

Nd ISOTOPIC VARIATIONS and PETROGENETIC MODELS

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Abstract: The decay of ^{147}Sm to ^{143}Nd allows $^{143}\text{Nd}/^{144}\text{Nd}$ to be used to trace Sm/Nd fractionation in long time-scale geologic processes. $^{143}\text{Nd}/^{144}\text{Nd}$ has been measured in terrestrial rock samples of different ages to establish the characteristics of Nd isotopic evolution in the crust and mantle. The evolution of $^{143}\text{Nd}/^{144}\text{Nd}$ in the mantle indicates Sm/Nd essentially equal to that of chondrites, and implies a chondritic REE distribution for the earth. Variations in $^{143}\text{Nd}/^{144}\text{Nd}$ do exist in the mantle, however, indicating Sm/Nd heterogeneity and the existence of distinct mantle reservoirs with characteristic $^{143}\text{Nd}/^{144}\text{Nd}$. $^{143}\text{Nd}/^{144}\text{Nd}$ in average crustal rocks today is much lower than found in recent mantle samples and reflects their age and low Sm/Nd. Oceanic tholeiites and alkali basalt are derived from sources with Sm/Nd which has been 5-10% greater than chondritic over the age of the earth. Alkali basalt can not be derived from mantle reservoirs which have been light REE-enriched for long times.

Long-lived, naturally-occurring radioisotopes are important not only in the measurement of absolute time, but also as indicators of chemical processes involved in rock formation. ^{147}Sm decays to ^{143}Nd with a half-life of 1.06×10^{11} years. Sm and Nd are even-numbered light lanthanide elements, so their cosmic abundances and chemical properties are similar. But, Sm/Nd fractionation is commonly observed in rocks and minerals, and is a sensitive indicator of fractionation in the light rare-earth elements (REE). The use of Sm-Nd as a dating method was pioneered by *Lugmair* (1974) and *Lugmair et al.* (1975 a,b,c,d) who determined ages of the Juvinas and Stannern achondrites and one lunar basalt. The purpose of this study is to investigate the isotopic composition of Nd in selected *terrestrial* rocks to gain information about its implications for petrogenesis and the history of the earth's crust and mantle. The potential usefulness of the Sm-Nd system for the dating of terrestrial rocks is also made manifest. A symbolism is introduced which may be useful in presentation and interpretation of the data.

As discussed by *Lugmair* (1974) the ratio $^{143}\text{Nd}/^{144}\text{Nd}$ is an indicator of changes in the relative abundance of ^{143}Nd due to ^{147}Sm decay. For formation and chemical evolution of a planet, the growth of $^{143}\text{Nd}/^{144}\text{Nd}$ with time in various reservoirs may be shown schematically (Figure 1). At T_C a planet condenses from the solar nebula (SN). The rate of $^{143}\text{Nd}/^{144}\text{Nd}$ growth in the bulk planet may be different from the growth rate in the solar nebula due to a change in Sm/Nd occurring during condensation (*Boynton*, 1975). If a reservoir with Sm/Nd = 0 were isolated at T_C , I_C would record $^{143}\text{Nd}/^{144}\text{Nd}$ at the time of condensation. If the planet remains a closed system with respect to Sm and Nd subsequent to T_C , the evolution of its average $^{143}\text{Nd}/^{144}\text{Nd}$ will be described by a line whose slope is proportional to its average Sm/Nd. The bulk planet is herein termed a "uniform reservoir" (UR) and the growth of $^{143}\text{Nd}/^{144}\text{Nd}$ in UR as a function of time is the curve $I_{UR}(T)$. The value of $^{143}\text{Nd}/^{144}\text{Nd}$ in UR today is defined as $I_{UR}(0)$. $^{143}\text{Nd}/^{144}\text{Nd}$ in UR at any time T in the past is given by

$$I_{UR}(T) = I_{UR}(0) - \left(\frac{^{147}\text{Sm}}{^{144}\text{Nd}} \right)_{UR}^0 (e^{\lambda T} - 1), \quad (1a)$$

where $(^{147}\text{Sm}/^{144}\text{Nd})_{UR}^0$ is that in UR today and $\lambda = 6.54 \times 10^{-12} \text{ yr}^{-1}$. If a rock is derived from this average reservoir at time T, its initial $^{143}\text{Nd}/^{144}\text{Nd}$ would be $I_{UR}(T)$.

Chemical differentiation in the planet subsequent to T_C will result in reservoirs with different Sm/Nd. The Sm/Nd of a reservoir can be expressed relative to UR in terms of a Sm/Nd

enrichment factor f, where $f = \left\{ \frac{(\text{Sm/Nd})_{\text{Res}}}{(\text{Sm/Nd})_{\text{UR}}} - 1 \right\}$. If at a time

$T_1 \ll T_C$ a secondary reservoir A is isolated from UR with initial value I_1 and $f < 0$, $^{143}\text{Nd}/^{144}\text{Nd}$ in this reservoir would evolve from (T_1, I_1) along a line of lower slope to the value R_A observed today. Similarly $^{143}\text{Nd}/^{144}\text{Nd}$ in a reservoir B, isolated from UR at T_1 with $f > 0$ would evolve along a steeper trajectory to R_B today. For rocks of zero age the Nd isotopic composition of the source region is identical to that measured in the rock. $^{143}\text{Nd}/^{144}\text{Nd}$ in source regions of old rocks is found by determination of the initial $^{143}\text{Nd}/^{144}\text{Nd}$ (I). This can be obtained from an internal isochron or, if the age is known, from the measured $^{143}\text{Nd}/^{144}\text{Nd}$, $^{147}\text{Sm}/^{144}\text{Nd}$, and the age T:

$$I = \left(\frac{^{143}\text{Nd}}{^{144}\text{Nd}} \right)_{\text{meas}} - \left(\frac{^{147}\text{Sm}}{^{144}\text{Nd}} \right)_{\text{meas}} (e^{\lambda T} - 1). \quad (1b)$$

As shown in Figure 1, two rocks of the same age T_1 , but different initial I_1 and I'_1 , must have been derived from distinct parent reservoirs.

In a reservoir whose Sm/Nd is equal to that in chondritic meteorites (0.31) (*Masuda et al.*, 1973), $^{143}\text{Nd}/^{144}\text{Nd}$ will increase by 1.13% in 4.5AE. REE abundance patterns in various rocks indicate that sufficient variation in Sm/Nd exists so that initial $^{143}\text{Nd}/^{144}\text{Nd}$ may be used to distinguish different source regions. Some of the isotopic patterns can be anticipated from the extensive experimental and theoretical studies of REE abundances and fractionation patterns. (cf. *Haskin et al.*, 1966a.)

Analytical Procedure and Data. In general, the chemical and mass spectrometric procedures used closely follow those which have been used here for the past eight years for Gd and Sm. Separation of Sm and Nd was accomplished using the procedure described for Gd separation by *Eugster et al.* (1970), with slight modifications. Sm and Nd were eluted from Dowex AG 50W-X4 cation exchange resin using 0.2M 2-Methylactic

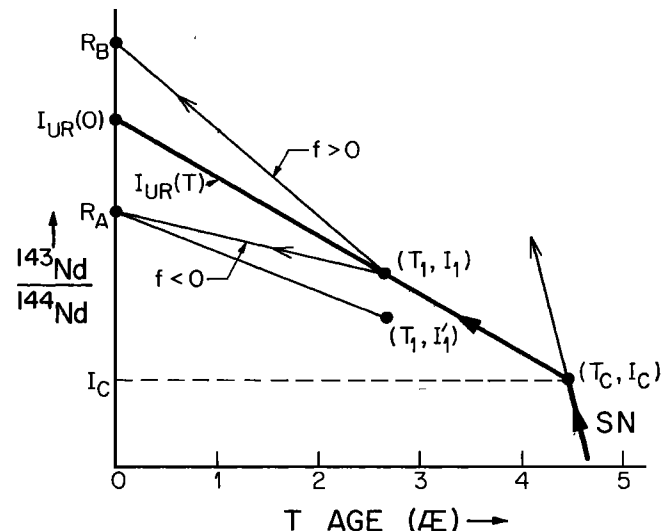


Fig. 1: Schematic representation of the evolution of $^{143}\text{Nd}/^{144}\text{Nd}$ with time in the solar nebula (SN) and in a hypothetical planetary object condensed at T_C . The growth rate of $^{143}\text{Nd}/^{144}\text{Nd}$ is proportional to Sm/Nd. f is the Sm/Nd enrichment factor relative to UR.

Table 1: Normalized Nd isotope ratios^a

Sample	142/144	143/144	145/144	146/144	148/144
113031	1.13821 ±8	0.512115 ±40	0.348952 ±30	0.724082 ±35	0.243066 ±30
111240	1.13828 ±5	0.512361 ±22	0.348975 ±18	0.724113 ±26	0.243091 ±26
113152	1.13823 ±7	0.512280 ±35	0.348950 ±42	^b	0.243112 ±43
BCR-1	1.13827 ±4	0.511839 ±22	0.348977 ±19	0.724088 ±36	0.243070 ±19
Khibina Ap.	1.13827 ±4	0.511862 ±17	0.348970 ±19	0.724116 ±30	0.243082 ±20
NAS-216D	1.13823 ±4	0.511101 ±27	0.348968 ±38	0.724086 ±54	0.243110 ±29
RHO-1D	1.13819 ±15	0.510994 ±48	0.348943 ±48	0.724079 ±113	0.243089 ±34
RN3-D(TR)	1.13830 ±8	0.510245 ±31	0.348977 ±42	0.724139 ±58	0.243072 ±38
RN3-D(TR)	1.13821 ±9	0.510234 ±37	0.348913 ±46	^b	0.243065 ±65
RN3 Ap.	1.13825 ±5	0.511343 ±23	0.348965 ±27	0.724122 ±31	0.243084 ±28
OGG128,10D	1.13826 ±6	0.510026 ±30	0.348965 ±17	0.724103 ±44	0.243089 ±22
NN1	1.13829 ±6	0.510306 ±19	0.348952 ±28	0.724091 ±43	0.243080 ±30
NN1	1.13829 ±5	0.510329 ±21	0.348978 ±15	^b	0.243091 ±17
NN2	1.13826 ±3	0.511132 ±16	0.348946 ±13	0.724115 ±20	0.243061 ±14
NN2	1.13827 ±6	0.511148 ±31	0.349009 ±17	0.724156 ±45	0.243092 ±31
NN2	1.13824 ±9	0.511124 ±18	0.348993 ±26	^b	0.243074 ±33

^aNormalized to $^{150}\text{Nd}/^{142}\text{Nd} = 0.2096$, errors are 2σ mean. ^bSpiked with ^{150}Nd and normalized to $^{146}\text{Nd}/^{142}\text{Nd} = 0.636155$

acid with pH adjusted to 4.60. Total procedural blank for Nd was 10^{-10} gm. Nd was loaded in 1.0 N HCl onto a single flat Re ribbon and oxidized. Nd isotopic ratios were measured on the Lunatic I mass spectrometer (Wasserburg *et al.*, 1969), as NdO⁺. The ion beam intensity at mass 160 ($^{144}\text{Nd}^{16}\text{O}$) was 10^{-11} A at filament temperatures between 1220° and 1280°C. Ion beam intensity ratios were calculated relative to mass 160. At each mass the high zero, peak and low zero are measured with an integration time of 1 sec at each position. Data is taken in sets of 10 mass scans, averaged; corrected for oxygen and then discrimination. The effect of peak tails on zeros was assessed by measuring the zeros with beam on and beam off. The background offset is less than 0.005% of the peak intensity for all isotopes. Oxygen corrections were made using the composition by Nier (1950). Mass discrimination corrections were made by normalizing to $^{150}\text{Nd}/^{142}\text{Nd} = 0.2096$, the average measured value in several mass spectrometer runs. In a typical run of 200 ratios, 1σ is 0.01% and 2σ mean is 0.005%. Possible spectral interferences were monitored by scanning at high sensitivity from mass 125 to mass 200. Peaks could be detected representing LaO⁺ and GdO⁺ at intensities $< 1.5 \times 10^{-6}$ A and SmO⁺ at 10^{-5} A. Occasionally Ba⁺ was detected ($< 10^{-5}$ A). No other peaks were observed at a detection limit of 2.5×10^{-7} A. Interference from SmO⁺ ions is corrected by monitoring the signal at mass 170 ($^{154}\text{Sm}^{16}\text{O}$). The net correction to $^{143}\text{Nd}/^{144}\text{Nd}$ when the signal at mass 170 is 0.01% of the 160 signal is only 4×10^{-4} %. Isotopic measurements were made on spiked and unspiked aliquants which were passed through chemistry. Sm and Nd concentrations were determined on the same aliquant. Internal consistency of isotopic measurements is shown by agreement of all isotope ratios from different samples and from spiked and unspiked runs on the same sample. Reproducibility is demonstrated by repeat runs on normals. Nd isotopic data are given in Table 1, and are the first high precision Nd abundances obtained using modern techniques.

Data representation. Because of the variations in $^{143}\text{Nd}/^{144}\text{Nd}$ are small, data will be presented normalized to a uniform reservoir (UR) as described above. This is a somewhat

different approach than has been used for Rb-Sr, where there are large variations of $^{87}\text{Sr}/^{86}\text{Sr}$ and there is no clearly defined, meaningful reference reservoir representative of the earth. $^{143}\text{Nd}/^{144}\text{Nd}$ measured in a sample today is given as fractional deviations from $I_{\text{UR}}(0)$ in parts in 10^4 (ϵ_0^{UR}):

$$\epsilon_0^{\text{UR}} = \left[\frac{(^{143}\text{Nd}/^{144}\text{Nd})_{\text{meas}} - 1}{I_{\text{UR}}(0)} \right] \times 10^4. \quad (2a)$$

Similarly, the initial $^{143}\text{Nd}/^{144}\text{Nd}$ (I) for a sample of age T is presented as the deviation of I from $I_{\text{UR}}(T)$ in parts in 10^4 (ϵ_1^{UR}):

$$\epsilon_1^{\text{UR}}(T) = \left[\frac{I_{\text{sample}}}{I_{\text{UR}}(T)} - 1 \right] \times 10^4 \approx \epsilon_0^{\text{UR}} - f_{\text{R}} QT, \quad (2b)$$

where f_{R} is the Sm/Nd enrichment in the rock relative to UR and $Q \equiv \frac{\lambda(^{147}\text{Sm}/^{144}\text{Nd})_{\text{UR}} \cdot 10^4}{I_{\text{UR}}(0)}$ is a constant. Thus a sam-

ple with a present value of ϵ_0^{UR} which was derived from UR T years ago would have $\epsilon_1^{\text{UR}}(T) = 0$. A value of $\epsilon_1^{\text{UR}}(T)$ different from zero indicates that the source region was fractionated relative to UR prior to T. The average fractionation factor for the source (f_{S}) over the time interval $T_{\text{C}}-T$ is related to ϵ_1^{UR} by:

$\langle f_{\text{S}} \rangle (T_{\text{C}}-T) \equiv \frac{\epsilon_1^{\text{UR}}}{Q} (\equiv f^* T^*)$. This information will be presented

in terms of a generalized quantity $f^* T^*$, where T^* represents the amount of time necessary to produce the deviation ϵ_1^{UR} with an enrichment factor f^* . From $\langle f_{\text{S}} \rangle$ and the measured Sm/Nd fractionation of the sample relative to UR (f_{R}), one can calculate the Sm/Nd fractionation factor for the sample relative to the source (g) assuming a simple two-stage history:

$1 + g = 1 + f_{\text{R}}/1 + \langle f_{\text{S}} \rangle$. A similar theoretical factor (g_{TH}) can be calculated using Sm and Nd mineral/melt distribution coefficients for an assumed source mineralogy and degree of melting. Consideration of both g_{TH} and g allows the construction of more rigidly constrained models for the history of the sample and source than would be possible by either concentration or isotopic studies alone.

The above discussion of fractionation in source regions could have been made in terms of model ages (Wasserburg and Papanastassiou, 1975), as is normally done for Rb-Sr. The model age

$$T_{\text{M}} = \frac{1}{\lambda} \ln \left[1 + \frac{(^{143}\text{Nd}/^{144}\text{Nd})_{\text{meas}} - I_{\text{C}}}{(^{147}\text{Sm}/^{144}\text{Nd})_{\text{meas}}} \right]. \quad (3)$$

Model ages give a strict upper limit to the time of last major equilibration of a system, but are most powerful where parent-daughter fractionation is large. For small fractionations, $T_{\text{M}} \approx T_{\text{C}}$ and the usefulness of model ages may be diminished. Therefore, we have tended to emphasize here the divergence of secondary growth curves from a primary reference curve. However, iso-

Table 2: Nd evolutionary parameters

Sample	Age (AE)	$\frac{^{147}\text{Sm}}{^{144}\text{Nd}}$	ϵ_0^{CHUR}	ϵ_1^{CHUR}	$f^* T^*$ (10^6 yr)
113031 (MORB)	0	0.1163±3	+5.4±0.8	+5.4±0.8	2.2
111240 (MORB)	0	0.204 ±4	+10.3±0.4	+10.3±0.4	4.2
113152 (Alk.Ba.)	0	0.2109±6	+8.7±0.7	+8.7±0.7	3.5
BCR (Cont.Ba.)	0	0.14 ^b	+0.1±0.4	+0.1±0.4	0.0
Khibina Ap.	0.29 ^d	0.0950±3	+0.5±0.3	+3.7±0.3	1.5
NAS(Shale)	'0'	0.12 ^c	-14.4±0.5	-14.4±0.5	-5.8
RHO (Gt. Dyke)	2.53 ^e	0.145 ±1	-16.5±1.0	-0.8±2.0	-0.3
RN3 (Grd.)	2.65 ^f	0.0996±3	-31.2±0.6	+0.6±1.4	0.2
OGG (Amitsoq)	3.59 ^g	0.118 ±1	-35.4±0.6	-0.7±1.7	-0.3
NN1	—	—	-29.7±0.4	—	—
NN2	—	—	-13.8±0.3	—	—
CHUR ^a	all T	0.1936 ^h	0	0	0

^aCHUR ≡ Chondritic uniform reservoir; $^{143}\text{Nd}/^{144}\text{Nd}$ in CHUR today = 0.511836 (Lugmair, pers. comm.) ^bApproximate value from literature. ^cHaskin *et al.* (1966b). ^dGerasimovsky *et al.* (1974). ^eDavies *et al.* (1970). ^fSteiger and Wasserburg (1969). ^gBaadsgaard (1973). ^hLugmair (pers. comm.)

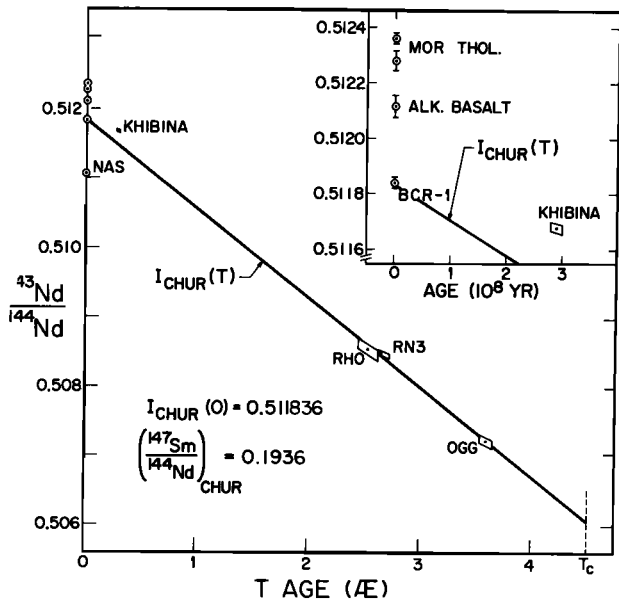


Fig. 2: Observed initial $^{143}\text{Nd}/^{144}\text{Nd}$ versus time. $I_{\text{CHUR}}(T)$ represents evolution of $^{143}\text{Nd}/^{144}\text{Nd}$ in a reservoir with chondritic Sm/Nd.

topic variations are small, so precise measurements and careful consideration will be necessary for their correct interpretation.

The data are given in Table 2 relative to a uniform reservoir whose characteristics are those of the Juvinas achondrite (Lugmair, 1974, pers. comm., and Lugmair *et al.*, 1975b). These characteristics were chosen because Juvinas has Sm/Nd very close to the average chondrite (0.308) (Masuda, 1973, c.f. Lugmair, 1975c) and therefore must approximate a chondritic uniform reservoir (CHUR), allowing direct comparison of terrestrial data to that expected in a chondritic earth. Since this paper was first submitted, we have been informed (Lugmair, pers. comm.) of a revised best estimate for $^{143}\text{Nd}/^{144}\text{Nd}$ in Juvinas, which differs significantly from that reported by Lugmair (1974). The revised value is used here, so that $I_{\text{CHUR}}(0) = 0.511836$ (normalized to $^{148}\text{Nd}/^{144}\text{Nd} = 0.243082$) and $(^{147}\text{Sm}/^{144}\text{Nd})_{\text{CHUR}}^0 = 0.1936$. Model ages can be calculated relative to the initial value for Juvinas ($I_{\text{JUV}} = 0.50598 \pm 10$) (Lugmair, pers. comm.). The evolution of $^{143}\text{Nd}/^{144}\text{Nd}$ in CHUR and initial ratios for the samples are plotted in Fig. 2.

Results. The samples can be divided into two groups; zero age rocks and old rocks. The zero age suite consists of two mid-ocean ridge tholeiitic basalts of high Fe, Ti character (MOR Thol.; USNM113152, USNM11240), one oceanic alkalic basalt (USNM113031) dredged near St. Pauls Rocks (Melson *et al.*, 1967), and a continental basalt (BCR-1). Grouped with these are a sample of apatite ore from the Khibina nepheline syenite complex, USSR, and a composite of the North American shales (NAS) prepared by Paul W. Gast (cf. Haskin *et al.*, 1966b). The old samples include a diabase from the Great Dyke, Rhodesia (RHO), a sample of the granodioritic Preissac-Lacorne batholith in the Superior Province of Canada (RN3), and a granodiorite Amitsoq gneiss sample from West Greenland (OGG). These samples have been well dated by other methods.

The four basalts and the apatite ore have small positive values of $\epsilon_{\text{I}}^{\text{CHUR}}$ indicating that they were derived from regions whose time-integrated Sm/Nd is close to but somewhat higher than that of chondrites. The shale, however, has a large negative $\epsilon_{\text{I}}^{\text{CHUR}}$ which undoubtedly reflects the low Sm/Nd of average crustal rocks. The basalts, presumably derived from the mantle, indicate that a range of $^{143}\text{Nd}/^{144}\text{Nd}$ is now found there. The old samples all have low $\epsilon_{\text{I}}^{\text{CHUR}}$ values, representative of old lithic reservoirs with low Sm/Nd.

To evaluate $^{143}\text{Nd}/^{144}\text{Nd}$ in the mantle in the past a Great Dyke sample was chosen because its basaltic composition and mode of emplacement suggest derivation from the mantle. While it has $\epsilon_{\text{I}}^{\text{CHUR}} = -16.5$, its initial ratio lies within error on

CHUR at 2.53 AE (see Figure 2), and is strong evidence that the CHUR curve is indeed relevant to mantle evolution. The other two ancient samples have large negative values of $\epsilon_{\text{I}}^{\text{CHUR}}$. Although these rocks have no clear or direct relationship to the mantle, their initial ratios nonetheless also lie on CHUR within errors. For sample RN3, a two-point internal isochron (see tables) yields a Sm-Nd age of 2.64 ± 0.13 AE, in agreement with the U-Th-Pb result (Steiger and Wasserburg, 1969).

The positions of initial ratios relative to the CHUR curve can be seen clearly in Figure 3. In general the data demonstrate that the earth has a chondritic Sm/Nd to within $\sim 5\%$. The variation of $\epsilon_{\text{I}}^{\text{CHUR}}$ in young basalts indicates the existence of isotopic heterogeneities in their source regions, a phenomenon which was previously known from Pb and Sr isotope variations (Gast, *et al.*, 1964, Tatsumoto, 1966, Gast, 1968, and others). Oceanic tholeiite samples have the highest values of $\epsilon_{\text{I}}^{\text{CHUR}}$ and must be derived from sources with higher (f_{S}) than the other samples. The alkali basalt sample is clearly derived from a different reservoir than the tholeiites. BCR-1 has a much lower $\epsilon_{\text{I}}^{\text{CHUR}}$ than the oceanic samples, which may indicate gross differences between basalt source regions under continents and those under oceans. However BCR-1 could also have acquired a lower $\epsilon_{\text{I}}^{\text{CHUR}}$ through contamination from old crustal material. The range in f^*T^* values for the young basalts indicates that for differences of f in the sources of ~ 0.1 , these sources must have been isolated for times > 1 AE.

Basalt 113031 has a low Sm/Nd typical of alkali basalts, but its positive $\epsilon_{\text{I}}^{\text{CHUR}}$ is evidence that this oceanic alkali basalt is not derived from an ancient source region which is significantly enriched in LREE relative to chondrites. The Khibina apatite sample is from an alkalic complex strongly enriched in LREE (Balashov, 1963, cited in Haskin *et al.*, 1966a), yet $\epsilon_{\text{I}}^{\text{CHUR}}$ is also positive. Thus this data strongly suggest that the highly fractionated REE patterns in alkali basalts and alkalic intrusions are the result of short-duration magmatic processes rather than the result of derivation from ancient, low Sm/Nd source regions.

The fact that $\epsilon_{\text{I}}^{\text{CHUR}}$ of the ancient granitic rocks is zero means that these rocks were derived essentially directly from a chondritic Sm/Nd source. This implies derivation from mantle sources, since their $\epsilon_{\text{I}}^{\text{CHUR}}$ are identical with that of the Great Dyke sample. These data are not compatible with their derivation from much older, highly fractionated material. However, larger errors in $\epsilon_{\text{I}}^{\text{CHUR}}$ for these samples, resulting from a sum of errors in $\epsilon_{\text{I}}^{\text{CHUR}}$, f_{R} , and the age, when coupled with the smaller time interval ($T_{\text{C}} - T$) place weaker constraints on their sources.

Inspection of Figure 3 shows that the range of $\epsilon_{\text{I}}^{\text{CHUR}}$ in young samples is larger than in the ancient samples. This may result simply from the fact that the difference in $^{143}\text{Nd}/^{144}\text{Nd}$ in reservoirs with different Sm/Nd grows with time. Alternatively, it may be indicative of a real difference in the degree of heterogeneity in the Archean mantle as compared to the modern mantle.

Partial melting generally produces a liquid with lower Sm/Nd

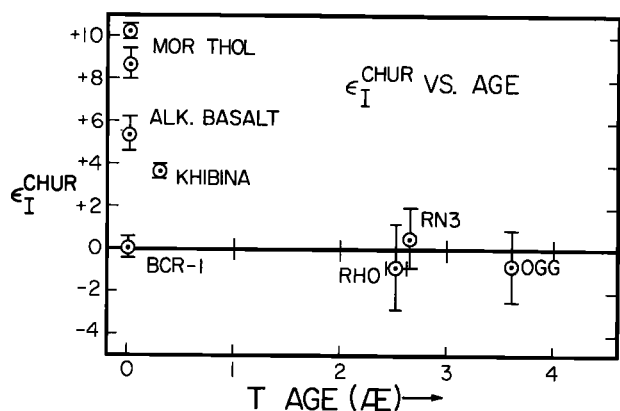


Fig. 3: Fractional deviations in parts in 10^4 of initial $^{143}\text{Nd}/^{144}\text{Nd}$ from evolution in a chondritic Sm/Nd reservoir (CHUR) vs. time.

and a residue with higher Sm/Nd than the starting material. This process tends to produce reservoirs with diverging $^{143}\text{Nd}/^{144}\text{Nd}$. The crust, since it represents the earth's low-melting fraction, must also contain the reservoirs of lowest $^{143}\text{Nd}/^{144}\text{Nd}$. If the Nd in the crust is a significant portion of that in the earth, then there must exist regions of the mantle with high $^{143}\text{Nd}/^{144}\text{Nd}$ corresponding to a high Sm/Nd residue. The source regions of oceanic tholeiites, by virtue of their high $^{143}\text{Nd}/^{144}\text{Nd}$ are the best candidates for this residue. This is clearly consistent with trace element (Gast, 1968, Kay and Gast, 1973) and other isotopic data (Peterman and Hedge, 1971) which indicate that these basalts are derivatives of a mantle which has been left as a residue from previous partial melting. In order to classify mantle source regions as having increased or decreased Sm/Nd on the basis of $^{143}\text{Nd}/^{144}\text{Nd}$, one needs precise knowledge of the bulk earth evolution curve. The CHUR curve appears to be a good first approximation.

The variation of $\epsilon_{\text{Nd}}^{\text{CHUR}}$ in the young basalts could be due to differences of Sm/Nd in source regions formed near the time of formation of the earth, or to differences formed by continuous large-scale differentiation and fractionation over a long time scale from some homogeneous initial reservoir, to form secondary reservoirs from which basalts are ultimately derived. The data presently provide no clear-cut indication of which is the case. For instance, tholeiite sample USNM113152 has a model age of 4.50 ± 0.07 AE. Using this datum, the model age of the source is $4.50 (1 + g_{\text{TH}})$ AE. If $g_{\text{TH}} = 0$, then one would conclude that the source region was formed during a very early terrestrial differentiation, essentially at the time of formation of the earth. But if $g_{\text{TH}} < 0$, then it is more likely that the source region for this basalt was generated in fractionation processes which occurred at least a few hundred million years after T_c .

If the isotopic composition and Sm/Nd of the shale are representative of average North American crust, then from f^*T^* we obtain $T^* = 1.5$ AE. This can be taken to be the "mean" age of this crustal material, i.e., the time it was fractionated from the CHUR evolution curve.

Conclusions. From the data presented we conclude that the Sm/Nd, and by inference the REE abundance pattern of the earth, is equal to the average of chondritic meteorites to within a few percent. Variations in $^{143}\text{Nd}/^{144}\text{Nd}$ in young basalts permits the identification of distinctive mantle sources and indicates the preservation of significant heterogeneities in the mantle for times of $\sim 1-4$ AE. The isotopic data also show that mantle source regions with Sm/Nd different by a factor of two from chondritic are not preserved for longer than a few hundred million years. Average continental crustal material has much lower $^{143}\text{Nd}/^{144}\text{Nd}$ than that found for the mantle, and reflects its low Sm/Nd, resulting from REE fractionation during formation of crust from the mantle.

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