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 been previously 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.

Lu and Nd isotopic compositions are normalized to $^{176}\text{Hf}/^{177}\text{Hf}=0.7219$ [1] and $^{148}\text{Nd}/^{144}\text{Nd}=0.512634$ [2], respectively. Eight analyses of Hf isotopic standard JMC-755 gave the following mean isotopic ratios: $^{176}\text{Hf}/^{177}\text{Hf}=0.721962 \pm 0.0034$, and $^{187}\text{Hf}/^{177}\text{Hf}=0.512634\pm 0.00015$. Five analyses of the La Jolla Nd standard yielded $^{143}\text{Nd}/^{144}\text{Nd}=0.511886 \pm 0.00012$, and a mean of $^{146}\text{Nd}/^{144}\text{Nd}=0.721874 \pm 0.00027$ was obtained for the standard and lunar samples. The Nd isotopic data obtained in this study were adjusted for instrumental bias to $^{143}\text{Nd}/^{144}\text{Nd}=0.511929$ for the La Jolla standard [2].

Initial Hf and Nd isotopic compositions (at the time of crystallization) are summarized on $e_{\text{Hf}}$ and $e_{\text{Nd}}$ vs. $T$ plots in Figure 1. $e_{\text{Hf}}$ and $e_{\text{Nd}}$ are deviations in parts per 10$^6$ from the Murchison chondrite [3,4] at any given time. Evolution parameters for Murchison are $^{176}\text{Hf}/^{177}\text{Hf} = 0.27978$, $^{148}\text{Nd}/^{144}\text{Nd} = 0.512634$, and $^{178}\text{Hf}/^{177}\text{Hf} = 1.46710 \pm 0.00005$, and $^{182}\text{Hf}/^{177}\text{Hf} = 0.88635 \pm 0.00010$.

Evolution lines (solid lines) are drawn assuming a two-stage model involving formation of the source at 4.55 Gy ago and crystallization of the basalts. This model involves Ra-depleted basalt formation and depleted by factors of -1.02-1.35 during source formation and depleted by factors of -0.62-0.64 relative to the sources during basalt formation.

Cumulates consisting of olivine, orthopyroxene, and clinopyroxene would have a ratio of bulk distribution coefficients (DLu/DHf) of $\approx 1$, and were almost completely depleted in the liquid from which they crystallized. The calculated DLu/DHf 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 on the time scale 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 represents calculated Lu-Hf evolution for a two-stage model assuming a secondary source to be significantly depleted by factors 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 on the time scale of basalt formation.

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The presence of ilmenite or significant trapped liquid in the source again suggests a shallow source. The observed fractionation 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 extremely
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 fraction of Sm/Nd and Lu/Hf (i.e. Sm/Nd = Lu/Hf = constant; for fractional crystallization Lu/(Sm+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 Hf/Nd ratio.

References