HAFNIUM AND NEODYMIUM ISOTOPIC CONSTRAINTS ON MARE BASALT GENESIS

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Lu-Hf analyses have been performed on mare basalts from the Apollo 11,12,15, and 17 missions in order to determine the constraints imposed by the Lu-Hf system on mare basalt evolution. Sm-Nd analyses were performed on samples which have not previously been analyzed, and on some samples which have been analyzed in other laboratories in order to evaluate interlaboratory biases. General models for mare basalt genesis are investigated in light of the new data.

Hf and Nd isotopic compositions are normalized to $^{179}Hf/^{177}Hf=0.7325$ [1] and $^{148}Nd/^{144}Nd=0.241572$ [2], respectively. Eight analyses of Hf isotopic standard JMC 475 gave the following mean isotopic ratios: $^{178}Hf/^{177}Hf=1.46710 \pm .00005$, and $^{180}Hf/^{177}Hf=1.88635 \pm .00010$; and 15 analyses yielded $^{176}Hf/^{177}Hf=0.282217 \pm .00009$. Five analyses of the La Jolla Nd standard yielded $^{143}Nd/^{144}Nd=0.511986 \pm .000012$, and a mean of $^{146}Nd/^{144}Nd=0.721874 \pm .000027$ was obtained for the standard and lunar samples. The Nd isotopic data obtained in this study were adjusted for instrumental bias to $^{143}Nd/^{144}Nd=0.511929$ for the La Jolla standard [2].

Initial Hf and Nd isotopic compositions (at the time of crystallization) are summarized on εHf_T and εNd_T vs. T plots in Figure 1. εHf_T and εNd_T are deviations in parts per 10^4 from the Murchison chondrite [3,4] at any given time. Evolution parameters for Murchison are $^{176}Hf/^{177}Hf_{T=4.55} = 0.27978$, $^{176}Lu/^{177}Hf = 0.0334$ [3], $^{143}Nd/^{144}Nd_{T=4.55} = 0.50669$, and $^{147}Sm/^{144}Nd = 0.1968$ [4]. Evolution lines (solid lines) are drawn assuming a two-stage model involving formation of the source at 4.55 Gy ago and crystallization at the time indicated by the symbol. In addition to this work, Nd data are taken from [5-8] and Hf data from [9].

Although the relative positions of the sample types on the figure are similar, the Lu-Hf system appears to have been much more fractionated both during formation of the sources and during production of the basalts. Given the two-stage models depicted in Figure 1, Lu/Hf was enriched by factors of ~1.2-2.3 relative to Murchison during source formation and depleted by factors of ~0.34-0.55 relative to the sources during basalt formation. Sm/Nd was enriched by factors of ~1.02-1.35 during source formation and depleted by factors of ~.83-.97 during formation of the basalts. This Lu/Hf appears to have been more fractionated during basalt genesis than during source formation. Clearly these results are at odds with models involving fractional crystallization of adcumulate sources from liquids with chondritic Lu/Hf followed by modal equilibrium partial melting at the time of basalt formation. Although little is known about Hf partitioning between basaltic liquid and crystallizing phases, one can make some generalizations using the limited data available [10]. Cumulates consisting of olivine, orthopyroxene, and clinopyroxene (± plagioclase) would have a ratio of bulk distribution coefficients ($\bar{D}Lu/\bar{D}Hf$) of ~4, and would therefore have Lu/Hf ~4 times that in the liquid from which they crystallized. The calculated $\bar{D}Lu/\bar{D}Hf$ for the Apollo 12 ilmenite basalts is >4.1 for >3% partial melting during basalt genesis and is in accord with the predicted ratio. However, the maximum fractionation, relative to an assumed chondritic liquid, at the time of source formation 4.55 Gy ago is only a factor of ~2.3. Although assuming a younger age for the source would increase the calculated amount of Lu/Hf fractionation at the time of source formation, this would also increase the required amount of fractionation at the time of basalt formation.

The data from Figure 1 are combined on a Hf-Nd evolution diagram in Figure 2. The heavy solid line represents Murchison evolution and the lighter solid line represent calculated Lu/Hf-Sm/Nd ratios relative to Murchison assuming a two-stage model. The broken line represents predicted Hf-Nd evolution of a cumulate source with $\bar{D}Lu/\bar{D}Hf=4$ and $\bar{D}Sm/\bar{D}Nd=1.5$. In order to explain the shift in the data to the right of the predicted evolution path one or more of the following hypotheses must be invoked. (a) A non-chondritic moon or "magma ocean". Nyquist et.al., [5,11] have suggested that the bulk moon or at least the magma ocean was depleted in Sm/Nd by ~11% relative to chondrites. A depletion of >30% in the Lu/Hf ratio would also be required. (b) A fractionated magma ocean. A liquid with the desired light REE-enriched and Lu/Hf-depleted characteristics can be obtained after extensive (>90%) fractional crystallization of olivine and pyroxene. (c) Hf retentive phases in the source. If the sources originally contained a phase or phases such as ilmenite ($\bar{D}Lu/\bar{D}Hf$ ~0.5 [10]) or trapped liquid which were preferentially melted during basalt genesis, then the less-than-expected Lu/Hf fractionation could be accounted for. The presence of ilmenite or significant trapped liquid in the source again suggests a shallow depth for the mare basalt sources. Binder [12] has suggested that the sources formed at <200Km depth and did contain up to ~6% ilmenite. (d) Mixing or contamination. Contamination of the magmas with Lu/Hf depleted material (KREEP?) might also account for the observed data. However, one would then expect the Hf initial ratios to be correlated with the K or Ti content and exmination of Figure 1 shows that this is generally not the case.

(e) A three stage model. The observed fractionation can be accounted for if the sources of the mare basalts are partial melts of earlier-formed cumulates (broken line and broken line with "?" in Figure 2). This model would require the age of the secondary source to be significantly older than the basalt age. If, on the other hand, $\bar{D}Lu/\bar{D}Hf$ is significantly less than that estimated (see [3]), then the large amount of apparent Lu/Hf fractionation at the time of crystallization can be accounted for if the partial melts were allowed to extensively crystallize before the residual liquid erupted to the surface [12]. However, this would require extremeley

small degrees of partial melting (<1%) and >95% crystallization of this partial melt prior to eruption.

(f) "Young" source age. A linear array in Figure 2 is obtained for samples whose sources formed at the same time with the same relative fractionation of Sm/Nd and Lu/Hf (i.e. Sm/Nd ÷ Lu/Hf = constant; for fractional crystallization $\bar{D}Lu \times \bar{D}Nd/(\bar{D}Sm \times \bar{D}Hf)$ = constant). Two linear trends (dotted lines in Fig. 2) are reflected by the data, and intersect the Murchison evolution line at ~3.7-3.9 Gy. However, because (1) the data are scattered on the individual Hf and Nd evolution diagrams (Fig. 1), (2) it has yet to be demonstrated that Sm/Nd and Lu/Hf fractionation are as well-correlated as required by the model and (3) in view of the wide variety of basalt types within each trend, we tentatively conclude that these linear trends are fortuitous. In any case, if such young ages are considered for the sources, the required apparent amount of fractionation during basalt genesis would then be so extreme as to require disequilibrium partial melting and a Lu/Hf-depleted mineral in the source which is preferentially melted.

Although the lack of a complete set of Hf partitioning data preclude a clear choice among the preceding models, the data thus far obtained tend to favor a late-stage origin for the mare basalt sources, provided of course that bulk moon has a chondritic Lu/Hf ratio.

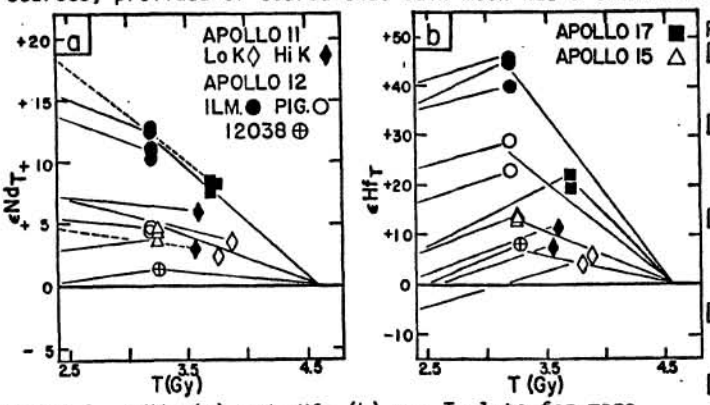

Figure 1. εNd_T (a) and εHf_T (b) vs. T plots for mare basalts. Deviations are in parts per 10^4 relative to the Murchison chondrite (ε = 0). Broken and solid lines show evolution paths assuming a two-stage model. Symbols are plotted at the crystallization age for each sample.

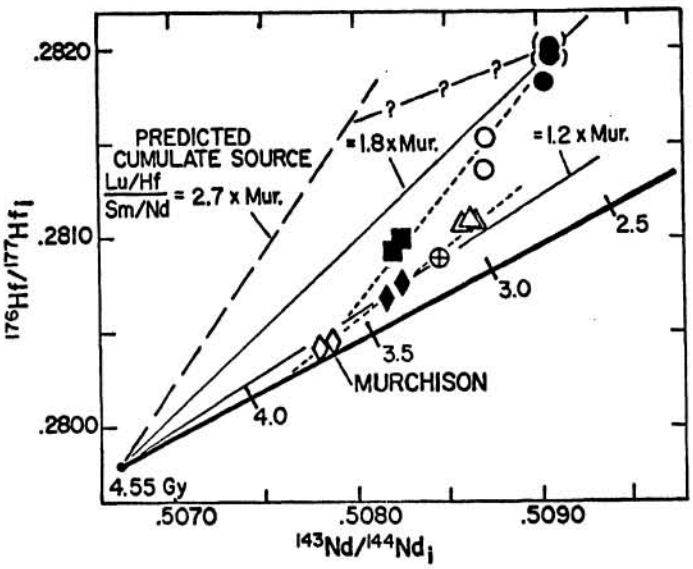

Figure 2. Hf-Nd evolution diagram. Samples are plotted with their respective initial Hf and Nd isotopic compositions at the time of crystallization. The heavy solid line shows evolution of Murchison through time and the lighter solid lines show Lu/Hf ÷ Sm/Nd = 1.2 and 1.8 times Murchison. The broken line shows a predicted evolution of an olivine, pyroxene source that formed from a chondritic liquid at 4.55 Gy ago. The broken line and broken line with "?"'s show a possible three-stage model, and the dotted lines show possible evolution paths from 3.7-3.9 Gy sources. The two Apollo 12 ilmenite basalts in parentheses are plotted using an average initial Nd isotopic composition for this group (see Fig. 1).

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