

THE SOURCE MINERALOGY OF HIGH- AND LOW-Ti BASALTS BASED ON THEIR Hf ISOTOPIC COMPOSITION

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Introduction: The Lu-Hf isotopic system is ideally suited for determining the mineralogy of source regions because of the large mineral dependent Lu-Hf fractionations that occur during partial melting and crystallization. However, because of the analytical challenges of Hf isotopic analysis the Lu-Hf isotope system has not been widely applied to studies of petrogenesis. We have developed a new technique for Hf isotopic analysis and Lu and Hf concentration determination by isotope dilution mass-spectrometry that is ideally suited for Lu-Hf isotopic analysis of high-Ti basaltic rocks [e.g., 1]. Using this technique we have analyzed 5 high-Ti mare basalts; 2 Apollo 11 samples with high ϵ_{Nd} values and 3 Apollo 17 samples with low ϵ_{Nd} values. These new data complement the existing Hf isotopic analyses of high-Ti basalts, which consist of 4 Apollo 11 samples with low ϵ_{Nd} values and 3 Apollo 17 samples with high ϵ_{Nd} values [2]. This combined data set clearly demonstrates that the Hf isotopic composition of high-Ti basalts is relatively constant over a range of ϵ_{Nd} values (Figure 1). The Hf - Nd isotopic array of high-Ti basalts is in marked contrast to the Hf - Nd isotopic data of low-Ti basalts which defines a strong positive correlation with $\epsilon_{\text{Hf}} = 4\epsilon_{\text{Nd}}$ (Figure 1). The differences for the Hf and Nd isotopic arrays of low- and high-Ti basalts implies that the low- and high-Ti basalt source regions have been distinct over nearly the entire history of the Moon. Moreover, these source regions must have formed with distinctly different mineralogies.

Hf and Nd isotopic composition of High-Ti basalts:

Our initial study of the Hf isotopic composition of high-Ti mare basalts is based on five 1 gram sized samples: 10044, 10047, 71545, 77516, and 78586 (Table 1). These samples have different ϵ_{Nd} values, at their respective landing sites, compared to the samples previously analyzed by Unruh et al. [2], thereby complementing this previous Hf isotopic study of lunar samples. All Hf isotopic analyses were conducted at the University of Wisconsin Radiogenic Isotope Laboratory using the methods outlined by Barovich et al. [3] and Scherer et al. [1]; the measured value for the JMC-475 Hf standard during this study was $^{176}\text{Hf}/^{177}\text{Hf} = 0.282125 \pm 19$ (2SE, n=30). The Nd isotopic data for these samples are from Paces et al. [4] and Snyder et al. [5]. Although the Nd and Hf isotopic compositions were measured on different sub samples, we do not believe that this compromised Nd - Hf isotopic trends because our results for the Nd - Hf isotopic trends for high-Ti basalts are similar to those of Unruh et al. [2], who determined Hf and Nd isotopic compositions on the same sub sample.

Interpretation: Patchett et al. [6] used the strong positive correlation of ϵ_{Hf} versus ϵ_{Nd} of oceanic basalts to successfully estimate the Lu/Hf fractionation factor ($f_{\text{Lu/Hf}}$) relative to the Sm/Nd fractionation factor ($f_{\text{Sm/Nd}}$; using the terminology of [6,7]) for the terrestrial mantle at approximately 2 to 1. This is possible because fortuitously Q_{Nd} is approximately equal to Q_{Hf} (using the terminology of [6,7]), implying that trends of ϵ_{Hf} vs ϵ_{Nd} are only a result of differences between Lu/Hf fractionation and Sm/Nd fractionation. Using this approach for lunar basalts implies that Lu/Hf fractionation of low-Ti basalts ($\epsilon_{\text{Hf}} = \epsilon_{\text{Nd}}$) was four times as large as Sm/Nd fractionation. The near constant ϵ_{Hf} value at variable ϵ_{Nd} values for high-Ti

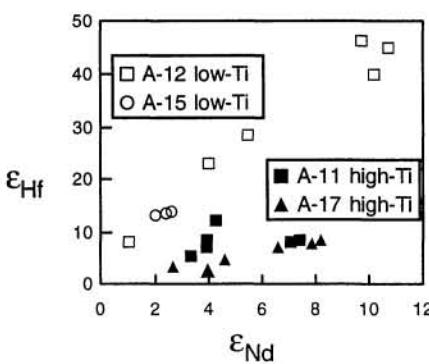


Figure 1

basalts implies that Lu/Hf fractionation was essentially buffered at a constant value without affecting Sm/Nd fractionation. These differences in Lu/Hf fractionation between the low- and high-Ti basalts can be used to place constraints on the possible mineralogy of source regions for these two suites of mare magma types. We have modeled the possible mineralogies by assuming that mare basalts are derived from remelting of cumulate layers that formed 4.4 billion years ago from a magma ocean with chondritic Nd and Hf isotopic compositions. Of the possible minerals that crystallized from the lunar magma ocean, orthopyroxene and ilmenite are the two minerals that will produce the largest Lu/Hf fractionations relative to Sm/Nd (see D-values reported in [8]); orthopyroxene dominated sources will have high Lu/Hf ratios whereas ilmenite accumulation will produce sources with lower Lu/Hf ratios. *The high positive ϵ_{Hf} values (up to +40) and requisite high Lu/Hf source ratios of the low-Ti basalt source region can only be produced by accumulation of a large proportion of orthopyroxene (70%).* Other phases such as clinopyroxene or pigeonite, which produce less Lu/Hf fractionation, can only be present in small proportions (5%). Moreover, *ilmenite that crystallized from the lunar magma ocean cannot be in the source region of low-Ti basalts because this would produce a source having a comparatively low Lu/Hf ratio.* Importantly, this includes the ilmenite basalts from the Apollo 12 landing site which have initial ϵ_{Hf} values of +40. The relatively constant ϵ_{Hf} values at variable ϵ_{Nd} values for the high-Ti basalt source region can be successfully modeled using a composition similar to that determined by Snyder et al. [8], which consists of sub-equal proportions of pigeonite and olivine, 5-10 % clinopyroxene, and a small amount of ilmenite (1-4%). If orthopyroxene is included in the source, then the percentage of ilmenite must be increased to offset the increase in Lu/Hf.

Conclusions: Calculations for determining the required source mineralogy to produce the time integrated Lu/Hf and Sm/Nd ratios of the Moon's mantle are highly dependent on a) starting composition, b) equilibrium vs fractional crystallization, c) and mineral-melt partition coefficients. However, we consider the conclusions regarding the presence or absence of orthopyroxene and ilmenite in the low- and high-Ti source regions to be robust. This is because of the dramatically different partitioning of Lu and Hf in these phases; orthopyroxene is strongly Lu-retentive relative to Hf, whereas ilmenite is Hf-retentive relative to Lu. Moreover, we note that modeling of this type is not possible using the Sm-Nd system because Sm/Nd fractions are much less compared to Lu/Hf fractionations.

Table 1: Lu and Hf isotopic data for high-Ti mare basalts

Sample	Lu ppm	Hf ppm	$^{176}\text{Lu}/^{177}\text{Hf}$	$^{176}\text{Hf}/^{177}\text{Hf}$	ϵ_{Hf}	ϵ_{Nd}
78586	1.096	6.998	0.02225	0.282057 ± 49	3.4	2.7
71545	1.059	6.633	0.02268	0.282124 ± 111	4.7	4.6
77516	1.015	6.400	0.02254	0.282020 ± 79	1.3	4.0
10044	2.618	15.887	0.02342	0.282282 ± 24	8.2	7.1
10047	2.430	14.664	0.02355	0.282310 ± 23	8.9	7.4

The measured value of JMC-475 Hf standard during the course of this study was $^{176}\text{Hf}/^{177}\text{Hf} = 0.282125$ which is equivalent to $^{176}\text{Hf}/^{177}\text{Hf}$ for CHUR of 0.282789. This is equivalent to present day CHUR of $^{176}\text{Hf}/^{177}\text{Hf} = 0.282827$ and JMC-475 $^{176}\text{Hf}/^{177}\text{Hf} = 282198$ [9,10], where JMC-475 has $\epsilon_{\text{Hf}} = -23.47$.

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