ARTICLE

The Earth's Early Evolution

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The Archean crust contains direct geochemical information of the Earth's early planetary differentiation. A major outstanding question in the Earth sciences is whether the volume of continental crust today represents nearly all that formed over Earth's history or whether its rates of creation and destruction have been approximately balanced since the Archean. Analysis of neodymium isotopic data from the oldest remnants of Archean crust suggests that crustal recycling is important and that preserved continental crust comprises fragments of crust that escaped recycling. Furthermore, the data suggest that the isotopic evolution of Earth's mantle reflects progressive eradication of primordial heterogeneities related to early differentiation.

The Earth is on an irreversible path toward compositional, thermal, and gravitational equilibrium through the processes of convection, melting, and differentiation. The geochemistry of continental and oceanic crust provides a basis for understanding, and a direct record of, these processes. Current debates in Earth history on such topics as its differentiation history, the scale of mantle convection, the source of mantle plumes, and the chemical mass balance of the Earth all involve assumptions made regarding events that occurred early in the planet's history. Although ocean basins cover about 70% of the Earth, the oldest preserved oceanic lithosphere formed only about 200 million years ago (Ma), whereas the oldest continental crust formed more than 4.0 billion years ago (Ga). Therefore, the oldest continental crust, although it accounts for only a small fraction of Earth's mass contained in all of the continental crust, contains direct geochemical information that can be used to study early planetary differentiation. The early crustal record is complex, reflecting both planetary differentiation and the cumulative effects of later events. In this article we examine the Nd isotopic record of Earth's oldest crust and discuss its implications for models of Earth evolution.

The moon, meteorites, and the other terrestrial planets preserve evidence of basaltic magmatism, differentiation, and meteor bombardment early in their history, and a similar history seems unavoidable for Earth. However, because of efficient resurfacing of the planet early in its history, we have no direct record of Earth's first 500 million years of evolution. The operation of plate tectonics over much of Earth's history is responsible for the episodic assembly and dispersal of continental lithosphere, the uplift and erosion of mountain belts, the growth and thermal reworking of continental crust at convergent margins, and the dispersal of eroded continents into the ocean basins. Thus, the continents are a collage of fragments that have escaped recycling into the mantle over the past 4.5 billion years and provide a highly biased record of Earth's evolution.

Geochemical models for the development of Earth's early crust and mantle are dominated by interpretation of radiogenic isotopic data (particularly Sm-Nd) from crustal rocks (*1–4*). The Sm-Nd system is ideal for investigating the evolution and interaction of chemical reservoirs within the Earth (*4*) because the formation of continental crust causes fractionation of Sm and Nd and a net enrichment of Nd in the crust (a reservoir having a low Sm/Nd ratio) and a complementary depletion in the mantle (a high Sm/Nd reservoir). Reservoirs that have a high Sm/Nd ratio, such as the source of mid-ocean ridge basalts, evolve toward positive ϵ_{Nd} with time and are described as depleted, whereas the complementary reservoirs that have a low Sm/Nd ratio evolve toward negative ϵ_{Nd} and are referred to as enriched. Rocks that have initial isotopic ratios that are similar to a depleted mantle source are referred to as juvenile, whereas those that are enriched are generally considered to contain a component of older crust. The Nd isotopic composition of Archean rocks can thus help constrain the geochemical characteristics of reservoirs sampled by magmas in the earliest part of Earth history.

Models of Crust-Mantle Evolution

Many models for Earth evolution assume that the Earth progressively differentiated over its entire history from a relatively simple and homogeneous parent body (*5–8*) to one presently characterized by extreme heterogeneity. It is important to distinguish between what we term "secular" and "primordial" heterogeneity in the Earth. Secular heterogeneity reflects the progressive development of geochemically and isotopically distinct components within the Earth over its history, whereas primordial heterogeneity reflects large-scale geochemical segregation resulting from core formation and an early, potentially massive, differentiation of the silicate Earth. In this article we discuss isotopic evidence from Archean rocks that argues for the existence of significant primordial heterogeneity and that Earth's evolution over the past 4.0 to 4.5 billion years comprises a tradeoff between progressive homogenization of primordial heterogeneity and the progressive development of secular heterogeneity through plate tectonics.

Most geochemical models of the outer Earth are based largely on the assumption that the preserved geologic record can be inverted to yield estimates of rates of differentiation and recycling between three principal components: continental crust, primitive mantle, and depleted mantle (*2, 3, 6, 9, 10*); however, other components are also invoked (*11, 12*). Most researchers have proposed crustal growth models in which the cumulative volume of continental crust has increased progressively with time at the expense of primitive mantle, leaving a complementary depleted mantle (Fig. 1). These models assume that the areal extent of continental crust of different ages preserved today directly reflects crustal growth through time. Recognition that the bulk composition of the continental crust is not basaltic {that is, that of primary mantle melts [see, for example, (*13*)]} raises problems for this class of models. Thus, proponents of progressive growth models have adopted models in which the primary magmas in Archean subduction zones are different from those today, forming the tonalite trondhjemite suites that

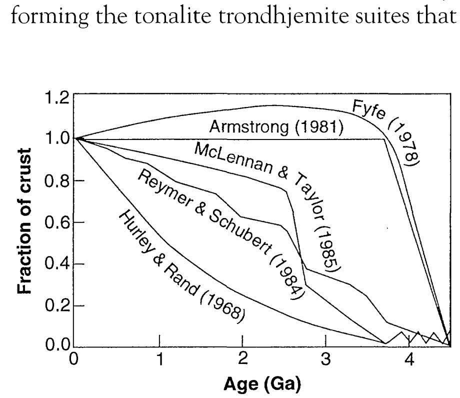

Fig. 1. Representative crustal growth models. With the exception of the models of Fyfe (*16*) and Armstrong (*14, 15*), most crustal growth models invoke a progressive increase in the net volume of crust over most of geologic history based on the areal distribution of Archean and Proterozoic rocks.

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characterize many Archean cratons. In contrast, Armstrong (*14, 15*) and Fyfe (*16*) proposed that the volume of continental crust has remained essentially the same over most of Earth history, with new crustal growth approximately balanced by recycling back into the mantle. A fundamental difference between the two types of models is that the former equate crustal preservation with crustal growth, whereas the latter do not and as a consequence can allow for massive crustal recycling.

When the present areal distribution of continental crust is used to constrain the rates of continental crustal growth (*17*), a strong episodicity in rates of crust formation results that becomes even more pronounced as new high-precision U-Pb zircon ages are obtained (*18*). However, if the preservation of continental crust is a function of its ability to survive as opposed to its rate of production, then the episodic nature of crustal age distributions may provide more insight into preservation mechanisms rather than crustal formation rates (*19*).

The degree to which continental crust, once formed, is returned to the mantle is a subject of much controversy, and radiogenic and isotope data do not uniquely constrain the problem (*2, 3, 15, 20–23*). The principal line of geologic evidence used to argue against a large volume of early continental crust is the small area of known rocks older than 3.8 Ga or their eroded equivalents contained within sedimentary rocks (*5–7, 11, 24*). However, crust older than 3.8 Ga (Fig. 2) is remarkably widespread and is now known from the Wyoming, Nain, and Slave cratons of North America (*25, 26*), west Greenland (*27*), China (*28*), Antarctica (*29*), and western Australia (*30*). These discoveries underscore the possibility that early Archean continental crust was once far more voluminous and widespread than at present; hence, models that assume a small volume of early Archean crust may be incorrect.

A variety of processes result in the destruction of continental crust and its lithospheric mantle. These include sediment subduction and subduction erosion (*31*), rifting (*32*), and delamination or continental subduction during continental collision (*33–35*). The present volume of sediment returned to the mantle along the ~4.35 x 10^4 km of subduction zones is 1.3 to 1.8 km^3 $year^{-1}$, or approximately the same amount added to the crust through arc magmatism (*31*). Assuming present rate and length scales, integration of this volume over 4.0 billion years indicates that a volume of crust (5.2 x 10^9 to 7.8 x 10^9 km^3) approximately equal to that of the existing continental crust (7.2 x 10^9 km^3) may have been returned to the mantle over Earth history. If processes other than sediment subduction such as lithospheric erosion during continental rifting and subduction of continental crust and delamination during collision are considered, estimates of recycling grow commensurately. However, the importance of these processes in influencing the isotopic evolution of the mantle is debated (*2, 3, 6, 14, 15, 21, 22, 36–40*).

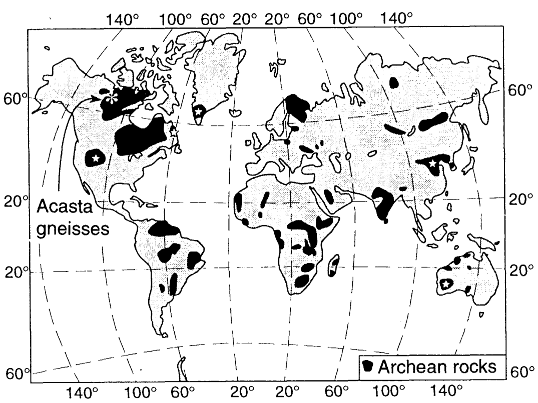
The Early Archean Record and the Acasta Gneisses

Earth's oldest rocks occur mainly within the central stable portions (cratons) of the continents and offer a key perspective on the thermal and chemical evolution of the planet. The Acasta gneisses represent the oldest outcrops of continental crust yet identified. The gneisses occur in the northwest corner of the Canadian shield (Figs. 2 and 3) and have ages that fall into two groups, one around 3.9 to 4.0 Ga and the other around 3.6 Ga (*25, 41, 42*). Gneisses from both groups are geochemically indistinguishable and together comprise a heterogeneous assemblage of foliated to gneissic tonalites, granodiorites, and granites, as well as an assortment of amphibolites and ultramafic rocks.

The gneisses exhibit a wide range of initial ϵ_{Nd} [+3.5 to −4 at 4.0 Ga and +4 to −7 at 3.6 Ga; Table 1 (*43, 44*)]. Modeling of the geochemical and isotopic data suggests that the granites, granodiorites, and tonalites represent mixtures between mantle-derived melts and crustal melts produced by partial melting of garnet-bearing amphibolites and older tonalitic gneisses (*45*), perhaps in a manner similar to that observed in continental magmatic arcs today. The widespread presence of older cores in the zircons (even in the oldest rocks) points to the existence and involvement of older crust (*25, 42*). Evidence for the presence of older crustal components in Earth's earliest preserved crust is not limited to the Acasta gneisses. In the last 10 years, rocks from a number of Archean cratons have yielded highly evolved Nd isotopic compositions (Fig. 4), indicating their interaction with, or derivation from, older light rare earth element (LREE)–enriched crust, some of it perhaps as old as 4.0 Ga (*41, 46–48*).

Early Crustal Evolution

A contentious issue among researchers studying Archean geology is the mechanism by which continental crust is "extracted" from the mantle. Archean cratons are commonly subdivided into granite-greenstone belts and gneiss terranes. Much attention is



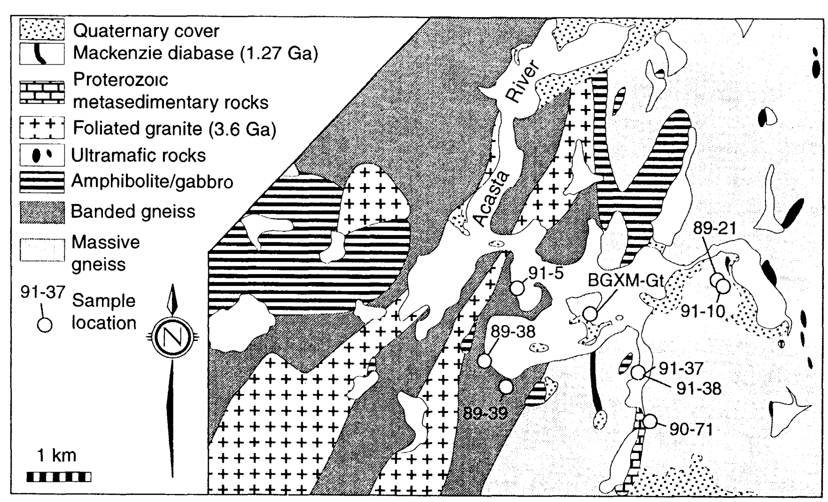


Fig. 2. (**Left**) Distribution of Archean nuclei (solid patches) after Goodwin (*82*). The approximate location of the Slave craton and the Acasta gneisses are indicated by the asterisk. Cratons with evidence for crust older than 3.8 Ga are indicated with stars. **Fig. 3.** (**Right**) Simplified geologic map of the type locality of the Acasta gneisses.

lavished on the structure and geochemistry of granite-greenstone belts; however, it is often the gneiss terranes, dominated by tonalitic to granodioritic gneisses and amphibolite, that contain the earliest record of crustal evolution. Models for the formation of the intermediate-composition gneisses characteristic of these terranes include partial melting of a subducted slab composed of either garnet amphibolite or eclogite (*39*, *49–51*), intracrustal melting of mafic or sedimentary rocks (*45*, *52–55*), arc magmatism, and magmatism associated with rising mantle plumes (*56*).

Tonalites and trondhjemites are commonly viewed as the primary components of early Archean crust. Campbell and Taylor (*49*) pointed out that Earth is the only planet with both extensive sialic crust and free water, which suggested to them a direct relation between oceans and continents in which water is necessary to form large volumes of tonalitic-to-trondhjemitic rocks, perhaps by melting of the hydrated slab during subduction. In fact, the production of early Archean tonalites and trondhjemites by slab melting is a critical component of some models for the generation of Archean crust (*39*, *50*). The intermediate-to-granitic composition of the Acasta gneisses also indicates that water plays an important role in their origin (*49*); however, the data suggest that the gneisses were derived, in large part, by intracrustal reprocessing involving both mantle-derived magmas or juvenile crust (or both), and older, hydrated mafic crust (*45*). Other areas for which a similar model is suggested include the Amitsoq gneisses (*54*), 3.1-Ga tonalitic gneisses from Finland (*53*), 3.4-Ga gneisses from Wyoming (*57*), and Archean tonalitic and trondhjemitic gneisses from Labrador (*58*). The geochemical and isotopic evidence presented in these examples is equally consistent with the production of Archean tonalite-trondhjemite suites as a result of mixing mantle melts and older crust.

Fragments of continental crust are preserved when they are incorporated into a thickened collage that is buoyant relative to the mantle. It is increasingly recognized, however, that the preservation of crustal rocks during continental collision can be biased because much upper crustal material is eroded from mountain belts, and lower crustal rocks can either be subducted (*34*) or episodically delaminated (*59*). Furthermore, this thickened collage may subsequently be a repeated site of further tectonic and magmatic activity. These processes result in the formation of a compositionally stratified continental crust (*13*) that does not reflect in any simple way single-stage derivation from mantle melts.

Early Mantle Evolution

The evolution of the Archean mantle is in large part inferred from the Nd isotopic compositions of mafic and intermediate-composition rocks preserved within the modern continental crust. The general approach in Archean isotopic studies has been to analyze rocks that are perceived to have the simplest magmatic evolution and to calculate initial Nd isotopic compositions for their age. Continental crust is commonly classified as either juvenile (mantle-derived) or evolved (derived at least in part from older enriched crust) on the basis of its initial Nd isotopic composition: positive ϵ_{Nd} is interpreted to reflect derivation from juvenile sources, whereas negative ϵ_{Nd} is interpreted to reflect derivation from evolved sources. In the early days of Nd isotopic studies, it was noted that most Archean rocks had positive ϵ_{Nd}, indicating derivation from a long-term depleted reservoir (Fig. 4) (*1*). This, coupled with an apparent absence of rocks with negative ϵ_{Nd}, was used to argue against a large volume of older, evolved crust. The idea that Archean crust comprises juvenile material persists, even though there is now a plethora of Nd isotopic data indicating the presence of enriched components most simply interpreted in terms of older, evolved crust from many Archean cratons (*3*, *41*, *46–48*, *53*). Furthermore, if it can be shown that rocks with depleted signatures interacted with older crust, then their Nd isotopic compositions may not reflect the composition of mantle reservoirs but, rather, mixtures of crust and mantle melts which, at best, provide only minimum estimates of the isotopic composition of the mantle. This leads to an underestimation of the amount of mantle depletion as well as inaccurate estimates of the volumes and rates of depletion and crustal growth.

Calculated initial ϵ_{Nd} values as high as +3.5 in 3.8- to 4.0-Ga rocks from the Acasta gneisses (Table 1 and Fig. 4) and similar values from Labrador and Greenland (*47*, *60*) indicate that a depleted reservoir with a Nd isotopic composition at least as high as +3.5 was in existence at that time.

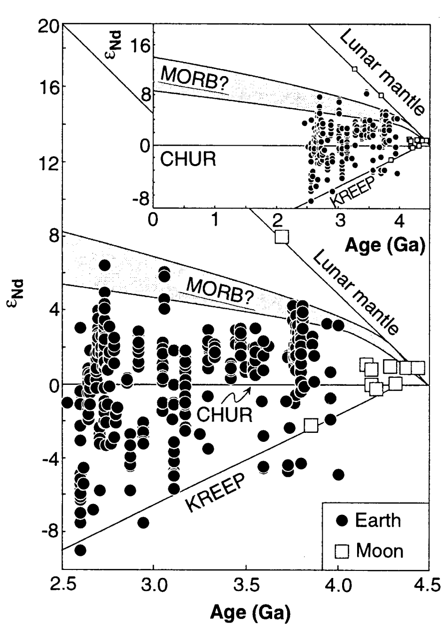


Fig. 4. Nd isotopic compositions of Archean rocks. The data are from Shirey and Hanson (*1*), Chase and Patchett (*11*), Bennett *et al.* (*47*), Frost (*48*), and references cited therein. The lunar data are from Nyquist and Shih (*72*). Inset shows the presumed evolution of the mid-ocean ridge basalt (MORB) source from Archean to present. CHUR, chondritic uniform reservoir; KREEP, potassium, rare earth element, phosphorus-enriched.

Table 1. Nd isotopic data for Acasta gneisses. Samples were spiked with ^{150}Nd and ^{149}Sm and dissolved in a mixture of HF and HNO_3. Sm and Nd were separated by a two-stage process of standard cation exchange columns and HDEHP-on-teflon columns. Sm was loaded on single Ta filaments with H_3PO_4 and analyzed in the static multicollector mode with a ^{152}Sm ion beam of 1 V. Nd was loaded on triple Re filaments with HCl and analyzed in the dynamic multicollector mode with a ^{144}Nd ion beam of 1.5 V. The Sm data are normalized to $^{152}Sm/^{147}Sm$ = 1.783 and Nd data are normalized to $^{146}Nd/^{144}Nd$ = 0.7219. Replicate analyses of La Jolla Nd yield $^{143}Nd/^{144}Nd$ = 0.511845 ± 0.000010 (2σ). ϵ_{Nd} is calculated with $^{143}Nd/^{144}Nd_{CHUR}$ = 0.512638 and $^{147}Sm/^{144}Nd_{CHUR}$ = 0.1967. The error in measured $^{143}Nd/^{144}Nd$ is equal to that of the reproducibility of the standard. The error in $^{147}Sm/^{144}Nd$ is approximately ±0.2%, resulting in an error for $\epsilon_{Nd}(t)$ of approximately ±0.5 epsilon units.

Sample	Rock type	Age (Ga)*	[Nd]†	[Sm]†	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	$\epsilon_{Nd}(t)$
SAB91-37	Tonalitic gneiss	4.0	37.58	5.28	0.08487	0.509854	3.5
SAB91-38	Amphibolitic gneiss	4.0	16.15	4.23	0.15830	0.511376	−4.8
SAB89-39	Granitic gneiss	3.94	15.99	1.94	0.07325	0.509598	3.6
SAB89-38	Tonalitic gneiss	3.74	34.41	5.64	0.09903	0.510108	−2.2
SAB90-71	Trondhjemitic gneiss	3.72	18.57	3.07	0.09982	0.510217	−0.7
BGXM-GT	Tonalitic gneiss	3.6	5.23	1.26	0.14519	0.511189	−4.4
SAB89-18	Tonalitic gneiss	3.6	11.20	2.02	0.10945	0.510610	1.0
SAB89-21	Granodioritic gneiss	3.6	91.36	12.20	0.08086	0.509746	−2.6
SAB91-10	Amphibolitic gneiss	3.6	50.59	9.38	0.11214	0.510420	−4.3
SAB91-5	Granite	3.6	5.72	1.07	0.11267	0.510767	2.6

*Ages are U-Pb zircon crystallization ages. †Concentration given in parts per million.

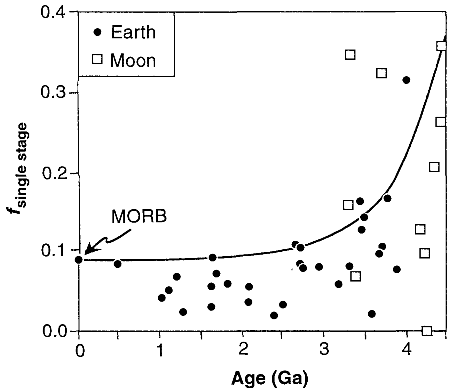


Fig. 5. Plot of single-stage $f = [(^{147}Sm/^{144}Nd)_{sample} / (^{147}Sm/^{144}Nd)_{CHUR} - 1]$ versus age. This shows the value of f needed to generate the most positive ϵ_{Nd} (most depleted source) for suites of both terrestrial and lunar rocks by single-stage growth since 4.55 Ga. The curve shows the approximate upper limit of single-stage f for terrestrial rocks since the early Archean.

A time-integrated $^{147}Sm/^{144}Nd$ greater than 0.246 is required to produce the highest Nd isotopic composition observed at 4.0 Ga ($\epsilon_{Nd} = +3.5$) in the Acasta gneisses by single-stage growth from an initially chondritic reservoir at 4.55 Ga. This $^{147}Sm/^{144}Nd$ value is approximately that inferred for the modern mid-ocean ridge basalt (MORB) reservoir (*4*), indicating that a reservoir was present in the early Earth that was at least as depleted as the mantle reservoir of today.

A compilation of available initial ϵ_{Nd} values for Archean rocks shows remarkably little variation through time among samples derived from the most depleted reservoirs (Fig. 4). The data do, however, indicate the existence of a long-term depleted reservoir with a restricted range of initial ϵ_{Nd} between +4 and +7 (Fig. 4), and the inferred isotopic composition of this reservoir changed little during the Archean (*40*, *47*). This implies that development of the isotopic composition of the depleted reservoir was retarded or buffered by either the addition of fresh undepleted mantle or recycling of enriched crust (*14*, *20–22*, *36*, *37*), long-term isolation of basaltic crust or lithosphere (*7*, *11*, *61*), or the existence of an enriched mantle reservoir (*12*). These data are inconsistent with the presence of transient, small-volume, highly depleted sources for Archean rocks (*6*, *47*) because the consistency of the most positive ϵ_{Nd} values from different cratons is not expected in that case.

Most researchers have hesitated to invoke recycling of early formed enriched continental crust as a mechanism to explain the observed Nd isotopic data because they perceived that early enriched continental crust did not exist (*6*, *11*, *24*); however, the isotopic data from the Acasta gneisses and other Archean cratons (*47*, *48*), as well as the discovery of 4.1- to 4.3-Ga detrital zircons derived from enriched continental crust (*62*), clearly indicate that continental crust with the appropriate characteristics was available for recycling.

The observed lack of isotopic evolution in the early Archean mantle requires a balance between the timing of depletion and the addition of enriched material. The Nd isotopic data for the Acasta gneisses and other Archean rocks require extreme early fractionation to generate the observed Nd isotopic compositions at 4.0 Ga and efficient recycling to retard further isotopic evolution. Because of the relative enrichment of Nd in the crust, as well as its more evolved isotopic composition, it is easier to buffer evolution of a depleted reservoir by the addition of old enriched crust rather than by the addition of either undepleted primitive mantle or enriched continental lithospheric mantle, because much smaller volumes of crust are required. If the present-day age distribution of continental and oceanic crusts is a measure of Archean distributions, then buffering is enhanced because the residence time of a volume of continental crust is on average an order of magnitude longer than that of oceanic crust. We interpret the present paucity of early Archean rocks to reflect the efficiency of this recycling rather than a lack of their production. Alternatively, if a large undifferentiated mantle reservoir was present throughout Earth history and has mixed with the depleted source, it is difficult to explain the lack of basaltic rocks with the appropriate isotopic composition (*21*, *63*). Additionally, the mixing of a dominantly depleted reservoir with varying amounts of a recycled component in upwelling plumes from the lower mantle is difficult to reconcile with a large volume of undepleted mantle (*64*)

^{142}Nd Systematics and the Archean Mantle

Harper and Jacobsen (*65*) reported the existence of excess ^{142}Nd, produced by the decay of the now extinct ^{146}Sm nuclide (half-life, $t_{1/2}$, of 103 million years), in a ~3.8-Ga metasedimentary rock from Isusakia, Greenland. The presence of this ^{142}Nd anomaly was interpreted by them to reflect the derivation of the rock from a mantle reservoir that was depleted sometime before 4.3 Ga. To date, only one other rock from Isua has a positive ^{142}Nd anomaly, and no other rocks yet analyzed, including several samples of the Acasta gneisses, have a discernible ^{142}Nd anomaly (*5*, *66*, *67*). Early depletion of the mantle before 4.3 Ga should result in the development of a positive ^{142}Nd anomaly in all rocks derived from it, as mantle depletion leads to higher Sm/Nd ratios. One explanation for the lack of ^{142}Nd anomalies and a crustal record older than 4.3 Ga is that the mantle did not effectively differentiate until after 4.3 to 4.2 Ga when ^{146}Sm became extinct (*65*, *67*). If this was the case, then a relatively high $^{147}Sm/^{144}Nd$ of 0.334 to 0.288 is required to obtain the observed minimum value of ϵ_{Nd} of +3.5 at 4.0 Ga.

Jacobsen and Harper (*68*) pointed out that if there was continuous growth and recycling of continental crust from early in Earth's history, not only would ^{142}Nd anomalies not survive at currently detectable limits [>10 parts per million (ppm)] in the mantle source region, but also that positive ^{143}Nd anomalies could. They further suggested that if the Isua sample is representative of the depleted mantle reservoir at 3.8 Ga, then recycling could not have been an important process before 3.9 Ga. However, as this sample is a pelitic metasedimentary rock with 68.8% SiO_2 (*69*), there is no a priori reason to suspect that it was derived from the depleted mantle. Rather, it seems reasonable that the rock was derived from older crust, some of which had itself been at least partially derived from the depleted mantle at an earlier time.

Another explanation of the lack of ^{142}Nd anomalies in crustal rocks is that the positive ϵ_{Nd} values of many Archean rocks are the result of Sm-Nd fractionation during metamorphism and that these rocks were not originally derived from a depleted mantle reservoir (*66*, *70*). Although metamorphic effects must be considered (*4*), the remarkable consistency of ϵ_{Nd} values for many early Archean rocks is hard to reconcile with this interpretation. If we view growth, preservation, and recycling of crust during the Archean as complex processes, then it seems possible that a few fragments of crust that preserve pre–4.3-Ga differentiation might exist. In fact, the Isua sample with a ^{142}Nd anomaly may itself be evidence for undiscovered pre–4.2-Ga crust in the North Atlantic craton that contributed detritus to the sample. We suggest that the absence of ^{142}Nd anomalies but the presence of positive and negative ϵ_{Nd} values in most early Archean rocks is consistent with continuous crustal growth and recycling during the early Archean.

Nd Isotopic Heterogeneity in the Early Earth

The development of isotopic heterogeneities is a function of both the degree of parent-daughter fractionation, mixing rates, and time. In old rocks a smaller range in isotopic compositions may reflect a larger amount of variation in parent-daughter ratios relative to younger rocks. It is difficult to evaluate the degree of heterogeneity by examination of plots of initial isotopic ratio as a function of time (Fig. 4). A better way to visualize the variations is to calculate the single-stage parent-daughter ratio for isotopic growth from a chondritic composition at 4.55 Ga to the most depleted compositions at a given time. For example, a range in 4 epsilon units at 4.0 Ga requires a 29% difference (relative to a chondritic reservoir at 4.55 Ga) in $^{147}Sm/^{144}Nd$ contrasted with a 3.5% difference for 4 epsilon units today. Figure 5 shows the range in single-stage $^{147}Sm/^{144}Nd$ calculated for the most positive values of ϵ_{Nd} plotted against age for suites of both terrestrial and lunar rocks. A prominent feature observed in this diagram is the progressive narrowing of the range in single-stage $^{147}Sm/^{144}Nd$ with decreasing age for terrestrial rocks. In contrast, the more limited data from the moon show no relation with time. A plausible explanation of this observation is that the early Earth and moon were characterized by a greater degree of primordial heterogeneity, at least on the scale at which magmas sample reservoirs, than the modern Earth. With respect to parent-daughter fractionation, this suggests that the Earth erased much of its record of early heterogeneity, whereas the moon preserved its primordial variations. The reservoir that yielded the most depleted samples from the Acasta gneisses had a single-stage $^{147}Sm/^{144}Nd$ at least as high as the modern MORB reservoir (~0.25); however, that this degree of depletion developed in the first 550 million years of Earth's history relative to the 4.55 billion years the modern MORB reservoir has had to evolve emphasizes the heterogeneity in the early Earth.

Increasing homogenization with time is not intuitive. Many existing models for Earth's evolution emphasize the progressive differentiation of the planet [see, for example, (*3*, *5*, *6*, *39*, *47*)]. Clearly the geochemical development of the Earth involves a tradeoff between processes resulting in increased differentiation, such as melt extraction, and those that contribute to homogenization, such as subduction recycling and convective mixing. Models that assume that recycling of continental crust and convective mixing are unimportant on Earth will necessarily result in a system characterized by increasing heterogeneity with time. However, the Nd isotopic data clearly indicate that the crust-mantle system is characterized by a progressive decrease in early formed heterogeneity. We interpret this decrease as a consequence of a planet characterized by large-scale convection in which recycling plays an important role.

Lunar Evolution

From a planetary perspective, it appears inescapable that the Earth and moon differentiated extensively early in their histories as they each formed a core, depleted mantle, and crust (*71*). The Nd isotopic composition of lunar basalts indicates considerable heterogeneity in their source regions resulting from early differentiation (*72*) (Fig. 4). Mare basalts were erupted on the moon from ~4.4 to 3.2 Ga and are characterized by positive initial ϵ_{Nd}, indicating a highly depleted source. It is widely accepted that these basalts are derived from a layered mantle comprising cumulates settled from an early magma ocean or oceans [see, for example, (*73*)]. The temporal isotopic evolution of mare basalts is consistent with subsequent long-term closed-system evolution of this source. In contrast, the lunar KREEP (potassium, rare earth element, phosphorus-enriched) basalts are characterized by lower ϵ_{Nd} values, indicating the presence of a highly enriched source (*72*, *74*). The variability in Nd isotopic composition and geochemistry of all lunar samples is consistent with interaction between melts derived from both depleted and enriched sources (*75*). Compared with the early moon, the early Earth was a dynamic environment. The lack of plate tectonics on the moon resulted in the preservation of a record of early differentiation and crust formation, whereas the larger, hotter, and hence more vigorously convecting, Earth largely eradicated the record of its earliest history. Even though most of that record has been destroyed, the growing database of Nd isotopic data from early Archean rocks suggests that the early Earth, like the moon, contained both highly enriched and depleted reservoirs (Fig. 4).

Why Is There So Little Old Crust?

A major unresolved question is, What was the fate of the Earth's early formed enriched crust? The fact that we do not observe much of this earliest crust today, coupled with the retarded Nd isotopic evolution of the depleted mantle reservoir, is consistent with efficient recycling back into the mantle. Most examples of early Archean crust are within cratons now presently characterized by thick lithospheric roots (*76*, *77*), suggesting that the development of a lithospheric mantle root may help to preserve ancient continental crust. Although the timing and mechanics of the development of a lithospheric mantle root are poorly constrained (*77*, *78*), it is likely that the development of lithospheric roots and the preservation of a particular fragment of Archean crust requires unusual conditions, such as protracted cooling of the asthenosphere beneath a growing yet stationary continental fragment (*79*) or underplating by subducted oceanic lithosphere (*78*, *80*), raising the possibility that the preserved record is highly biased (*81*). Today, an extreme example is the preferential destruction of oceanic lithosphere relative to continental lithosphere. Cooling of the Earth is expedited if the volume of continental lithosphere is minimal because the most efficient heat transport is by advection (sea floor spreading and mantle plumes), not conduction through the base of the lithosphere. A large volume of Archean crust may have formed, but, not being stabilized by the presence of a lithospheric mantle root, it may have been recycled back into the mantle. Thus, crustal "growth" curves (Fig. 1) based on the preserved geologic record may strongly skew net crustal growth to younger ages and be highly unrepresentative of Archean crustal history. We endorse the view first articulated by Armstrong (*14*, *15*, *23*, *36*) over 25 years ago—that the Earth differentiated early in its evolution into a crust, depleted mantle, and core—and we further suggest that the Earth's evolution toward thermal, compositional, and gravitational equilibrium has been dominated by the formation and destruction of oceanic and continental lithosphere ever since. The gradual increase in the most positive initial ϵ_{Nd}'s over 4.0 billion years of Earth history is consistent with a gradual increase in the volume of preserved continental crust with time as a result of Earth's waning thermal regime and a decrease in recycling rates.

Nd isotopic data from the Acasta gneisses and other early Archean terranes provide important constraints on the geochemical evolution of the Earth. Early Archean rocks contain evidence for involvement of both older enriched sialic crust and a highly depleted source. Consideration of this data as well as the chemical composition of continental crust leads to the conclusion that the Earth differentiated early in its history and that the record of this differentiation was largely obliterated by subsequent recycling of crustal materials back into the mantle. Outstanding questions relate to how much of the Earth's mantle has participated in the formation and recycling of continental crust, whether there has been secular change in exchange between the lower and upper mantle, and reconciliation of heavy radiogenic and nobel gas isotope data (*70*) and the seismic velocity structure of the mantle (*12*).

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tope ($^{143}Nd/^{144}Nd$) is a function of variations in the Sm/Nd ratio of terrestrial reservoirs. For simplicity, we also use the epsilon notation where

$$\epsilon_{Nd}(t) = \left[\left(\frac{^{143}Nd/^{144}Nd_{sample}(t)}{^{143}Nd/^{144}Nd_{CHUR}(t)} \right) - 1 \right] 10{,}000$$

CHUR is the chondritic uniform reservoir that has a present-day $^{143}Nd/^{144}Nd = 0.512638$ and $^{147}Sm/^{144}Nd = 0.1967$, and t is the crystallization age of the sample. Positive $\epsilon_{Nd}(t)$ indicates a long-term depletion in Nd relative to Sm in the source of the sample, whereas a negative $\epsilon_{Nd}(t)$ indicates a long-term enrichment in Nd. The potential effects of metamorphism on the initial Nd isotopic composition of the Acasta gneisses must be considered. The determination of the initial Nd isotopic composition in Archean rocks can be approached in two ways. The simplest way is to determine a whole-rock isochron and corresponding initial ratio from a suite of rocks with different Sm/Nd ratios but the same initial Nd isotopic composition. However, the Acasta gneisses are compositionally and temporally heterogeneous and thus were not all derived from a single homogeneous reservoir at the same time. Therefore, any linear array on an isochron diagram for these samples is a mixing line, and calculated ages and initial isotopic ratios have no geological significance. The Acasta gneisses discussed in this paper are a sequence of layered metaigneous rocks that have been subjected to deformation. This geologic history resulted in a series of layered rocks in which the layers reflect differences in primary igneous compositions. Layers can occur on scales of meters to centimeters. Individual layers within the Acasta gneisses analyzed in this study do not have sufficient variation in Sm/Nd to allow an isochron age to be calculated. Therefore, the best estimate of the age of the Acasta gneisses is from U-Pb zircon analyses. Nd isotopic data reported in this article come from samples whose crystallization ages have been determined by either SHRIMP ion-microprobe or conventional single-grain–grain fragment ages. All samples reported in this article were taken from homogeneous layers in the Acasta gneisses and are interpreted to represent primary igneous lithologies. In many cases several samples from each layer have been analyzed and yield identical results, within uncertainties, that are distinct from adjacent lithologies (*44*). The preservation of centimeter- to meter-scale heterogeneity corresponding with rock type argues against metamorphic disturbance of the Sm-Nd whole-rock systematics.

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Sm-Nd Isotopic Data and Earth's Evolution

Samuel A. Bowring and Todd Housh (*1*) report Sm/Nd isotopic data giving a wide range of initial ϵ_{Nd} values, from +3.5 to −4 at 4.0 billion years ago (Ga) and from +4 to −7 at 3.6 Ga. Their samples were from the Acasta gneisses of northern Canada, which represent the oldest known outcrops of continental crust (*2*). Their modeling of the Sm-Nd isotopic data is taken to suggest that the Acasta granitoid rocks were formed from mixtures between mantle-derived melts and crustal melts derived from extremely ancient (about 4.3 Ga), heterogeneous, depleted (high Sm/Nd) and enriched (low Sm/Nd) reservoirs. We consider it likely that the wide range of initial ϵ_{Nd} values has a much simpler explanation.

We plot the Acasta gneiss Sm-Nd data of Bowring and Housh (*1*) and Bowring *et al.* (*3*) on a Sm-Nd isochron diagram (Fig. 1). Ten out of 13 points define a well-correlated regression line ("errorchron"), yielding an age of 3239 ± 150 million years ago (Ma) (2 σ errors; MSWD = 36), with an initial ϵ_{Nd} value of −7.9 ± 1.8. These data points are based on samples for which SHRIMP ion-microprobe zircon U-Pb dates range between 4.0 and 3.6 Ga (*1, 3*). If we consider only those samples with the oldest zircon U-Pb dates of about 4.0 Ga, the regression age for five out of six samples is 3156 ± 100 Ma (MSWD = 6.4) and the initial ϵ_{Nd} value is −9.0 ± 1.3 (Fig. 1).

We therefore propose that the Acasta gneisses suffered a tectonothermal event at about 3.2 Ga that caused open-system behavior of Sm-Nd and resulted in an approximation to Nd-isotope homogenization on the scale of sampling, regardless of whether the samples were originally cogenetic or not. Geological scatter (MSWD > 1) about the errorchron shows that either pre-3.2 Ga ϵ_{Nd}–heterogeneities were not totally eradicated, or that post-metamorphic disturbance [for example, at about 1.9 Ga (*4*)] caused limited additional open system behavior in the Sm-Nd system. Nevertheless, an Nd-isotope evolution diagram (Fig. 2) illustrates that calculated initial ϵ_{Nd} values in rocks about 4 Ga old that underwent approximate Nd-isotope homogenization at 3.2 Ga would yield a wide range of apparent initial ϵ_{Nd} values with no geological significance whatever. On the other hand, initial ϵ_{Nd} values of about −8 to −9, obtained from the regression lines in Fig. 1, point to the existence of an enriched (low Sm/Nd) crustal protolith with an age greatly exceeding 3.2 Ga. Assuming an age of 3.96 Ga for the oldest Acasta gneisses (*1, 2, 3*) and an initial $\epsilon_{Nd}(3.96)$ ratio of +1.0 in line with the conventional depleted-mantle model of De Paolo *et al.* (*5*), then an average Sm/Nd ratio of 0.17 is required for the rocks to evolve to an ϵ_{Nd} value of −9.0 at 3.2 Ga. This correlates with the average Sm/Nd ratio of 0.17 for upper continental crust (*6*). This consistency of plausible parameters provides independent, though circumstantial, evidence for the great age of the Acasta gneiss protolith.

In summary, our interpretations are that (i) the Sm-Nd system in the Acasta Gneisses was opened and largely reset by metamorphism some 0.7 to 0.8 Ga after the time of rock formation and, therefore, (ii) precise U-Pb dates on zircon cannot necessarily be used as a basis for inferring the existence of extremely heterogeneous, rare earth element–fractionated mantle and crust reservoirs during earliest earth history (that is, pre-4 Ga in the present case) because the calculated ϵ_{Nd} values may be spurious.

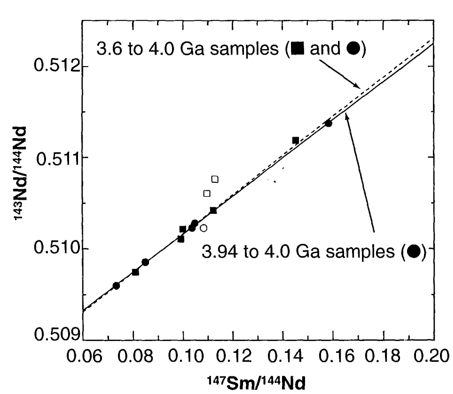

Fig. 1. Sm-Nd isochron diagram for Acasta gneiss samples analyzed by Bowring and Housh (*1*) and Bowring *et al.* (*3*). The dashed line includes samples whose zircon U-Pb age ranges from 3.6 to 4.0 Ga [3239 ± 150 Ma; $\epsilon_{Nd}(t)$ = −7.9 ± 1.8; (n = 10; MSWD = 36)], while the continuous line includes those from 3.94 to 4.0 Ga only [3156 ± 100 Ma; $\epsilon_{Nd}(t)$ = −9.0 ± 1.3 (n = 5; MSWD = 6.4)]. Open symbols were omitted from the regression.

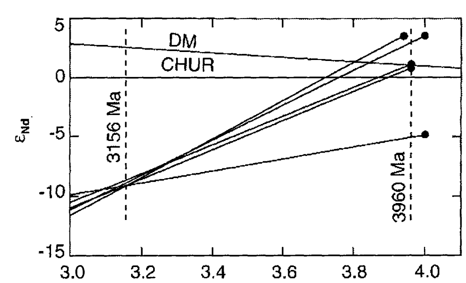

Fig. 2. Nd isotope evolution for the five oldest Acasta gneiss samples which plot on the continuous line in Fig. 1. Extrapolation from the Nd-isotope homogenization age of 3156 Ma (Fig. 1) back to the average age of 3960 Ma for the samples yields a wide range of apparent initial ϵ_{Nd} values.

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Response: The effect of metamorphism on whole rock Nd isotopic data is an important issue, and we welcome the opportunity to address it in more detail. Moorbath and Whitehouse challenge our interpretation of highly variable initial ϵ_{Nd} values in different rock types of the Acasta gneisses largely on the basis of the distribution of our data on a $^{143}Nd/^{144}Nd$ - $^{147}Sm/^{144}Nd$ isotope correlation diagram. If 3 of the 13 data points are disregarded, the remainder "define" a linear array that Moorbath and Whitehouse interpret as an isochron. The age it suggests is considerably less than the crystallization ages of the rocks (about 3.2 Ga) and is referred to by Moorbath and Whitehouse as a time of "Nd-isotope homogenization." This interpretation is in error for several reasons: (i) Moorbath and Whitehouse use "errorchrons" with MSWDs significantly greater than 1 and conclude that the age and initial ratio calculated for the slope of this linear array has statistical significance. This is a statistically invalid approach, as outlined by Wendt and Carl (*2*); (ii) they hand-pick a subset of rocks to lower the MSWD of the linear array by arbitrarily removing points (the three that are the most displaced); and (iii) they refer to the scatter about the linear array as "geologic scatter," which they interpret as being caused by either incomplete homogenization of pre-3.2 Ga heterogeneities or another younger disturbance. This seems essentially an ad hoc explanation that relies on the assumption that the calculated age is significant. An equally plausible interpretation is that the scatter is a result of the fact that the samples were never isochronous.

It is possible to produce linear arrays on isotope correlation diagrams (even statistically significant ones) that do not have any age significance and are best interpreted as mixing lines. The half-life of ^{147}Sm is so long that even for geologically significant periods of time (hundreds of millions of years) little change occurs in the Nd isotopic composition of rocks; thus, a number of rocks that start with slightly different initial ratios and Sm/Nd may produce linear arrays on an isotope correlation diagram with no age significance.

As described in the notes of our article (*1*), we selected our samples with an understanding of their geological history. Our test for metamorphic disturbance is to analyze multiple samples from the same rock unit to see if this results in variable calculated initial ratios or an isochron that is considerably younger than its crystallization age as determined by U-Pb geochronology. The data presented in Bowring and Housh (*1*) passed the screening tests. The geology of the Acasta gneisses is complex, and we are working on a better understanding of it. However, we have yet to document evidence for a metamorphic event at 3.2 Ga, as suggested by Moorbath and Whitehouse, despite the application of a wide variety of thermochronometers to the Acasta gneisses (U-Pb zircon, U-Pb titanite, $^{40}Ar/^{39}Ar$ hornblende, and others).

There is a significant difference between interpreting all linear arrays on isotope correlation diagrams as having geological significance and actually documenting it. We are in agreement that the role of metamorphism must be understood; the key to doing so lies in the integration of both geochemical and geological constraints, something that Moorbath and Whitehouse do not address in their comment.

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