimum* values for the depleted reservoir as mixing or contamination processes with older LREE enriched crust would only lower the ϵ_{Nd} values of mantle derived rocks. The gneisses represent the final stages in a sequence of partial melting events whereby (in sim-

plistic terms) ultramafic mantle partially melts to give rise to mafic oceanic crust, which, in a hydrated state, in turn partially melts (with or without involvement of upper mantle or 'old' continental crust) to give rise to tonalites and diorites [e.g., 39]. Therefore, the +4 initial ϵ_{Nd} values reported here for tonalites, dioritic and mafic rocks are not a *direct* measure of the ϵ_{Nd} value of the mantle reservoir from which they were ultimately extracted. The processes leading to the formation of stable crust in the early Archean are under debate; however, within the framework of plate tectonic, plume tectonic *and* meteorite impact crustal evolution scenarios, tonalites and diorites are considered to be the melting products of mafic rocks which were extracted from the mantle, with a short crustal residence time (ca. 50 Ma). Thus these second-generation silicic rocks may have lower (less positive ϵ_{Nd}) initial values than the coeval depleted mantle owing to contamination with older, LREE enriched, negative ϵ_{Nd} , lower crust.

3.2 Implications for isotopic models of early Earth differentiation

The presence of ϵ_{Nd} values $\geq +4$ at 3800 Ma places constraints on the age and average depletion history of the depleting mantle (Fig. 3). The relationship between LREE enrichment or depletion as represented by the f value, and the change in the ϵ_{Nd} value, is approximated by the equation:

$$\Delta\epsilon_{\text{Nd}} = f \times Q \times \Delta T$$

where Q is a constant = 25.13 Ga^{-1} and T is time (Ga) [24]. The upper age limit for the initiation of the depleted reservoir is provided by the age of the Earth, i.e. $\approx 4550 \text{ Ma}$. To generate the most radiogenic isotopic compositions of the Greenland rocks by 3810 Ma, i.e., 740 m.y. after formation of the Solar System, requires that the time-averaged f value was 0.22. This value is more than twice the average value ($f \approx 0.10$) estimated for the upper mantle based on its present-

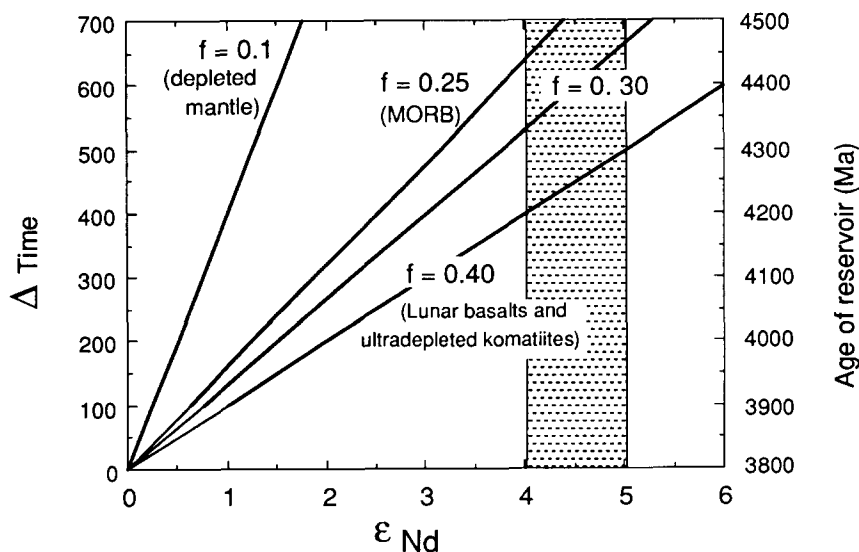


Fig. 3. The relationship between f , the chondrite-normalized Sm/Nd ratio, ϵ_{Nd} evolution and time. The curves represent rate of ϵ_{Nd} change for different f values. Even for an ultradepleted reservoir ($f \approx 0.4$) such as the source of some lunar basalts and early Archean ultramafic rocks, a minimum of 400 m.y. is required to produce ϵ_{Nd} values $\geq +4$ (shaded region). This implies that the age of the reservoir that gave rise to the Greenland samples was $> 4210 \text{ Ma}$. More moderate f values, such as those that characterize the present-day depleted mantle ($f \approx 0.25$) require that the differentiated reservoir became isolated $> 600 \text{ m.y.}$ before the formation of the Greenland samples (i.e., with an age of $> 4400 \text{ Ma}$, ϵ_{Nd} values $\geq +4$ cannot be produced in geologically reasonable time using the estimated time-averaged value of the depleted mantle ($f = 0.1$)).

day isotopic composition ($\epsilon_{\text{Nd}} \approx +10$) starting from an initial $\epsilon_{\text{Nd}} = 0$ at 4.55 Ga.

The minimum age of the depleted reservoir can be calculated from estimates of the maximum plausible f value. Some ultradepleted, early Archean, ultramafic rocks from Labrador have measured f values of +0.16 to +0.59, with an average $\approx +0.4$ [3]. These are among the most highly depleted terrestrial samples yet identified and are similar in average Sm/Nd ratio and therefore rate of Nd isotopic evolution to some lunar basalts [e.g., 40]. Assuming that the depleted mantle source region of the Greenland rocks became fractionated to this extreme f value, 400 Ma is the minimum time required to evolve to an ϵ_{Nd} value of +4 at ca. 3820 Ma (Fig. 3). Thus, based on the estimated maximum possible Sm/Nd fractionation in the source region, the minimum age for formation of this reservoir is 4220 Ma.

The requirement of a highly fractionated Sm/Nd ratio in the early Archean mantle ($f = +0.22$ to +0.40) (Fig. 3) limits the differentiation processes that may have been operative. Based on measurements of Sm and Nd contents in MORBs the depleted mantle today is estimated to have an instantaneous $f = +0.25$ (as opposed to the time-averaged f value $\approx +0.10$). This degree of depletion reflects extraction of the entire present-day mass of continental crust [e.g., 41]. The similarity between the minimum possible f value (+0.22) for the Archean depleted reservoir and the value for the upper mantle today which resulted from removal of the continental crust suggests that extraction of large amounts of felsic crust in the early Archean could balance the depleted reservoir. It is readily demonstrable using partial melting or mass balance models that sufficient depletion of the mantle to generate values of $\epsilon_{\text{Nd}} = +4$ at ca. 3800 Ma cannot be accomplished by gradual extraction of continental crust [e.g., 8,11,7] and results in values of +1 to +2 at 3800 Ma.

Similar mass balance approaches demonstrate that extraction of a mass of continental crust approximately equal to that in existence today and formed in the earliest Archean is necessary to generate the Nd depletions inferred for the early Archean upper mantle. For example, Jacobsen and Dymek [2], assuming an $\epsilon_{\text{Nd}}(3800) = +2$,

estimated that 30–60% of the current mass of the continental crust had to be in existence by 3.8 Ga. If we duplicate their calculation with a substitution for the depleted mantle composition of $\epsilon_{\text{Nd}}(3800) = +4$, the result suggests that 70–130% of the present-day mass of crust was formed by 3800 Ga. Scenarios calling for large volumes of ancient continental crust approach the ‘no-growth’ model advocated by Armstrong [5,42], in which the entire continental mass formed as part of an early global differentiation process. The arguments against these types of models have been discussed in detail elsewhere [e.g., 11] and include the problem of the lack of evidence for copious amounts of ancient crust based on U-Pb and Hf isotopic compositions of zircons in Archean rocks. Additionally, in the consideration of the data presented here it is difficult to explain the required absolute absence of recycling before 3.8 Ga combined with the necessary vigorous recycling after 3.8 Ga in order to create a rapid change in Nd compositions.

Explaining the high ϵ_{Nd} values observed in early Archean rocks has provided the impetus for consideration of additional types of models of early Earth differentiation. An alternative to continental crust extraction to deplete the ancient upper mantle is the formation and storage of mafic–ultramafic crust [e.g., 9,8,11]. As described by Chase and Patchett [8], generation of the necessary Sm/Nd fractionation in the mantle requires production and nearly quantitative storage of mafic and/or ultramafic crust in the early Archean (30–50% partial melts) equal to more than ten times the volume of the present-day continental crust. Although this mechanism is mathematically possible, as discussed in Galer and Goldstein [11], the residue from extraction of this mafic–ultramafic crust by large amounts of partial melting would be extremely depleted in Nd as well as other incompatible elements; to generate an $\epsilon_{\text{Nd}}(3800 \text{ Ma})$ value $\geq +4$ would result in the Nd concentration of the upper mantle being less than 10% of its initial concentration. The data of this study and others [e.g., 43,2] suggest that the average Nd concentration of early Archean continental rocks was similar ($\pm 50\%$) to present-day values. Remelting of the highly depleted residue from basalt–komatiite extraction will not be able to produce melts of the

appropriate composition to be the precursors to 'average' crust.

Most quantitative models of terrestrial mantle evolution have assumed that the mass of depleted mantle is fixed and of the same volume as the present day, i.e. representing approximately the upper third of the total mantle. In some models, the consequences of allowing the depleted mantle to increase with time have been considered [e.g., 7,44,10]. In these types of models, because the initial volume of depleted mantle is considered to be less than the entire upper mantle (i.e., less than 0.33 mantle masses), extraction of the continental crust is a much more effective means of depletion and can theoretically create the necessary isotopic compositions. A variation of this concept that has not been explored is that the early Archean mantle may have been laterally heterogeneous. The early Archean database is

currently based primarily on samples from Greenland and Labrador with the areal extent of the reconstructed early Archean part of the North Atlantic craton covering a few thousand square kilometres. The only other examples of well-documented early Archean rocks that may be derived from highly depleted mantle sources are the Acasta gneisses of Canada [6]. It is conceivable that the entire early Archean database requiring a highly depleted mantle source may represent one cratonic nucleus. If the depletion of the mantle were linked to the extraction of the adjacent overlying continental crust, and this depleted mantle was able to remain isolated, only limited parts of the mantle may have been affected. A test of this proposal lies in the continued determination of accurate initial isotopic compositions of early Archean rocks from other areas (e.g., China [45]) to determine if the very

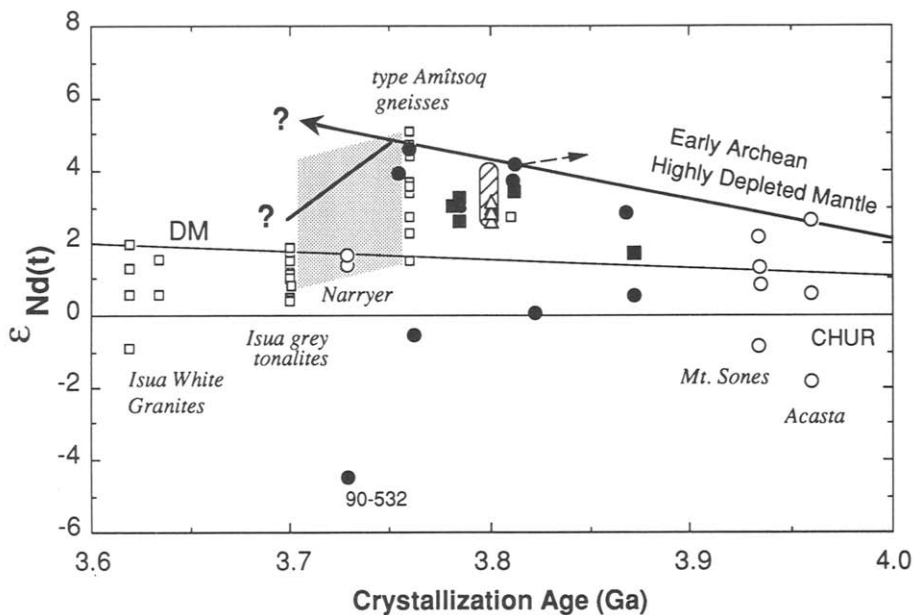


Fig. 4. Initial ϵ_{Nd} values for selected early Archean rocks. ● = Amîtsoq gneisses of this study; ■ = Akilia gabbros of this study; △ = Labrador 'residual mantle' suite [3]; stripe ornament = Isua metasediments [2]; □ = Isua and Amîtsoq gneisses [16,32,33]. In contrast to this study, the initial ϵ_{Nd} values for these gneisses are calculated using ages derived from bulk zircon U-Pb chronology and by correlation with other dated samples, and in most cases are maximum estimates. As an example, the effect of the age uncertainty on the ϵ_{Nd} values for the type Amîtsoq gneisses is shown by the shaded region. The ages of the Akilia gabbros (■) of this study are *minimum* ages based on the ages of intrusive gneisses. Older ages for these rocks will generally result in more positive ϵ_{Nd} values (dashed arrow). Also shown are the initial values for the early Archean rocks of Mt. Sones, Antarctica [30], the Acasta gneisses [6] and the oldest components of the Narryer gneiss complex ([29] and unpublished data). All these are shown with circles (○). The bold arrow depicts the evolution of a highly depleted mantle reservoir based on these samples in comparison to estimates of a depleted mantle reservoir (DM) based on a model of linear evolution. The negative ϵ_{Nd} value of gneiss sample 90-532 corresponds to a model age of 4240 Ma.

high ϵ_{Nd} values are a global or craton-scale feature and if each early Archean craton has its own Nd evolution history.

Alternatively, processes other than crustal extraction may account for the severe depletions evident in the early Archean rocks. It is widely argued that the Earth was at least partially molten early in its history due to accretionary processes, as was the Moon and at least some asteroids. It follows that the Earth, like the Moon and asteroids, may have experienced some form of global differentiation either within a magma ocean or by cumulate processes at depth. The nature of differentiation that resulted from this early heating is a subject of considerable current debate [e.g., 12]. Depending upon the participating mineral phases, cumulate processes can be much more effective at creating early, extreme depletions in a planetary body compared with extraction of partial melts, as witnessed by the isotopic compositions of lunar basalts. It is intriguing that the lunar mare basalt source regions, which are proposed to have formed as cumulates from a global magma ocean, have an f value of $\approx +0.36$ [46,40],

similar to the values we propose for the early Earth, and to the highly depleted values measured in some early Archean ultramafic rocks [32]. If a magma ocean > 400 km deep existed on the Earth, garnet may have been a cumulate phase [e.g., 47] and Sm/Nd fractionation of the amount required to generate $\epsilon_{\text{Nd}} = +4$ in the early Archean could potentially be effected. If garnet was the main fractionating mineral, then owing to Lu/Hf fractionation as well as Sm/Nd, correlated Hf and Nd isotopic anomalies in early Archean rocks would also be expected. Hf isotopic compositions determined by SHRIMP on ca. 4200 Ma zircons [48] are consistent with chondritic Lu/Hf ratios (i.e., no garnet fractionation), but the data are not precise enough to totally eliminate the possibility that garnet was a cumulate phase in their source regions. Initial Hf isotopic compositions of early Archean rocks from highly depleted reservoirs (initial $\epsilon_{\text{Nd}} \geq +4$) which should exhibit the most extreme anomalies have not yet been determined.

A possible exception to the assertion that the highly depleted reservoir did not persist into the

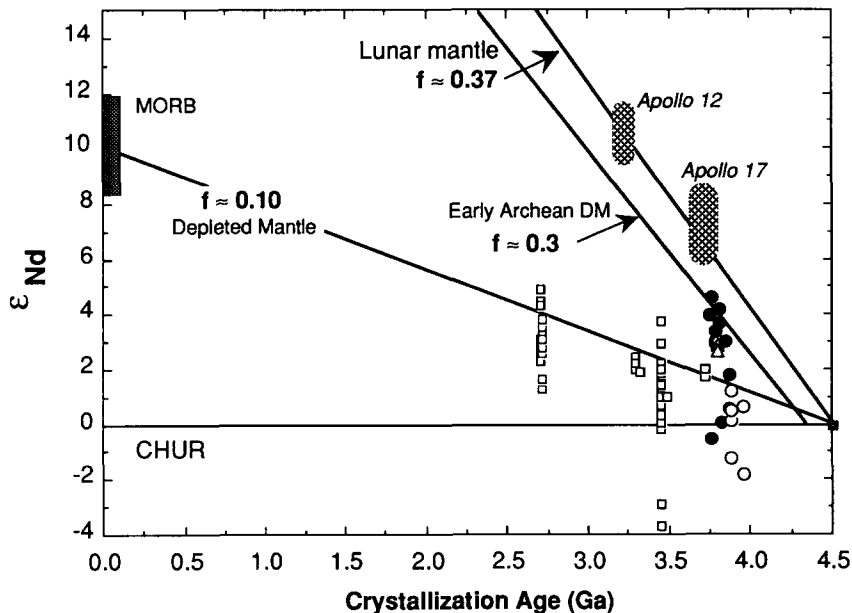


Fig. 5. Nd isotopic evolution and average f values of depleted reservoirs for the Moon, early Archean mantle, and average terrestrial depleted mantle. Early Archean depleted reservoir evolution starts from $\epsilon_{\text{Nd}} = 0$ at 4.4 Ga. Shaded regions = fields of initial ϵ_{Nd} values of lunar mare basalts; ● = data of this study; ○ = Acasta and Mt. Sones gneisses; Δ = Labrador ultradepleted komatites [3]; □ = data from the literature and include the most positive ϵ_{Nd} values from early Archean Narryer gneisses [29], Pilbara greenstones [4], Barberton greenstones [51,4], and data from late Archean greenstone belts (see text).

late Archean comes from a garnet-pyroxenite from the Yakutia kimberlite pipes. A mineral isochron for this sample indicates an age of 2600 Ma with an initial $\epsilon_{\text{Nd}}(2600 \text{ Ma})$ value of $+20 \pm 3$ [49]. The Nd isotopic composition is that expected for a highly depleted reservoir similar to that which produced the early Archean Greenland samples. Thus this rock may represent a relict of a cumulate layer formed in the early Earth.

3.3 Fate of the highly depleted reservoir

Nd isotopic evolution curves for the depleted mantle are constructed from the locus of most positive initial ϵ_{Nd} values determined for mantle derived rocks of different ages. By looking in detail at the Nd isotopic evolution curve for the early Earth, as defined by the Archean database, we should be able to discern the development and lifetime of the highly depleted mantle reservoir. The initial Nd isotopic compositions of the samples of this study, along with data for other early Archean samples, are shown in the evolu-

tion diagram of Fig. 4. The most positive values evolve progressively from +2, as determined for the 3960 Ma Acasta gneisses [6] to values of +4.5 in the 3760 Ma Greenland rocks. If this reservoir continued to exist and evolve unmodified, we should see rocks with initial $\epsilon_{\text{Nd}} = +8$ to +10 at 3500 Ma and $\epsilon_{\text{Nd}} \geq +15$ at 2600 Ma (Figs. 4 and 5). What actually is observed is that after 3760 Ma there is an apparent abrupt change to less positive epsilon values. The initial compositions of the 3700–3730 Ma Amitsoq tonalitic gneisses are from +2 to -4 [16,33] and provide no evidence of derivation from a highly depleted source.

For comparison, in another well-documented early Archean terrane, the Narryer Gneiss Complex of Western Australia, 3730 Ma tonalites have been identified as the oldest rocks using SHRIMP zircon geochronology [50]. These tonalites are characterized by initial ϵ_{Nd} values of +2 (Table 2). Based on the absence of inherited zircon components, the narrow range of initial ϵ_{Nd} values, and the lack of evidence for any older crust presently in the region despite extensive

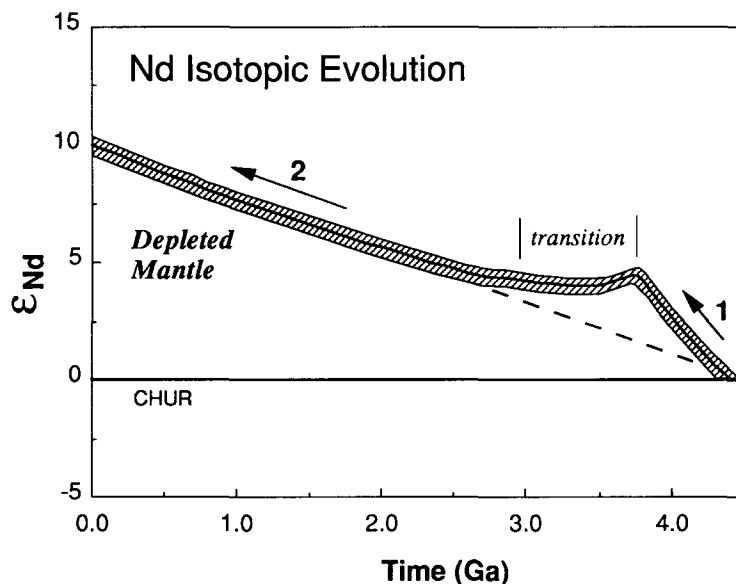


Fig. 6. Refined estimate of terrestrial depleted mantle Nd isotopic evolution. The early Archean part of Earth history (1) is characterized by rapid evolution of Nd isotopic compositions, corresponding to extreme early Sm/Nd fractionation in some regions of the mantle. The transition zone from approximately 3.73 Ga to the late Archean is characterized by relatively stable isotopic compositions, which may reflect mixing of depleted with undepleted or enriched reservoirs. The change in depleted mantle composition from the late Archean to the present day is approximately linear (2). The difference between (1) and (2) reflects a change in processes between the early Archean and 'modern' style depleted mantle evolution.

whole-rock Nd and U-Pb zircon studies, the $\epsilon_{\text{Nd}} \approx +2$ values are interpreted to represent the composition of their mantle source region [29]. None of the 3730–3300 Ma Narryer Gneiss Complex rocks show evidence of being derived from a highly depleted reservoir. This implies that either the highly depleted reservoir was not a global phenomenon or was already modified by 3730 Ga.

If we consider younger Archean rocks the oldest regions of extensive and well-dated mafic and ultramafic rocks are the early Archean greenstone belts of the Barberton region, South Africa and the Pilbara craton of Western Australia. The initial values for the most primitive komatiites and basalts of the Barberton belt ($\epsilon_{\text{Nd}}(3450 \text{ Ma}) \approx +1$ to $+3$ [51] and for the Pilbara basalts and komatiites ($\epsilon_{\text{Nd}}(3450 \text{ Ma}) \approx +3$ to $+4$ [4] are slightly above estimates for the early Archean depleted mantle composition based on linear evolution, but far below the expected $\epsilon_{\text{Nd}} \geq +8$ expected for derivation from a highly depleted reservoir. In contrast to the relative scarcity of preserved early Archean mafic and ultramafic rocks, greenstone belts are common in the late Archean geological record. Several extensive and well-preserved greenstone belts of late Archean age include the Abitibi and Wabigoon belts of Canada and Norseman–Kambalda greenstones of Western Australia. Late Archean greenstone belts worldwide are characterized by a narrow range of ϵ_{Nd} values from $+2$ to $+5$ [e.g., 52] (Fig. 5), with the best preserved samples from Canadian greenstone belts, including data from relict pyroxenes [53] yielding values of $+2.5 \pm 0.3$. The narrow range of compositions for late Archean greenstone belts worldwide suggests that they are not the result of some mixing process, but represent the prevalent depleted mantle composition. Clearly the highly depleted reservoir that gave rise to the Greenland samples, and would be expected to have $\epsilon_{\text{Nd}}(2.7 \text{ Ga}) \geq +15$, was either not in existence at this time or was not extensively sampled.

It is evident that linear or simple curve models of mantle Nd evolution connecting the $\epsilon_{\text{Nd}} = 0$ value at ca. 4.5 Ga to MORB values ($\approx +10$) today are inadequate to describe the early Archean data. The evolution of Nd isotopic compositions in at least some parts of the mantle

during the first 700 m.y. of Earth history equalled the isotopic change over the next 3800 m.y. Either the rate of processes responsible for creating the depletions decreased, or the processes themselves have changed. In consideration of the data presented here we propose an evolution curve as in Fig. 6. This curve shows two styles of development: (1) rapid evolution reflecting rapid early depletion from 4.5 to 3.76 Ga, a transition period, and then (2) more moderate evolution in the Proterozoic and Phanerozoic. The transition zone as defined by data from ca. 3450 Ma komatiites and to a lesser extent late Archean greenstones is characterized by more positive ϵ_{Nd} values than predicted based on linear mantle evolution models and with little change overall change. It is unclear whether this relative stability reflects lowering of the depleted mantle to near-chondritic isotopic compositions after 3.76 Ga and then subsequent redepletion and evolution, or a more gradual buffering of mantle isotopic compositions to maintain values of $+3$ to $+4$. In either case the large change in the rate of Nd isotopic evolution of the depleted mantle after 3.76 Ga requires efficient homogenization of the ultradepleted source with an enriched or chondritic composition mantle.

Various speculative suggestions can be put forth to account for this rapid change. It may represent the time that isolated depleted regions or cumulate layers within the early Earth became chemically or thermally unstable and mixed with mantle of chondritic composition. Recent models of mantle convection based on theoretical and experimental results and incorporating multiple phase transitions [54] have demonstrated an increased tendency to layering in the mantle with larger Rayleigh numbers, a condition that would be expected in the early Earth due to higher internal heating. A change in convective regimes related to decreased internal heat production could then explain both the initial chemical isolation of parts of the mantle and the later rapid remixing. Alternatively, this rapid change in depleted mantle evolution may have been driven by external events. The approximate correspondence between the termination of cataclysmic bombardment (based on the ages of lunar cratering) and the age of the oldest cratons has led to the suggestion that meteorite impacts influenced early

crust–mantle interaction [e.g., 43]. There is a similarity in age between the end of cataclysmic bombardment as constrained by lunar studies and the last vestige of the early terrestrial highly depleted mantle reservoir as recorded in the Greenland gneisses, although the relationship between these two events, if any, is currently purely conjectural.

Finally, the refined Nd mantle evolution curve constructed here should be considered in the calculation of depleted mantle model ages for early Archean rocks. For samples actually derived from a highly depleted mantle source, depleted mantle model ages calculated based on a linear mantle evolution curve, as is commonly used, will be in gross error, with the model ages being significantly younger than the crystallization ages. For example, the depleted-model ages calculated for the > 3760 Ma Greenland samples with very positive ϵ_{Nd} values of this study are from 3550 to 3640 Ma, i.e. 140–240 Ma younger than the crystallization ages for these rocks based on U–Pb zircon chronology. It is almost certainly the case that the ages of early Archean rocks have been underestimated in other studies by using model ages. Because of the complexity of Nd mantle evolution in the early Archean, Nd model ages may be of little utility for this time period.

4. Summary

Data for carefully selected samples of early Archean Amîtsoq gneisses and Akilia gabbros and leucogabbros from Greenland imply the existence of a large range of ϵ_{Nd} values in the early Archean. Some of these samples indicate that the depleted mantle was characterized by $\epsilon_{\text{Nd}} \approx +4$ at 3810 Ma. Using geologically plausible Sm/Nd ratios this reservoir must have formed between 4210 and 4400 Ma. It is not possible to account for the inferred depletion in the early Archean mantle by growth of the continental crust from the entire depleted mantle reservoir (upper third of the whole mantle). We suggest instead that the highly depleted reservoir formed by either extraction of continental crust from a limited part of the mantle, perhaps on the craton scale, or by Sm/Nd fractionation caused by cumulate processes in a partially molten early Earth.

A single Amîtsoq gneiss sample has an initial

ϵ_{Nd} value of -4.45 , with a CHUR model age of 4200 Ma. This is the lowest ϵ_{Nd} value yet measured for an early Archean rock. Regardless of the primary mechanism for formation of the highly depleted reservoir, this sample demonstrates that some LREE enriched continental crust was being formed on the early Earth in proximity to the highly depleted reservoir.

Based on the worldwide Archean Nd isotopic database, no evidence exists for this highly depleted reservoir in neither the North Atlantic craton nor in any other Archean terranes later than 3760 Ma. The questions remain as to whether the highly depleted reservoir which gave rise to $\epsilon_{\text{Nd}}(3810 \text{ Ma}) > +4$ values was a continent-scale phenomenon reflecting incipient crust formation processes on the oldest craton, or whether this is the last vestige of the effects of a global magma ocean preserved in a unique early crustal remnant. The test lies in continued coordinated geochronological, geological and geochemical studies of relict early Archean terranes.

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Appendix A: Sample location and description

89-462 tonalitic gneiss and 90-525 Akilia association amphibolite: 63°55'40"N 51°41'30"W, southwest corner of Akilia island. 89-462 is in contact with, and intrudes the type-Akilia association enclave. The gneiss is moderately well layered and contains smears and clots rich in hornblende (which we interpret as small fragments of the adjacent amphibolites belonging to the Akilia association enclave) and contains quartz veins. Both the hornblende clots and the quartz veins

were removed during sample processing. 90-525 is a homogeneous amphibolite from the Akilia association enclave and belongs to a > 5 m thick layered unit which grades from ultramafic and mafic amphibolite, through homogeneous amphibolite (represented by 90-525), then heterogeneous amphibolite, and finally to a 1 m thick banded iron formation unit. This sequence is interpreted as a layered flow capped by a chemical sediment. This sequence is then repeated within the same Akilia association enclave.

90-527 tonalitic gneiss: 63°56'20"N 51°40'15"W, east side of large inlet on the south coast of Akilia island. Rather coarse grained migmatitic gneiss.

110999 tonalitic gneiss: 63°55'45"N 51°43'55"W, eastern side of Angissorssuaq island. The gneiss is very homogeneous, and where sampled it is devoid of partial melt segregations and strong banding.

91-680 tonalitic gneiss and 92-118 leucogabbro inclusion: 64°58'N 49°59'40"W, close to edge of inland ice, approximately 17 km south of the Isua supracrustal belt. The Amîtsoq gneisses at this locality and in surrounding areas contain abundant, scattered inclusions of leucogabbro, gabbro and ultramafic rocks, some of which contain chromite layers. This locality is marked by a star on a detailed map of this area presented by Chadwick and Crewe [60]. The gneisses are weakly layered and where sampled are devoid of partial melting segregations and well-defined pegmatite bands. The leucogabbro is equigranular, homogeneous and devoid of partial melt segregations. A thin pegmatite vein was removed during sample processing.

91-249 tonalitic gneiss: 64°21'N 51°7'40"W, south side of Qingaap ilua, Støro. Very close to Amîtsoq gneiss specimens 155798 and 155799 reported in Moorbath et al. [55]. Close to a well-preserved Ameralik dyke. The sample is overall homogeneous, and devoid of partial melt segregations and pegmatite banding.

G85-496 quartz-dioritic gneiss: 63°21'5"N 51°30'20"W, promontory on northside of the mouth of the tidal race into Kuuglip tasersua. Gneisses range from rather nebulitic to moderately banded. Pre-Ameralik dyke partial melt segregations are widely developed in the gneisses. Sample used was as homogeneous as possible.

90-410 quartz-dioritic gneiss: 65°2'35"N 50°8'15"W, neck of land separating lakes 682m and 678m in the Isukasia area. Rather homogeneous hornblende-biotite gneiss, devoid of both strong layering and well-developed segregations. Approximately 100 m to the north of sample locality, related? tonalitic gneisses contain inclusions of gabbroic and leucogabbroic amphibolite.

90-532 tonalitic gneiss: 64°29'20"N 50°48'W, Uummanaq island, on rocks by abandoned Moravian mission settlement. Finely layered but homogeneous gneisses cut by thin, anastomosing, weakly deformed to undeformed pegmatite veins.

211042, 211048 and 211238 Akilia association leucogabbroic amphibolites: 63°50'10"N 51°37'30"W, south end of the Ingerssuartût group of islands. Homogeneous to weakly layered leucogabbroic amphibolite from a thick sheet which cuts interlayered mafic amphibolites and banded iron formation, but is itself intruded by Amîtsoq gneisses and cut by Ameralik dykes.

92-369 63°56'N 51°43'30"W, small island elongated N-S off east coast of Angissorssuaq island. Quartz diorite inclusion in tonalitic gneiss. In turn, 92-369 contains an inclusion of amphibolite, which was avoided in sampling. From a small area of low deformation and minimal granitic migmatization.

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