

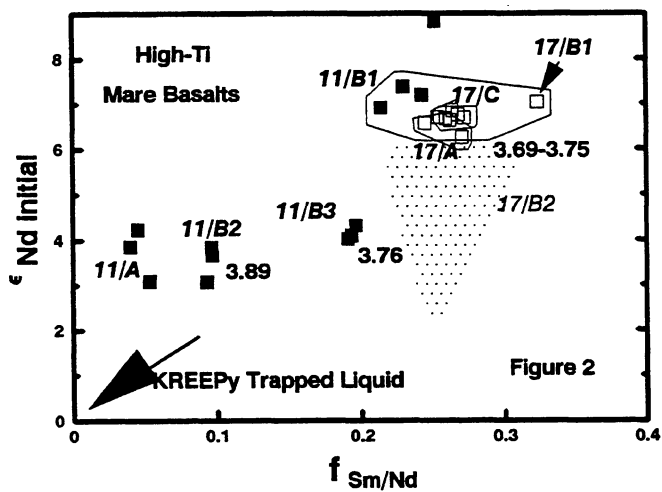
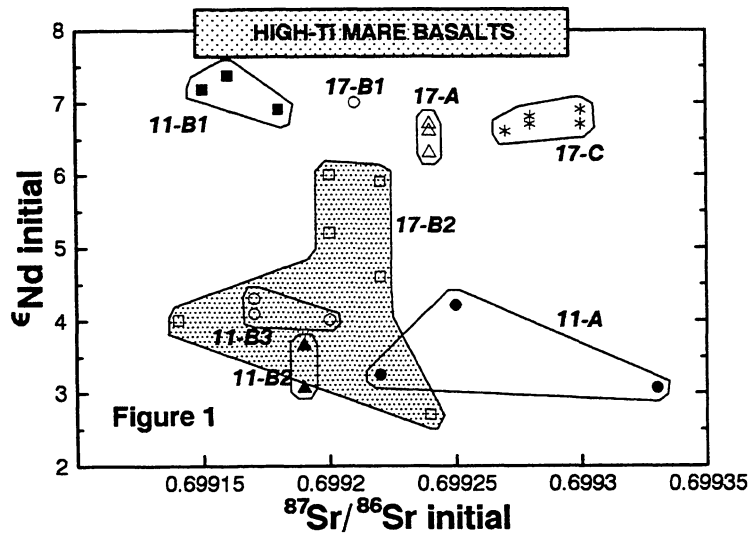
ISOTOPIC CONSTRAINTS ON THE LUNAR UPPER MANTLE: EVIDENCE FROM HIGH-Ti BASALTS Gregory A. SNYDER, Eric A. JERDE, and Lawrence A. TAYLOR, Dept. of Geological Sciences, University of Tennessee, Knoxville, TN 37996; Der-Chuen LEE and Alex N. HALLIDAY, Dept. of Geological Sciences, University of Michigan, Ann Arbor, MI 48109.

It is generally believed that the upper mantle of the Moon can be modelled as the layered cumulate residue of a deep lunar magma ocean (LMO). This LMO formed early and crystallized to form the lunar upper mantle by 4.4 Ga [1]. At both the Apollo 11 and Apollo 17 landing sites, the discovery of high-Ti basalts that are similar in mineralogy and major-element chemistry lends credence to the simple layer-cake model of the lunar upper mantle. In an effort to better understand the high-Ti source from which these basalts were derived by partial melting, an integrated isotopic and trace-element study has been undertaken of high-Ti basalts at Mare Tranquillitatis (Apollo 11 landing site; [1,2] and [3], this volume) and the Valley of Taurus-Littrow (Apollo 17; [4]).

Nd AND Sr ISOTOPIC DATA FROM LUNAR HIGH-Ti BASALTS

Data from high-Ti basalts display a broad scatter in initial Nd and Sr isotopic composition as shown in Fig. 1. However, basalts from Apollo 11 generally plot in the lower left of this diagram, whereas those from Apollo 17 plot in the upper right. Snyder et al. [5] have indicated the similarity in trace element compositions between Type C basalts from the Apollo 17 landing site and Type B3 basalts from the Apollo 11 landing site. They have inferred that these two basalt types were generated from the same source. Furthermore, Jerde et al. [6] have indicated a possible genetic link between the type B1 and B3 basalts from the Apollo 11 site. It therefore seems likely that types B1 and B3 basalts from Apollo 11 and Type C basalts from Apollo 17 were derived from the same (or a similar) source.

These apparent relationships are endorsed when the initial ϵ_{Nd} values are considered in consort with the Sm/Nd ratios of the samples. On Figure 2, initial ϵ_{Nd} values for all high-Ti basalts are plotted versus $f_{Sm/Nd}$ [$= (Sm/Nd_{measured}) / (Sm/Nd_{CHUR}) - 1$; i.e., the measured Sm/Nd ratio relative to a chondritic uniform reservoir, CHUR]. The stippled field is for the A-17 Type B2 basalts which plot in a diffuse region. Their interpretation is equivocal [4], and they will not be dealt with further. The A-11 Type A basalts are the youngest of all samples and are explained by a special model, unique to only this group [6]. Also indicated on this diagram are the eruption ages of the various basalt suites: A-11/B2=3.89 Ga --> A-11/B3=3.76 Ga --> A-17/A=3.75 Ga --> A-17/C=3.72 Ga --> A-17/B1, A-11/B1=3.71 Ga. The degree of LREE-depletion of these groups increases (i.e., $f_{Sm/Nd}$ increases) with age. These depletions are minimum values for the source, as partial melting, and subsequent fractional crystallization of the melt, will tend to decrease the $f_{Sm/Nd}$.



AN ADCUMULATE-TRAPPED-LIQUID, SUCCESSIVELY DEPLETING SOURCE MODEL

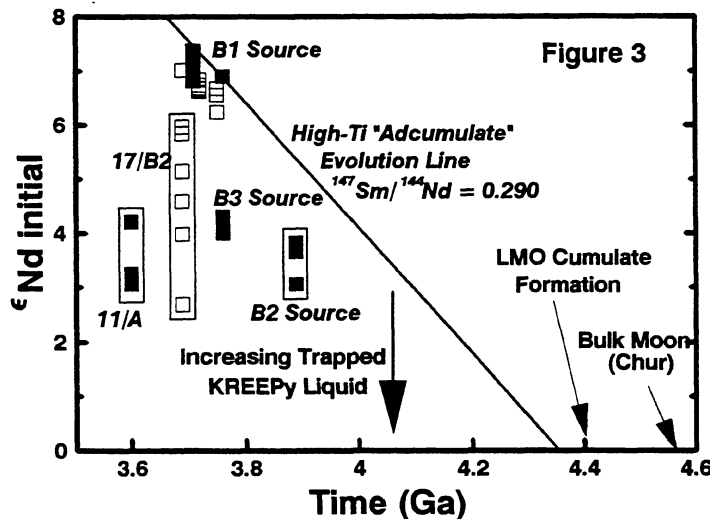


Figure 2 suggests a consistent and rather simple model for the cumulate source region of the high-Ti mare basalts. This scenario includes at least two successive depletion events in the high-Ti basalt source over time, leading to basalts with successively higher Sm/Nd ratios and higher ϵ_{Nd} values (Fig. 2,3). The original cumulate source contained a small proportion of trapped liquid which, at the advanced stage of crystallization of the LMO [5], would have been KREEPy. An early low-percentage partial melt (at 3.89 Ga) of this source would have taken out a large proportion of this trapped liquid. The KREEPy nature of this melt is evidenced by the presence of whitlockite in the Apollo 11 B2 basalts. Each successive stage of

melting would extract proportionately less of this KREEPy trapped liquid, as there would be less trapped liquid remaining in the source. At 3.76 Ga, effectively all of the trapped liquid was melted out of the source. Basalts generated after 3.76 Ga lie along an upper mantle adcumulate ($^{147}\text{Sm}/^{144}\text{Nd}=0.290$) evolution line (Fig. 3), indicating little or no trapped KREEPy liquid (which would lie off of the diagram at negative ϵ_{Nd} values). There still may have been trapped liquid in the source which wetted the grain boundaries of the cumulate minerals, but it was a vanishingly small proportion.

This model also can be represented as simple two component mixing of the cumulate source with progressively less trapped liquid with time. The KREEPy trapped liquid is the residual liquid left after 90-95% crystallization of the LMO (as per Snyder et al. [5]). The isotopic and trace-element composition of this KREEPy liquid component may be represented by KREEP basalt sample 15382 (Rb=16 ppm, Sr=195 ppm, $^{87}\text{Sr}/^{86}\text{Sr}_{(3.9\text{ Ga})} = 0.70034$; Sm=31 ppm, Nd=112 ppm, $\epsilon_{Nd(3.9)} = -2$; [7,8]). The cumulate portion of the source is modelled as a cpx-pigeonite-ilmenite-olivine perfect adcumulate (Rb=0.165 ppm, Sr=4.16 ppm, Sm=0.631 ppm, Nd = 1.2 ppm, again as per Snyder et al. [5]; Fig. 2) that has an extremely elevated ϵ_{Nd} (+47 at 3.9 Ga) and the lowest Sr initial ratio (0.69903, or LUNI) at 3.9 Ga. However, as mentioned above, it is not likely that a truly perfect adcumulate exists in the lunar upper mantle. Instead, a "nearly perfect" adcumulate, with trapped KREEPy liquid wetting the mineral edges, is more realistic. This depleted component is approximated by the A-17 B1 samples (Fig. 2,3). Radiogenic isotopes in the high-Ti basalts are controlled by the melting of this cumulate source, whereas trace-element variations, for the most part, are controlled by near-surface fractional crystallization and assimilation processes [6].

CONCLUSIONS

High-Ti basaltic volcanism on the Moon occurred over a period of roughly 250 Ma, but may have involved the melting of the same cumulate layer in the mantle, leading to its successive depletion. The source for lunar high-Ti basalts is undoubtedly found in cumulates left from fractional crystallization of the LMO prior to 4.4 Ga. Trace-element variations within groups of basalts are controlled by fractional crystallization of liquidus phases [6]. The range in Sr and Nd isotopic ratios seen in high-Ti basalts from both Apollo 11 and 17 landing sites is due to melting of a clinopyroxene-pigeonite-ilmenite-olivine cumulate layer with progressively less trapped, intercumulus, KREEPy liquid over time.

REFERENCES: [1] Papanastassiou et al. (1977), *PLSC 8th*, 1639-1672; [2] Unruh et al. (1984), *PLSC 14th*, B459-B477; [3] Snyder et al. (1992), *LPSC XXIII*, this volume; [4] Paces et al. (1991), *GCA 55*, 2025-2043; [5] Snyder et al. (1992), *GCA*, submitted; [6] Jerde et al. (1992), *LPSC XXIII*, this volume; [7] Nyquist (1977), in *Chemistry of the Moon*, 103-142; [8] Lugmair and Carlson (1978), *PLSC 9th*, 689-704.