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USING APOLLO 17 HIGH-TI MARE BASALTS AS WINDOWS TO THE LUNAR MANTLE. Clive R. Neal¹ and Lawrence A. Taylor², ¹Department of Civil Engineering and Geological Sciences, University of Notre Dame, Notre Dame IN 46556, USA, ²Department of Geological Sciences, University of Tennessee, Knoxville TN 37996, USA.

Detailed study of mare basalts and volcanic glasses is critical in our understanding of the lunar mantle because, as yet, no mantle xenoliths have been recognized in the current collection. Primitive endmember, volcanic lunar glass compositions can be considered primary mantle melts because of their glassy, uncrystallized nature, and analyses of such samples yielded important information regarding the mantle source (e.g., [1–3]). The fact that no relationship between the glasses and the crystalline mare basalts has been established suggests that the basalts were derived from a separate source and therefore have the potential to yield further critical information regarding the lunar mantle. By understanding the processes that have occurred during post-magma-generation evolution, parental or possibly primary compositions can be highlighted for further study, possibly leading to source evaluation. However, where it is demonstrable that the composition chosen as the parental/“primary” melt has experienced some post-magma-generation evolution (i.e., a vitrophyre containing olivine/ilmenite/chromite-ulvöspinel phenocrysts), this composition cannot be used for direct calculation of a mantle source. In this case, incompatible trace-element ratios can be utilized to remove the effects of fractional crystallization and allow an evaluation of the source region (e.g., [4,5]).

Apollo 17 Source Modeling: The source composition and location of Apollo 17 high-Ti mare basalts has been under debate for many years and several models have been proposed. The one unifying theme of 99% of these models is that they require a mafic, cumulate mantle source. This is where the similarity ends! Models for titaniferous basalt petrogenesis include those requiring early LMO cumulates of olivine and opx [6], late-stage cumulates [4,7–9], to those requiring a mixture of early and late-stage cumulates [10–15] or hybrid sources [3,16]. Experimental evidence puts the depth of origin of the Apollo 17 high-Ti mare basalts at between 200 and 400 km ([17]; source dominated by olivine and low-Ca pyroxene with ilmenite) to ≤ 150 km [10–12]. The degree of partial melting ranges from 5% to 20%. It is generally agreed that a Fe-Ti oxide mineral is required in the source of Apollo 17 high-Ti mare basalts.

Determination of the depth of origin is critical in understanding the composition, stratigraphy, and dynamics of the lunar mantle. For example, at depths exceeding 300–350 km within the Moon, the source for the high-Ti basalts would be eclogitic [18] and such a source would not yield the inherently LREE-depleted signature of the Apollo 17 high-Ti mare basalts. Therefore, depths must be shallower than 300 km. Furthermore, there are two points of contention in

defining the source regions of Apollo 17 high-Ti mare basalts: (1) Was ilmenite exhausted or retained in the residue? (2) Was plagioclase present in the source? Shih et al. [13] proposed a source composition of olivine + clinopyroxene + ilmenite \pm plagioclase, all of which were retained in the source. On the basis of experimental evidence, Walker et al. [10,11], suggest that ilmenite remains in the residue, and plagioclase, if present, would be exhausted; conversely, Green et al. [17] demonstrate that ilmenite would be exhausted and suggests plagioclase was never present. Hughes et al. [3] conclude that both ilmenite and plagioclase are exhausted from their modeled source composition. Clearly, the nature of the Apollo 17 high-Ti mare basalt source region composition is far from resolved, and the situation is complicated by the recognition of four, possibly five, separate magma types: A, B1, B2, C, and D [19–23].

Recognizing the Apollo 17 High-Ti Mare Basalt Source Region Components: The purpose of this abstract is to use incompatible trace-element ratios to evaluate the nature of the source regions of Apollo 17 type A, B1, B2, and possibly C high-Ti basalts in an attempt to answer the two questions posed above. A database of practically all analyzed Apollo 17 basalts was assembled and the nature of any potential fractionating assemblage evaluated using petrographic observations, coupled with the MAGMAFOX program of Longhi [24]. Samples chosen for processing by the MAGMAFOX program were either fine grained or vitrophyric. The results demonstrate a fractionating sequence dominated by chromite-ulvöspinel, olivine, ilmenite, and pyroxene (low and high Ca). Plagioclase becomes a liquidus phase only after $\approx 55\%$ crystallization. As demonstrated by Neal et al. [21], over 98% of all types A, B1, and B2 can be modeled by 40% closed-system fractional crystallization of olivine, chromite-ulvöspinel, armalcolite, ilmenite, and augite. This assemblage is generally supported by the MAGMAFOX program, except for armalcolite (calculated as ilmenite), and the program results also include pigeonite. Therefore, because plagioclase is not part of the fractionating assemblage, Sm and Eu can be considered as incompatible elements, as are La, Yb, and Hf. Although ilmenite is fractionating, the Hf crystal/liquid partition coefficient for ilmenite is ≈ 0.4 [25]. As part of this study, the Yb/Hf ratio is used because although both are incompatible (i.e., $K_d < 1$), these elements will have approximately the same partition coefficient value in the fractionating assemblage described above. Significant changes in this ratio will

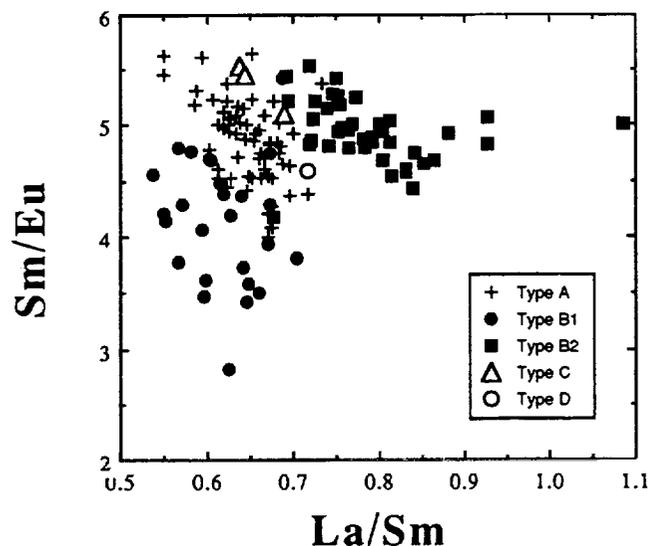


Fig. 1.

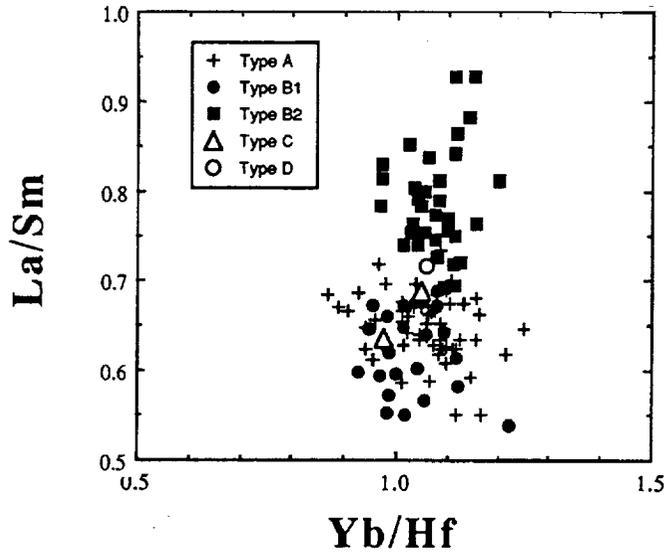


Fig. 2.

signify preferential exhaustion of ilmenite or pyroxene in the source. Other incompatible trace elements, such as Ba, Zr, Nb, etc., have not been used because they have only been analyzed for a few samples in the database.

Results: This study uses three ratios to (1) track the degree of partial melting (La/Sm, which will decrease with increasing degrees of partial melt); (2) examine the role of plagioclase (Sm/Eu); and (3) examine the role of ilmenite (Yb/Hf). Figure 1 is a plot of Sm/Eu against La/Sm. Types A, B1, and B2 all form parallel to subparallel negative correlations. In Fig. 2, Sm/Eu is plotted against Yb/Hf with each group of basalts exhibiting a large range of Sm/Eu and a limited range of Yb/Hf. In Fig. 3, La/Sm is plotted against Yb/Hf. The type B2 basalts have the highest La/Sm ratios, but all Apollo 17 high-Ti mare basalts contain similar Yb/Hf ratios between 0.9 and 1.2.

Discussion: The parallel negative correlations observed in Fig. 1 are interpreted as representing the presence of plagioclase in the

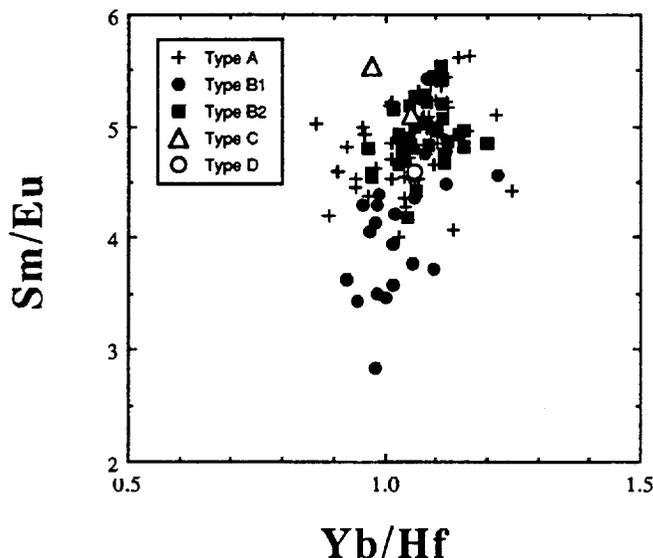


Fig. 3.

source that becomes exhausted with increasing degrees of partial melt. As plagioclase is not part of the fractionating sequence, the range in Sm/Eu can only be accounted for by plagioclase in the source that does not remain in the residue (à la [11]). The type B2 basalts show a decreasing La/Sm ratio at constant Sm/Eu followed by increasing Sm/Eu with decreasing La/Sm. It is tempting to conclude that this trend documents the point at which plagioclase is exhausted in the B2 source. However, Paces et al. [26] demonstrated the open-system behavior of the type B2 basalts; such interpretation of this trend must be undertaken with a degree of caution. This is also supported by Fig. 2, but the restricted range of Yb/Hf suggests that neither pyroxene nor ilmenite is exhausted during partial melting. The small scatter of Yb/Hf is probably due to ilmenite becoming a liquidus phase before pyroxene during crystal fractionation. If ilmenite was exhausted in the source relative to pyroxene, the range in the Yb/Hf ratio would be dramatic (see inset on Fig. 2). Figure 3 affirms the conclusions derived from Figs. 1 and 2, with a range of Sm/Eu and a restricted range in Yb/Hf. The type B2 basalts have higher La/Sm and Yb/Hf ratios relative to the other Apollo 17 high-Ti basalt types, which may be a result of open-system behavior (KREEP/KREEP residue assimilation?).

Summary: The Apollo 17 high-Ti mare basalts are derived from source regions containing plagioclase that was not retained in the residue. Ilmenite appears to remain as a residual phase, but plagioclase is exhausted. The open-system behavior of the type B2 basalts results in slightly higher Yb/Hf and La/Sm ratios. The nature of the added component is not clear, but may be a KREEP derivative or residue. The recognition of plagioclase in the source(s) of these basalts suggests that the location of the source region(s) would be more likely to be <150 km (i.e., closer to the plagioclase-rich crust), which would allow incorporation of plagioclase into the source through incomplete separation of crustal feldspar, supporting the conclusion of [15].

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