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LUNAR MARE VOLCANISM: MIXING OF DISTINCT, MANTLE SOURCE REGIONS WITH KREEP-LIKE COMPONENT

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Mare basalts comprise less than 1% of the lunar crust, but they constitute our primary source of information on the moon's upper mantle. Compositional variations between mare basalt suites reflect variations in the mineralogical and geochemical composition of the lunar mantle which formed during early lunar differentiation (4.5-4.4 AE). Three broad suites of mare basalt are recognized: very low-Ti (VLT) basalts with TiO_2 < 1 wt%, low-Ti basalts with TiO_2 = 2-4 wt%, and high-Ti basalts with TiO_2 = 10-14 wt% [1-3]. Important subgroups include the Apollo 12 ilmenite basalts (TiO_2 = 5-6 wt%) [4], aluminous low-Ti mare basalts (TiO_2 = 2-4 wt%, Al_2O_3 = 10-14 wt%) [5-7], and the newly discovered Very High potassium (VHK) aluminous low-Ti basalts, with K_2O = 0.4-1.5 wt% [8-10]. The mare basalt source region has geochemical characteristics complementary to the highlands crust, and is generally thought to consist of mafic cumulates from the magma ocean which formed the felsic crust by feldspar flotation. The progressive enrichment of mare basalts in Fe/Mg, alkalis, and incompatible trace elements in the sequence VLT basalt -> low-Ti basalt -> high-Ti basalt is explained by the remelting of mafic cumulates formed at progressively shallower depths in the evolving magma ocean. This model is also consistent with the observed decrease in compatible element concentrations and the progressive increase in negative Eu anomalies [11].

Despite the appeal of this simple model there is increasing evidence that more complex scenarios are required. The hybridization of Fe- and incompatible element-rich late magma ocean cumulates with more magnesian early magma ocean cumulates seems necessary to explain the major and trace element compositions of the mare basalt source region: mare basalts are too magnesain to be derived from a magma ocean cumulate formed after >95% fractional crystallization, but such high degrees of fractional crystallization are needed to create the necessary trace element rich source [12, 13]. This hybridization is gravitationally driven since the late magma ocean cumulates are more Fe-rich and denser than the underlying magnesian cumulates. Recent hybridization models generally assume three end members: early magnesian cumulates with low Ti (dominantly olivine + Opx), late Fe,Ti-rich cumulates (Cpx + ilmenite), and a late magma ocean trapped-liquid component similar to KREEP in composition [13, 14]. These end members are mixed in various proportions to create the range in observed mare basalt compositions.

Recent studies of the Apollo 14 aluminous mare basalt suite have revealed a wide variety of previously unknown mare basalt types, many of which seem to require assimilation as an important process in their petrogenesis [5-10]. Two main components have been identified: KREEP, the incompatible element-rich mafic component concentrated in soils and impact breccias [5-7], and lunar granites [8-10]. The Apollo 14 aluminous basalt suite is important because it has many compositional characteristics intermediate between normal, low-alumina mare basalts and high-Ti mare basalts. Apollo 14 high-alumina basalts have high MG#s (similar to low-Al, low-Ti basalts), high alkali and incompatible trace element contents (similar to high-Ti basalts or higher), and compatible trace elements intermediate between high and low Ti basalts [15]. In a cumulate remelting model, these characteristics suggest a mantle source region which lies above the normal low-Ti basalt source and below the high-Ti basalt source. In addition, Apollo 14 high-Al basalts are also high in CaO, suggesting either plagioclase assimilation [12] or plagioclase in the source region.

When data for all mare basalt types (including Apollo 14 aluminous mare basalts and VHK basalts) is plotted on ratio-ratio or ratio-element plots, two distinct trends are observed (figures 1,2). One trend is defined by low-Ti basalts *sensu lato* (including VLT, VHK, and high-Al, low-Ti basalts); the other trend is defined by the high-Ti basalt suite. Both trends resemble hyperbolic mixing curves [16] whose incompatible element-rich end points asymptotically towards KREEP. There is little or no overlap between the two trends, however, and their incompatible element-poor asymptotes point to distinct end-member compositions. If these curves are considered simple mixing hyperbolas, up to 65% assimilation of KREEP is indicated. Alternatively, these curves may be due to fractional crystallization, as suggested by fractionation trends on MG# plots. If so, the trends toward a KREEP-like composition suggest that this composition may represent an incompatible element-rich end member mixed into the mare basalt source prior to melting. Fractionation of phase assemblages with bulk distribution coefficients similar to the refractory mineral assemblage will drive the melt composition towards the KREEP-like mixing component.

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These observations suggest that the compositional variations observed in mare basalts result from a complex source hybridization process similar to that suggested by Hughes et al [13]. In this scenario a late stage magma ocean component similar in composition to KREEP sinks into earlier magma ocean cumulates and the resulting mixture undergoes partial melting to form the mare basalt parent magmas. These magmas subsequently undergo fractional crystallization to create the observed fractionation trends. The major difference between our model and previous models such as Hughes et al [13] is that the KREEPy component mixes with distinct low-Ti and high-Ti mantle source regions, and that there is no significant mixing between these two source regions (e.g., figures 1,20). The physical process by which the KREEP component mixes with the cumulate mantle rocks is uncertain; the KREEPy component may sink as solid blocks of crystalline material or as a liquid. For this material to sink, it must have been an Fe-rich precursor to KREEP and not true "urKREEP", whose density is lower than that of mare basalt.

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Fig. 1. Ti/Sm vs Sm for mare basalts from all sites. High-Ti basalts plot along the upper mixing curve, low-Ti basalts along the lower curve.
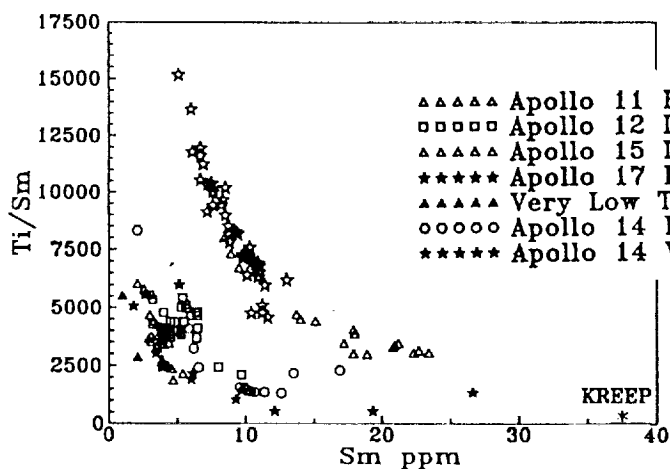
Fig. 2. Sc/Sm vs Sm for mare basalts from all sites. Same symbols as figure 1.