ANOTHER (RE)VIEW OF LUNAR BASALTIC MAGMATISM

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INTRODUCTION

Early perceptions of lunar basaltic magmatism were that it was far less complicated than its terrestrial analog. However, over twenty years of lunar research has defined much more complex scenarios. End-member mare basalt generating models developed over the years include (A) partial melting of a primitive mantle source [1,2], (B) assimilation [3], (C) partial melting of a processed cumulate mantle source [4, 5], and (D) partial melting of a hybrid mantle source [6,7]. Superimposed on these melt generating processes are a number of possible secondary magmatic processes, such as fractional crystallization, AFC, and liquid immiscibility. This presentation emphasizes the generation of basaltic magmas in the lunar mantle.

Mare basalts comprise less than 1% of the lunar crust [8]. Assuming 35% partial melting (other models suggest less than 10% partial melting) less than 2% of the lunar mantle was involved in the partial melting events that produced all the basalt flows throughout lunar history. Compared to their terrestrial analogs, mare basalts show an incredible range in compositions. Early basalt studies differentiated high Ti basalt-glasses, low Ti basalt-glasses and very low Ti basalt-glasses. Individual fractionation trajectories have been distinguished within these groups. Later studies have identified aluminous basalts [9, 10, 11], very high potassium aluminous basalts [9,11,12], and a wide compositional range of picritic volcanic glasses [13]. Partial melting models must address these wide major element compositional ranges and relationships among these basalt types.

CONNECTION BETWEEN PICRITIC GLASSES AND MARE BASALTS

Lunar picritic magmas (glasses) and crystalline mare basalts are products of basalt generation processes in the lunar mantle. As such, it is fundamental to our understanding of mare basalt petrogenesis to not only comprehend the generation of each, but to also grasp the linkages between these magmas. The glasses tend to have higher Mg/(Mg+Fe) than crystalline mare basalts [13]; and therefore, a logical assumption is that the crystalline basalts were derived from primary magmas with compositions similar to the picritic glasses. However, liquid lines of descent for major and trace elements suggest that most mare basalts are not directly derived by simple low-pressure fractionation from parental melts with compositions identical to that of the picritic glasses [14, 15, 16]. Numerous lines of evidence may be interpreted as suggesting the picritic glasses and mare basalts represent magma generation from two distinct sources: (a) lack of low pressure fractionation linkages between glasses and basalts, (b) differences in experimentally determined multiple saturation depths, (c) volatile-rich source for the picritic glasses suggested by mode of eruptive mechanism (fire-fountaining) and U/Pb isotopic ratios [17, 18]. However, (a) may also be interpreted as indicating a sampling problem, whereas (b) may reflect the more derivative nature (via fractional crystallization) of the crystalline basalts (see below). In any event, present data [15, 16, 19] indicates a heterogeneous mantle at depths of >300 km, capable upon melting of generating a wide spectrum of compositionally distinct picritic magmas (high-, low-Ti) with a range of incompatible trace element signatures (i.e., KREEP). The relationship between the picritic and basaltic magmas may reflect (A) derivation of most basalts from below 300 km as picritic magma. Mare basalts are derived from a volatile-poor, heterogeneous mantle source and are fractionated on their path to the lunar surface, while the picritic magma are derived from a volatile-rich, heterogeneous source and delivered to the lunar surface rapidly; or (B) picritic magma are derived from a deeper (>300 km), heterogeneous source than the mare basalts (<300 km). PROBLEMS: Are the sources for the mare basalts as heterogeneous as the picritic magma source? What are the mechanisms for extensive mantle fractionation and heterogeneity? How can one distinguish between models (A) and (B)?

SOURCE FOR CRYSTALLINE MARE BASALTS

Like the evidence from the picritic glasses, various studies have shown that the crystalline mare basalts were derived from source regions with dramatic (high-Ti to very low-Ti sources) to subtle compositional differences. As an example of the latter, Rhodes et al. [20], Beaty et al. [21], Nyquist et al. [22], Ryder [23], and Neal et al. [24] concluded that the high-Ti basalts from the A-11 and A-17 sites define at least 10 distinct batches of magma unrelated by fractional crystallization or partial melting. Using the empirical models of Longhi [14], we calculated liquid lines of descent for the picritic magmas and liquid lines of "ascent" for the crystalline mare basalts. Approximately 10-20% olivine fractionation is required to extend the most primitive crystalline mare basalts (i.e., 70215, 74275) into the picritic glass field. The existence of lunar picritic magmas (glasses) of compositions which at least approach these back calculated picrites and multiple saturation at low pressures of many of the most Mg-rich, high-Ti basalts [25] suggest many may have been derived from the fractionation of picritic parent magmas. These picritic parents for the crystalline basalts may have been derived at depths equivalent to that of the multiple saturation depth of the picrites glasses. Walker et al. [26], Kesson [25], and Kesson and Lindsley [27] implied that the most Mg-rich magmas of the crystalline basalt high-Ti suite were not a product of near surface fractionation. Therefore, 10-20% fractionation may have occurred in route to the lunar surface. If even the most Mg-rich members of the crystalline basalt suite are products of 10-20% fractional crystallization, estimates of melt segregation depths and trace element mantle inversion models based on the crystalline basalts may be inadequate. The empirically calculated picritic compositions and picrite

glasses indicate the lunar mantle is capable of producing high-Ti picritic magmas with a wide range of incompatible and compatible element signatures. It is important to note that the high-Ti basalts are depleted in Ni relative to the low-Ti basalts and that the calculated picritic melt compositions have lower Ni than the picritic glasses. PROBLEMS: Proposed models must take into account this behavior in Ni in addition to accounting for heterogeneity of a single basalt suite, LREE fractionation at constant Sr/Sm and substantial variation in magmaphile element abundances and ratios with near constant values for Mg/(Mg+Fe), Sc and Cr [5, 20].

POSSIBLE MODELS FOR MARE BASALT MAGMATISM

Trace element abundances and systematics (Ni, Sr, Eu, REE), high pressure experimental studies of mare basalts and isotopic systematics provide strong evidence for the mare basalt source experiencing a prior differentiation history. This cast doubts on the validity of a chondritic, primitive source for mare basalts thus far sampled. The remaining three models (assimilation, cumulate melting, and hybridization) fit within the context of a differentiated, cumulate model [4]. PROBLEM: If a primitive lunar mantle does form the base of such a cumulate pile, what does its lack of involvement in lunar magmatism suggest about the physical and thermal conditions of the processed-primitive mantle interface?

Assimilation and cumulate melting models which function on the concept of a simple "layer cake" cumulate pile are also inappropriate for basalt generation. Such models imply dramatically different multiple saturation depths for compositionally distinct magmas and do not account for thermal problems of AFC [15], low-Ti magmas with KREEP signatures [15] and the low Ni content of high-Ti magmas [5]. To transport and mix the LMO cumulate pile to account for these experimental and chemical observations, Ringwood and Kesson [6] defined a transport mechanism involving the sinking of high-Ti cumulate diapirs into early cumulates, whereas Hess [28] and Spera [29] predicted large scale, catastrophic overturning and mixing of the cumulate pile. Can we differentiate between end-member mixed mantle that these processes may create: melting of hybrid mantle vs melting of a heterogeneous, yet unhybridized mantle? Using hybrid cumulate models of Hughes et al. [7] for high-Ti basalts and an early cumulate Ni concentration of 800 ppm [30], we calculated that small degrees of partial melting (less than 5%) will produce picritic, high-Ti basalts with Ni concentrations in excess of 100 ppm. This value exceeds the Ni content of crystalline high-Ti mare basalts, their calculated picritic parents and high-Ti picritic glasses [13]. Various metal [6] and sulfide melt [31] separation mechanisms have been suggested to explain this Ni depletion in the context of hybridization models. However, comparisons between high- and low-Ti glasses often show a slight Co enrichment in the high-Ti glasses even though Co is a strongly compatible element between metal or sulfide and silicate melt. In addition, it is debatable whether the picritic magmas are saturated with either metal or sulfide phases. It, therefore, appears that melting of various compositionally distinct cumulate packages in zones of melting at depths greater than 300 km produced a wide compositional spectrum of picritic magmas. Large scale hybridization appears to be less appropriate for generating these picritic basalts. However, evolved trace element signatures in some picritic glasses suggest hybridization does occur to a much more limited degree.

SUMMARY

Our preliminary model for the generation of mare basalts is as follows (a) Fractionated cumulate pile, (b) Extensive gravitational overturning of cumulate pile with transport of various cumulate lithologies to depths greater than 300 km, (c) Minor hybridization of mantle cumulates, (d) Local partial melting (3-20%) of compositionally distinct cumulate packages to produce a broad spectrum of chemically distinct picritic magmas. This localized melting of cumulate packages will result in the eruption at each sample site of distinct compositional suites with similar trace element signatures [15]. Melting of volatile-rich cumulate packages may result in rapid ascent of picritic magmas to the lunar surface, whereas melting of volatile depleted (or larger degrees of partial melting (3% vs 20%)) will result in slower transport of the picritic magmas to the lunar surface resulting in 10-30% fractional crystallization and (e) Mare basalts subjected to further near surface fractional crystallization, AFC processes and immiscibility.

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