EVIDENCE FOR AGE-PROGRESSIVE MELTING OF INCREASINGLY INCOMPATIBLE-ELEMENT-ENRICHED MANTLE RESERVOIRS ON THE MOON?

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Introduction: Impact-related decompression or internal heating of lunar mantle sources enriched in incompatible radioactive elements are just two of the possible explanations for the large range in ages for lunar volcanism (4.3 to < 3Ga). KREEP-rich mantle sources could produce enough heat to generate melting (e.g., [1]), and the KREEP-like signature of a 2.9 Ga meteorite (NWA 773) has served to strengthen such arguments [2]. Here we present new trace-element and Sr-Nd-Hf isotope data which suggest age-progressive trends in KREEP-enrichment for low- and high-Ti mare basalts. If such trends are robust, it can be inferred that either; 1) melting was more vigorous early in lunar history, and the existing sample suites are not representative; 2) KREEP-rich material was mixed into melting regions via lunar mantle convection up to at least 3 Ga; or, 3) impact-induced decompression enhanced preferential melting of KREEP-rich mantle domains later on in lunar history.

Analytical Methods: Six Apollo 17, 5 Apollo 15, and 5 LaPaz meteorite (LAP 02205, LAP 02224, LAP 02226, LAP 02436 and LAP 03632, hereafter referred to collectively as LaPaz) samples were analyzed in this study. The samples have been well characterized in terms of petrography and mineral chemistry by our group [3,4,5], and are also being used for on-going Re-Os isotope studies [6,7]. Sample splits of 2-3 g were crushed in an agate mortar and pestle under class 100 air flow to create homogenized whole-rock powders. Major element analyses were performed by EMP on 10-20 mg fused beads at the University of Tennessee. The fused beads were also used to perform LA-ICP-MS trace element analyses at ANU. Additional trace element analyses were performed on 20 mg splits of whole-rock powder using an ELAN 6000 ICP-MS at AHIGL. Sr, Nd, and Hf isotope analyses were performed on 100 mg whole-rock aliquots, after separation/purification via cation-exchange chromatography, using the AHIGL NEPTUNE MC-ICP-MS.

Results and Discussion: Major element compositions of the basalts are in excellent agreement with results from previous studies. Trace-element results from solution ICP-MS and average analyses by LA-ICP-MS of fused beads are also consistent. This data illustrates the LREE-depleted nature of high-Ti basalts versus flatter, and on average, lower abundance REE patterns for low-Ti basalts, despite the similar estimated degrees of partial melting (Fig. 1). Although ratios of trace elements are invariant, we have noted similar chemical variations, within repeat analyses of coarse grained samples (e.g., 15555), to previous studies [e.g., 8], due to the relatively small sample split sizes.

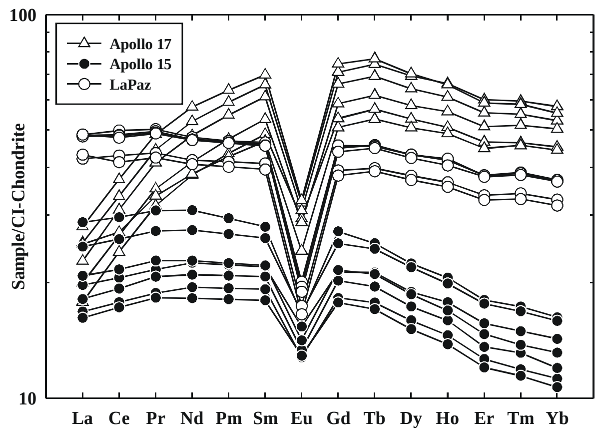

Fig. 1: Solution ICP-MS REE patterns for high-Ti Apollo 17 and low-Ti Apollo 15 and LaPaz mare basalts.

The new $^{87}Sr/^{86}Sr_i$, εNd_i, and εHf_i values for Apollo 15 and Apollo 17 mare basalts are similar to those from previous studies [9]. The LaPaz mare basalt possesses more radiogenic $^{87}Sr/^{86}Sr_i$, lower εNd_i, and similar εHf_i values to Apollo 15 mare basalts.

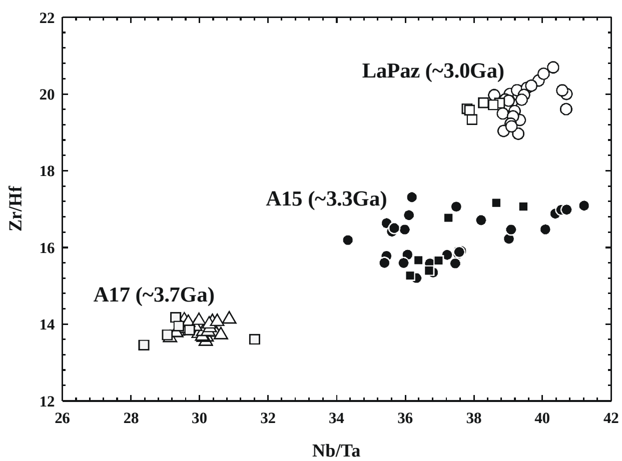

Fig. 2: Nb/Ta versus Zr/Hf for high-Ti Apollo 17 and low-Ti Apollo 15 and LaPaz mare basalts. Squares distinguish solution ICP-MS from LA-ICP-MS data.

KREEP is enriched in incompatible elements and has a relatively flat to slightly LREE-enriched REE pattern. The KREEP geochemical signature is also likely to have elevated Zr/Hf, Nb/Ta, and Rb/Sr, and lower Sm/Nd and

Lu/Hf, due to the relative incompatibilities of these elements.

LA-ICP-MS data on fused beads that are homogeneous with respect to major elements, but inhomogeneous with respect to trace elements, yield coherent trends in Nb/Ta versus Zr/Hf space. These trends indicate that with age, Nb/Ta and Zr/Hf increase in the presented datasets (Fig. 2). Plots of $^{87}Sr/^{86}Sr_i$ vs. εNd_i also indicate increasing incompatible element enrichment in younger basalts (Fig. 3).

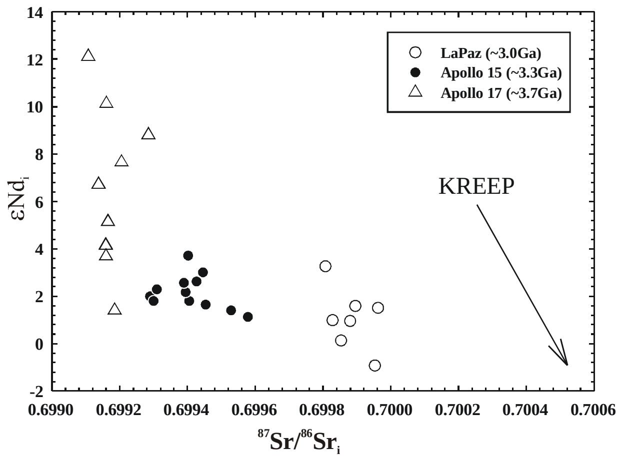

Fig. 3: εNd_i versus $^{87}Sr/^{86}Sr_i$ for high-Ti Apollo 17 and low-Ti Apollo 15 and LaPaz mare basalts.

The nature of the $^{87}Sr/^{86}Sr_i$ and εNd_i signatures indicates that the source of the younger mare basalts was relatively more incompatible-element-enriched than the mantle sources of older volcanism. Source mixing between a relatively depleted-mantle component and KREEP can explain the enriched $^{87}Sr/^{86}Sr_i$ and depleted εNd_i signatures in young mare basalt volcanism. Addition of a KREEP component may also explain the discrepancy between high-Ti and low-Ti REE patterns. LREE-rich KREEP will generate flat REE patterns, either as trapped liquid in a cumulate mantle source or via mixing later in lunar history. However, sources lacking a KREEP component will be relatively LREE depleted.

Age-progressive melting of mantle sources enriched in incompatible-elements appears to have occurred on the Moon. It is notable that the majority of incompatible-element-enriched rocks of the lunar surface occur in the Procellarum KREEP Terrane (PKT). Therefore, it is likely that the mare basalts presented here track the melting history of the mantle beneath that region; it is currently difficult to elucidate the melting history of regions of the lunar mantle outside of the PKT.

The apparent age-progressive incompatible-element-enrichment in the mantle sources of low-Ti mare basalts is hard to reconcile with crustal-assimilation processes. Considering the ancient age of KREEP (> 4.3 Ga [10]), it is difficult to envisage how older flows did not incorporate such a geochemical signature on the way to the lunar surface, unless a shallow-lying KREEP-rich layer is heterogeneously distributed beneath the lunar crust. Although assimilation and fractional crystallization can generate mixing trends, and LaPaz mare basalts are more evolved than their Apollo 15 or Apollo 12 counterparts, there is limited evidence in these rocks for assimilation processes [3].

Alternative possibilities for the age-progressive incompatible-element-enrichments include; 1) large-scale melting early in lunar history and poor preservation of incompatible-element-rich lavas (i.e., only high-Ti lavas are preserved); 2) KREEP-rich material was stirred into cumulate mantle sources through time, generating age-progressive volcanism; or, 3) trapped instantaneous liquids in low-Ti mantle sources allowed preferential melting, perhaps induced by impact-related decompression of the lunar mantle.

Although feasible, there is little current evidence either from remote sensing or chemical investigations to merit alternative (1). Alternative (2) also seems unlikely considering the poor correlation between depth of source melting and age. Convective overturn of the lunar mantle is required in some models, however, the time period for this process is envisaged as millions rather than billions of years. Of the three possibilities alternative (3) appears the most consistent with previous models. It is unclear, however, why the incompatible-element-rich mantle sources did not melt earlier in lunar evolution. Possible explanations include decompressional melting in response to large impacts, or gradual convective overturn and thermal blanketing resulting in partial melting of lunar magma ocean cumulates.

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