INFERENCES ABOUT MAGMA SOURCES AND MANTLE STRUCTURE FROM VARIATIONS OF ^{143}Nd/^{144}Nd

D. J. DePaolo and G. J. Wasserburg

The Lunatic Asylum of the Charles Arms Laboratory, Division of Geological and Planetary Sciences*,
California Institute of Technology, Pasadena, California 91125

Abstract: Continental flood basalts and mid-ocean ridge (MOR) tholeiitic basalts have distinctly different ^{143}Nd/^{144}Nd which may permit *a priori* distinction between "continental" and "oceanic" igneous rocks. Initial ^{143}Nd/^{144}Nd of continental igneous rocks through time fall on a Sm/Nd evolution curve with chondritic REE abundance ratio. These observations indicate that many continental igneous rocks are derived from a reservoir with chondritic REE pattern which may represent primary material remaining since the formation of the earth. Oceanic igneous rocks are derived from a different ancient reservoir which has Sm/Nd higher than chondritic. Initial ^{143}Nd/^{144}Nd and ^{87}Sr/^{86}Sr in young basalts from both oceans and continents show a strong correlation suggesting that Sm-Nd and Rb-Sr fractionation events in the mantle may be correlative and caused by the same process. From this correlation Rb/Sr for the earth is inferred to be 0.029.

This study was undertaken to determine if there exists a systematic difference in ^{143}Nd/^{144}Nd between young volcanic rocks from ocean basins and continental areas. It builds upon a small body of Nd isotopic data which suggested this contrast (*DePaolo* and *Wasserburg*, 1976, referred to as *DPW*). In the same study it was shown that continental igneous rocks of varying ages appear to be derived from a single uniform reservoir with chondritic relative REE abundances. Typical old continental crustal material was found to have ^{143}Nd/^{144}Nd today which is drastically different from that of young basalts suggesting that ^{143}Nd/^{144}Nd could be used to identify products of remelted ancient crust. This study tests with an extended data base the hypotheses that continental igneous rocks through time have been derived from a uniform reservoir with chondritic Sm/Nd (CHUR) and that oceanic igneous rocks are derived from a distinctly different reservoir. In addition it presents evidence that variations in initial ^{143}Nd/^{144}Nd and ^{87}Sr/^{86}Sr in young volcanic rocks are correlated.

To test these hypotheses ^{143}Nd/^{144}Nd, ^{87}Sr/^{86}Sr, Sm/Nd and Rb/Sr were measured in three groups of samples. 1) Mid-ocean ridge (MOR) tholeiitic basalts and continental flood basalts were measured to compare oceanic and continental magmas, since these represent the most voluminous lava types found in the two settings; 2) Samples of various volcanic lithologies from continents, including alkali basalt, rhyolite, and a carbonatite and basalts from oceanic islands were measured to further explore the variations found in young volcanic rocks; 3) Initial ^{143}Nd/^{144}Nd in five more Precambrian continental intrusive rocks of various ages were determined to further evaluate the uniform reservoir hypothesis for continental igneous rocks.

Analytical Procedure and Data: Chemical separation of Sm and Nd and mass spectrometry have been described by *Eugster* et al. (1970) and *DPW*. For all samples measured in this study, no corrections to Nd isotope ratios were necessary due to interferences from other species in the ion spectra or from chemistry blank. The intensity of the ^{144}NdO ion beam was between 3 and 6 x 10^{-11} A during data acquisition. All Nd isotopes were measured in every run. The measured values for the non-radiogenic Nd isotopes for all runs are shown in Figure 1. Strontium was separated using conventional ion exchange techniques. ^{87}Sr/^{86}Sr are normalized to ^{86}Sr/^{88}Sr = 0.1194.

Isotopic data, locations, and lithologic classifications for all samples are given in Table 1 and summarized in Figures 2, 3, and 4. Nd data are expressed using the notation of *DPW*.

Results. I. *Continental Flood Basalt and MOR Tholeiites:* Nd isotopic data for these samples are shown in a histogram in Figure 2a. Included in this figure are data from *DPW* on two MOR tholeiites and BCR-1. BCR-1 was selected as representative of the chemically and (Sr) isotopically uniform Yakima basalts of the Columbia River province, the most voluminous lava type found in that province (McDougall, 1976). The Picture Gorge sample (PG16D) was selected for analysis because it is petrochemically distinct from BCR-1. Its ϵ_I^{CHUR} is much different that what appears to be the normal range for continental tholeiites, showing affinities to oceanic basalts. Sample PEA-3 was taken from an old collection and was assumed to be a Karroo basalt as it was labelled. Discussion of this sample must be deferred until it can be documented that its ϵ_I^{CHUR} is not a result of an incorrect age assignment. If the age is correct, this sample could be the product of massive crustal contamination or a derivative of a special mantle reservoir. As seen in the figure, the samples fall into two distinct groups. The MOR basalts have ϵ_I^{CHUR} averaging $\sim$ +10 and ranging from +7 to +12 while continental flood basalts have ϵ_I^{CHUR} averaging $\sim$ 0 and showing a range from -4 to +2. This striking data array confirms the existence of a profound difference in ^{143}Nd/^{144}Nd between major basalt provinces in continental and oceanic regions. It implies the existence of two distinctly different, widespread mantle magma sources. From the difference of f*T* values of $\sim 4 \times 10^8$ yr for the two groups of samples (Table 1), and assuming a difference of f_S of less than 0.4, we calculate that these two reservoirs must have been separate for at least 10^9 years. Thus MOR tholeiites and continental flood tholeiites appear to be derived from two ancient, profoundly different reservoirs in the earth's mantle. Differences in concentrations of certain minor and trace elements between these two lithologic types (*Schilling*, 1971; *Haskin* et al, 1966) thus are most likely a reflection of
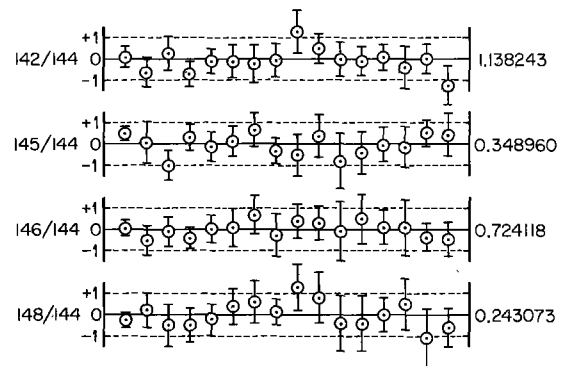
Fig. 1: Measured values of non-radiogenic Nd isotope ratios for each run plotted as fractional deviations in parts in 10^4 from the average of 16 runs given at right. Ratios are normalized to ^{150}Nd/^{142}Nd = 0.2096; error bars are $2\sigma_{mean}$. These data demonstrate that reproducibility of measured ratios is ±5 parts in 10^5 or better. Measurements of non-radiogenic isotopes are used in this laboratory as an indication of data quality.

ancient differences rather than a result of differentiation processes occurring at the time of magma generation as has been suggested (Schilling, 1971). The nominal value of $\epsilon_I^{CHUR} \approx 0$ for the continental flood basalts indicates they are derived from a reservoir which has maintained an unfractionated, chondritic Sm/Nd throughout the history of the earth. The MOR basalts, however, are derived from a reservoir which has had Sm/Nd at least 10% greater than chondritic.

II. *Other young volcanic rocks:* Nd isotopic data on these samples, plus an alkali basalt from the mid-Atlantic Ridge (OAB-1) (113031 of DPW) and three ocean island samples from *Richard* et al. (1976) are shown in Figure 2b. With the exception of two samples, the oceanic rocks have significantly higher ϵ_I^{CHUR} than the continental samples. For the most part ocean island basalts (both tholeiitic and alkalic) have ϵ_I^{CHUR} of +4 to +8, somewhat lower than those of the MOR tholeiites but definitely higher than the majority of continental basalts. The alkali basalts give no indication of being derived from an ancient light − REE enriched source, as has been suggested by *Sun* and *Hanson* (1975). Such a reservoir would yield basalts with $\epsilon_I^{CHUR} = -10$ to -30. Sample OLC-1 from a Na, Ca-carbonate lava flow represents an extreme rock type with highly fractionated REE pattern and high REE concentrations, but has ϵ_I^{CHUR} identical to the average continental flood basalt. This sample thus gives no evidence that carbonatites are derived from unique mantle reservoirs. The Hawaiian tholeiite has ϵ_I^{CHUR} similar to those of the continental flood basalts. A melilite nephelinite from the same island, however, has a drastically different ϵ_I^{CHUR}, similar to those found in other ocean island basalts and in MOR tholeiites. Thus these two basalts are derived from different reservoirs despite their coincident location. These data again show that a single volcanic conduit system can access a variety of mantle reservoirs of distinctive chemistry and age. The tholeiite sample provides the only evidence that the reservoir represented by the continental flood basalts is present in oceanic areas. The Pisgah crater alkali basalt (PCB) differs markedly from the other continental basalts. Its ϵ_I^{CHUR} is similar to oceanic basalts and identical to that of the Picture Gorge sample. This basalt may be representative of the mantle underlying the Basin and Range province of the western United
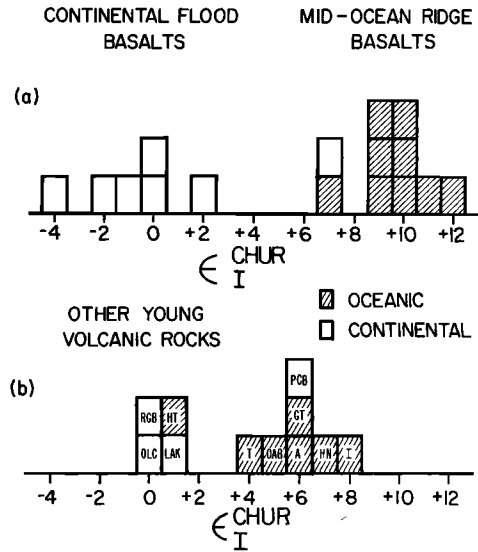

CONTINENTAL FLOOD   MID-OCEAN RIDGE
BASALTS   BASALTS

(a)

OTHER YOUNG   ▨ OCEANIC
VOLCANIC ROCKS   ☐ CONTINENTAL

(b)

Fig. 2: Histograms of Nd isotopic results on young volcanic rocks and the Duluth gabbro, normalized as in *DPW*. In 2a) mid-ocean ridge samples include samples ARP74, PD1P, 111327, and AD3-3 of *Richard*, et. al. (1976). In 2b) samples T, A, and I are samples TF110, T4, and NAL27 of *Richard*, et. al. (1976).

States which resembles oceanic mantle in seismic structure and heat flow. ϵ_I^{CHUR} of the rhyolite sample is the same as that of the continental basalts, indicating that it appears to be derived from the same reservoir as the basalts.

III. *Precambrian igneous rocks:* All of the Precambrian samples analyzed, with the exception of the Mountain Pass sample, have been well-dated by other methods. The values of ϵ_I^{CHUR} as a function of age for all continental samples measured in this work and by *DPW* are shown in Figure 3. Of the samples analyzed in this work WYWR-4D and WGA210 fall within error on the CHUR evolution curve, and ZL-3D lies slightly above. The Duluth gabbro sample DUL-4, which represents an ancient continental basalt, lies slightly below the

Table 1: Nd evolutionary parameters and $^{87}Sr/^{86}Sr^a$

Sample	Age (AE)	$\frac{^{147}Sm}{^{144}Nd}$	ϵ_0^{CHUR}	ϵ_I^{CHUR}	f^*T^* (10^8 yr)	$\left(\frac{^{87}Sr}{^{86}Sr}\right)_I$
I. Continental Flood Basalts						
PG-16D (Picture Gorge tholeiite, Columbia R. province)	0	nm	+6.6±0.5	+6.6±0.5	2.7	0.70341±6
DTB-8 (tholeiite, Mahableshwar plateau, Deccan, India)	0.05	0.1645	+1.5±0.7	+1.7±0.7	0.7	0.70413±12
SK-38 (tholeiite, Miki's Fjord, E. Greenland)	0.05	0.1329	−4.3±0.6	−3.9±0.6	−1.6	0.70540±11
SWB-1D (tholeiite, Stormberg series, Warmbad, S. Africa)	0.15	0.1691	−1.2±0.5	−0.7±0.5	−0.3	0.70630±6
PEA-3 (Karroo ? basalt, Mozambique)	0.15?	0.1170	−20.1±1.6	−18.6±1.6	−7.5	nm
PD-1 (Palisades diabase, 200' above base, Edgewater, N.J.)	0.20[b]	0.1540	−1.2±0.7	−0.2±0.7	−0.1	0.70604±10
II. Mid-ocean Ridge tholeiites						
VG295 (tholeiite, mid-Atlantic Ridge, 22.5N, 45W)	0	nm	+10.6±0.9	+10.6±0.9	4.3	0.70226±6
BD37-2 (tholeiite, mid-Atlantic R.; DSDP 37-332B-19-1)	0	0.1930	+11.0±3.0	+11.0±3.0	4.5	nm
BD17-1 (tholeiite, central Pacific; DSDP 17-164-28-6)	0.15[c]	0.1988	+7.4±1.3	+7.4±1.3	3.0	nm
III. Other young volcanic rocks						
OLC-1 (carbonatite, Oldoinyo Lengai, Tanzania)	0	nm	+0.1±0.9	+0.1±0.9	0.0	nm
HN-1 (nephelinite, Oahu; USNM 113095-50)	0	0.1229	+7.3±0.6	+7.3±0.6	3.0	0.70320±8
HT-1 (tholeiite, Oahu; USNM 113095-60)	0	0.1590	+0.8±0.6	+0.8±0.6	0.3	0.70403±6
RGB-1 (alk. olivine basalt, Rio Grande Rift)	0	nm	+0.2±0.7	+0.2±0.7	0.1	0.70436±12
LAK-8D (rhyolite, Mt. Konocti, California)	0	0.112[j]	+1.3±0.8	+1.3±0.8	0.5	nm
GT-2 (tholeiite, Galapagos Is., USNM 113180, F436)	0	0.1155	+6.2±0.8	+6.2±0.8	2.5	nm
PCB-1 (alk. basalt, Pisgah Crater, California)	0	0.1228	+6.2±0.8	+6.2±0.8	2.5	0.70346±6
IV. Precambrian intrusive rocks						
ZL-3D (Town Mtn. Granite, Llano, Texas)	1.01[d]	0.1420	−4.4±0.7	+2.3±0.8	0.9	(0.706)[d]
DUL-4 (Anorthositic gabbro, Duluth complex, Minn.)	1.13[e]	0.1036	−14.5±0.6	−1.7±0.7	−0.7	0.70655±7
MP22D (shon kinite, Mtn. Pass, California)	1.4-1.7[f]	0.1053	−19.9±0.4	−3-0	−1.2-0	nm
WYWR-4D (Louis Lake granodiorite, Wind R. Mtns., Wyo.)	2.65[g]	0.1095	−29.6±0.6	−0.9±1.0	−0.4	nm
WGA210 (Fiskenaesset anorthosite, West Greenland)	2.8[h]	0.1146	−29.9±0.8	−1.1±1.7	−0.4	nm

Initial $^{87}Sr/^{86}Sr$ of OAB-1 (113031 of *DPW*) = 0.70287±15; 111246 *(DPW)* = 0.70236±11   nm = not measured
[a]Nd data normalized as in *DPW*   [b]*Eriksen* and *Kulp* (1961)   [c]DSDP Inventory of Igneous Rock Recovery (1973)   [d]*Zartman* (1964)
[e]*Silver and Green* (1972)   [f]*Lamphere* (1964)   [g]*Naylor*, et. al. (1969)   [h]*Gancarz* (1976); *Black* et. al. (1973)   [j]*Bowman*, et. al. (1973)

curve. MP22D is not plotted due to uncertainty in its age (*Lanphere*, 1964). However, the age of MP22D is bracketed between 1.4 and 1.7 AE so that its ϵ $\int_I^{CHUR}$ must be between −3 and 0. Thus all of the Precambrian intrusive rocks, representing a wide variety of rock types, as well as the young continental volcanics appear to be derived from an *approximately* uniform, chondritic-Sm/Nd reservoir. Note in particular that four samples with ages of 2.5 to 2.8 AE from widely separated localities all lie within error on the curve and closely limit the position of the growth curve at 2.6 AE. Among the continental samples studied are gabbroic rocks which are taken to represent ancient continental flood basalts. All these data, when considered with the "zero" age continental samples, provide strong evidence that the CHUR curve describes Nd evolution in an important and widespread reservoir, most probably the mantle, and as such, can be taken as a representation of the bulk earth's evolution curve. As discussed by *DPW*, definition of the bulk earth evolution curve is necessary in order to infer what processes are responsible for variations of ϵ $\int^{CHUR}$. The CHUR evolution curve given here was calculated from data of *Lugmair* (pers. comm.) on the Juvinas achondrite which has Sm/Nd within 1% of the average of ordinary chondrites (0.309 atom ratio) as determined by *Masuda* et. al. (1973) and *Nakamura* (1974). Thus the earth appears to have Sm/Nd and presumably REE relative abundances essentially identical to chondritic meteorites.

Discussion: The data shown in Figure 3 clearly suggest that the source of magmas during the first 2 AE of Earth history was a uniform chondritic-Sm/Nd reservoir. *DPW*, however, suggested that this might only appear to be the case since the Sm/Nd heterogeneities of ∼ 10% which can be inferred from Nd isotopic variations to exist today, may have produced only indiscernable isotopic differences 3 AE ago. However, as shown by *Lugmair* (1975) and *Lugmair*, et. al. (1976), data for the moon show no suggestion of a long-lived, uniform magma source with chondritic Sm/Nd. Lunar basalts with ages of 3.3-4.0 AE show a range of ϵ $\int_I^{CHUR}$ from +7 to −2 which is much larger than the range shown by the terestrial samples which were formed a billion years later. The lunar data clearly indicate that planetary differentiation processes exist which could have caused sufficient Sm/Nd fractionation to produce large variations in ϵ $\int^{CHUR}$ in old terrestrial rocks. Thus the terrestrial data suggest that the earth, unlike the moon, did not undergo an early differentiation event which greatly fractionated the rare earth elements, or if it did, a mixing process operated during the subsequent AE to erase the variation of Sm/Nd produced in this event.

The data shown in Figure 3 also provide information on the origin of silicic rocks in the continental crust. As seen in Figure 3 all silicic rocks have ϵ $\int^{CHUR}$ ∼ 0. Thus remelting of much older continental crust does not appear to be important in the formation of silicic igneous rocks. This surprising result strongly suggests that most continental igneous rocks are derived from ancient reservoirs, possibly original materials undifferentiated over all of geologic time.

The observation that the CHUR evolution curve is the locus of initial ratios of continental igneous rocks attaches age significance to the measured $^{143}Nd/^{144}Nd$ of these rocks. If the initial $^{143}Nd/^{144}Nd$ is given by the CHUR curve then measurement of $^{143}Nd/^{144}Nd$ and $^{147}Sm/^{144}Nd$ in any continental rock today gives a model age (T $_{CHUR}$):

$$T_{CHUR} = \frac{1}{\lambda} \ln \left[1 + \frac{^{143}Nd/^{144}Nd_{meas} - I_{CHUR}(0)}{^{147}Sm/^{144}Nd_{meas} - (^{147}Sm/^{144}Nd)_{CHUR}} \right]$$

T $_{CHUR}$ may provide a real "crust-formation" age for a wide variety of rocks, since studies to date have shown that metamorphism does not significantly affect REE patterns (*Haskin* et. al., 1968). T $_{CHUR}$ ages may be a way to see past metamorphic events to the time when the sialic material differentiated from its source region.

The data reported here imply the existence of at least two distinct ancient magma sources, one which supplies the MOR
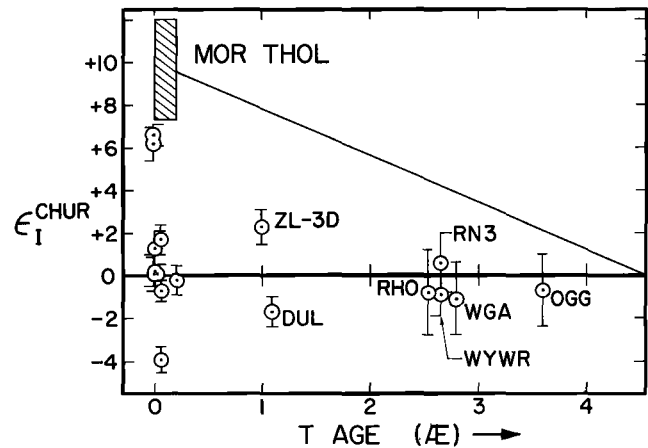

Fig. 3: ϵ $\int_I^{CHUR}$ vs. Age with points plotted for all continental samples Field of mid-ocean ridge (MOR) tholeiites is shown at upper left with simple growth curve diverging from CHUR at 4.5 AE.

basalts (ϵ $\int_I^{CHUR}$ ≈ + 10) and one which supplies continental rocks (ϵ $\int_I^{CHUR}$ ≈ 0). The ocean island samples (ϵ $\int_I^{CHUR}$ ≈ +6) may either represent a third magma source, or a blend of the other two. This grouping is not a detailed description of the data as evidenced by the sizeable dispersion within each group, but is used here to assess some elementary models. For simplicity, let us assume only two *sources* exist, that of the continental rocks (CHUR) and that of the MOR basalts (MORR). Any model given to explain the distribution of magmas derived from these sources must take into account the constraints that 1) CHUR supplies continental igneous rocks for all time and rarely supplies magmas in oceanic areas and 2) MORR supplies oceanic igneous rocks and rarely supplies magmas in continental areas. In addition, in the process of making continental crust with low Sm/Nd, residual matter (C*) from CHUR is left with increased Sm/Nd. This material may then evolve the Nd isotopic character of MORR after a time period of ∼ 1 AE. Thus CHUR and MORR may be distinct entities dating from the formation of the earth (congenital sources), or MORR (=C*) may be derived from CHUR in the process of making continental crust (evolved sources).

One possible interpretation of the data might be that with the exception of a few anomalous areas, CHUR is found only under continents and MORR only under oceans. For stationary continents this model would be acceptable for the congenital case. For the case of evolved sources a mechanism for allowing the residual material C* from CHUR to migrate from under the continents to under the oceans over times of ∼ 1 AE or more is necessary. For drifting continents it is necessary that CHUR is attached to the continents. This presents a problem in that the amount of mantle present in the attached lithosphere beneath the continents is at best barely sufficient to supply the Nd now present in the continents if primitive mantle has Nd equal to ∼ 2x chondrites and continental crust has ∼ 25x chondrites (*Taylor*, 1976).

Alternatively both sources could be present under both continents and oceans. MORR (shallow) supplies the MOR basalts but is essentially inactive under continents. CHUR (deep) is active under continents and oceans, but in oceanic regions its products are volumetrically insignificant in comparison to those of MORR. This configuration is much the same as hypotheses of mantle plumes (*Morgan*, 1971, *Wilson*, 1965) and may provide a reasonable explanation of the basalt data. That is, most continental basalts and some oceanic basalts are derived from diapirs originating from CHUR deep in the mantle. This would imply that continental granitic rocks are also derived from the same deep mantle sources.

A third possibility would be that MORR exists at shallow levels only under oceans and at deeper levels under both continents and oceans. At shallow levels beneath the continents a region with the isotopic character of CHUR is maintained in a
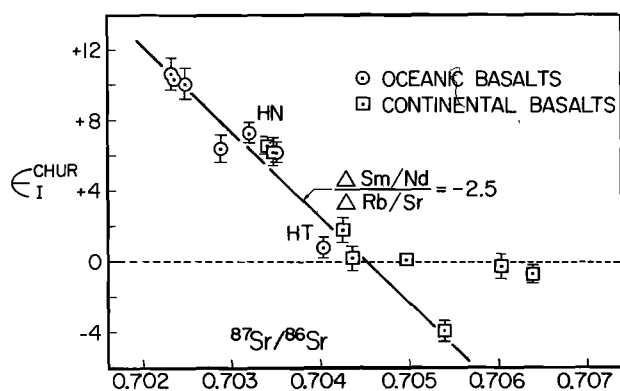
Fig. 4: ϵ_I^{CHUR} vs. initial $^{87}Sr/^{86}Sr$ for young basalts. Included are two samples from *Richard*, et. al. (1976) (PD1P, ARP74) and BCR-1 ($^{87}Sr/^{86}Sr$ for BCR-1 from *Pankhurst* and *O'Nions*, 1973). The solid line shows the inferred trend of the correlation and the relative magnitudes of correlated variations of Rb/Sr and Sm/Nd necessary to produce such a trend. The dashed line indicates the trend defined by four continental basalt samples which have $\epsilon_I^{CHUR} \approx 0$ but different $^{87}Sr/^{86}Sr$, all lying to the right of the main correlation line. This trend may result from contamination of magmas with crustal radiogenic Sr or indicate the existence of magma sources which have become enriched in Rb relative to Sr, but have retained unchanged Sm/Nd. Should new data populate the correlation line to values of ϵ_I^{CHUR} much less than zero, it would require serious revision of the simple two-reservoir model.

dynamic steady state. In this region Nd is continually transported to and stored in the crust in preference to Sm, but is continually replenished from MORR below or by transfer in subduction zones where material from MORR passes beneath the continent. This model requires a delicate balance but is consistent with drifting continents while still implying a fundamental chemical difference between suboceanic and subcontinental mantle.

Correlation of Sr and Nd Data on samples for which both Nd and Sr isotopes were measured are shown in Figure 4 and show a correlation between initial Nd and Sr. The MOR basalts have the lowest $^{87}Sr/^{86}Sr$ and highest ϵ_I^{CHUR} while the continental basalts have highest $^{87}Sr/^{86}Sr$ and lowest ϵ_I^{CHUR}. Oceanic alkali basalts are intermediate but can be distinguished from the continental samples. This correlation suggests that Sm-Nd and Rb-Sr fractionation in the formation of magma sources in the mantle are correlative. Samples PD-1 and SWB-1D may represent cases where significant Sr contamination occurred but the Nd isotopes were essentially unaffected. This possibility is plausible since reservoirs of extremely radiogenic Sr exist in the continental crust which could act as contaminants, whereas the existence of reservoirs of extreme Nd isotopic composition is unlikely due to the limited variation of Sm/Nd in nature. This suggests that Nd may provide a better tool for the study of sub-continental mantle magma sources than Sr. From Figure 4 it can be seen that a value of $\epsilon_I^{CHUR} = 0$ corresponds roughly to $^{87}Sr/^{86}Sr \sim 0.7045$. If $\epsilon_I^{CHUR} = 0$ represents an unfractionated reservoir then 0.7045 ± 5 might be taken as the present value of $^{87}Sr/^{86}Sr$ in unfractionated mantle. From this number and BABI we calculate Rb/Sr of unfractionated mantle material to be $0.029\pm.003$. A $^{87}Sr/^{86}Sr$ growth curve calculated from this Rb/Sr may be more useful for interpretation of initial $^{87}Sr/^{86}Sr$ of ancient rocks than is one calculated from the present value of $^{87}Sr/^{86}Sr$ in MOR rocks (~ 0.7025).

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