

A VIEW OF KREEP-RICH LUNAR BASALTIC MAGMATISM THROUGH THE EYES OF NWA 773.

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Introduction: The record of basaltic magmatism on the Moon indicates that lunar mantle melting and basalt transport to the lunar crust occurred over a period of at least 3.4 billion years from 4.46 Ga [1,2] to 1.0 Ga [3,4]. The production of KREEP-rich basalts appears to extend over a significant portion of this period from the emplacement of the Mg-suite (starting at 4.46 Ga) to basaltic magmas represented by olivine cumulate clasts in NWA773 at 2.865 Ga [5]. This KREEP geochemical signature probably represents the last dregs of residual liquid remaining from the crystallization of the lunar magma ocean (LMO). Isotopic ratios and ratios of incompatible trace elements of KREEP-rich rocks virtually all conform to a single uniform pattern, suggesting that the KREEP component was derived from a single source. This component appears to dominate the near-side terrain of the Moon. Here and in a companion abstract [5], we use geochemical and isotopic characteristics of the olivine cumulate clast in NWA773 to explore the: (1) the petrologic relationships among products of KREEP-rich basaltic magmatism and (2) the mechanisms by which the KREEP signature was incorporated into these basaltic magmas. Based on trace element characteristics of olivine in NWA773 and isotopic systematics of this lithology from a concurrent study [5,6], we conclude that the most likely model for the production of the wide range of compositionally distinct KREEPy basalts is melting of distinct LMO cumulate horizons that contain small abundances of a KREEP component.

Analytical Approach: Lunar meteorite NWA773 has been studied extensively using a wide range of observational and analytical approaches [7, 8]. In this study, trace elements in olivine ($F_{0.70-62}$) in the cumulate clast in NWA773 were analyzed because it represents the earliest phase to crystallize from the basaltic magma parental to the cumulate. Therefore, it potentially records the earliest processes affecting the evolution of this basalt. The olivine was first analyzed by electron microprobe for major elements. A suite of trace elements were analyzed using a Cameca 4f ims ion microprobe (Sc, V, Cr, Ti, Mn, Co, Ni, and Y) using previously documented analytical approaches [9]. The logic behind analyzing Y in olivine ($D \sim 0.01$) rather than Sm ($D \leq 0.01$) is that its higher abundance in olivine results in higher precision.

Relationship among KREEP-rich magmas: Although most lunar researchers will agree that the KREEP basalts are products of lunar magmatism, there are numerous lithologies that contain this

KREEP component. These include the Mg-suite cumulates, some lithologies of the high-Al basalts, some A14 mare pyroclastic glasses, and the olivine cumulate clasts in lunar meteorite NWA773. The most distinguishing feature of the products of KREEP-rich basaltic magmatism is that they all have KREEP-dominated trace element and isotopic signatures. These signatures include elevated REEs, enriched LREE, and distinct Ti/Sm, Ti/Sc, and Ti/Y. These enrichments and fractionations of incompatible elements are also reflected in the isotopic systematics. These are discussed in the companion abstract by Borg et al. [5] and [6].

Although many of the insights for the petrogenesis of these basalts are based on their incompatible element abundances and isotopic systematics, these systematics primarily reflect the role of the KREEP component. Compatible element abundances and phase relationships place somewhat different constraints on the petrogenesis of these samples. For example, the A14 pyroclastic glasses and NWA773 appear to be products of mare-style magmatism with variable TiO_2 and with plagioclase as a liquidus phase only after substantial crystallization. On the other hand, the Mg-suite represents basaltic magmas that had plagioclase as a liquidus phase fairly early in the crystallization sequence. Another interesting comparison among these KREEP-rich magmas is the highly variable Ni-Co contents of their olivines (Fig. 1), which imply that their sources also have a wide range of Ni and Ni/Co. The Ni-Co values in the olivine in NWA773 are consistent with it being more closely related to mare magmatism than Mg-suite magmatism.

KREEP incorporation into lunar basalts: The above observations indicate that the KREEP-rich basalts represent either the assimilation of KREEP by ascending basaltic magmas produced in the deeper lunar mantle, or the melting of KREEP hybridized LMO sources in the deep lunar mantle. Both of these models account for the compositional diversity of KREEP-rich samples. In the first model, a variety of LMO cumulates are melted and the resulting basalts assimilate various amounts of KREEP. In the second model, numerous LMO cumulate lithologies contain a KREEP component due to cumulate mixing resulting from gravitational destabilization of LMO cumulate pile. Key geochemical fingerprints in unraveling the addition of the KREEP component to basaltic magmas are the overall abundance of incompatible elements and Ti/Sm - Ti/Y ratios. The Ti/Sm and Ti/Y are sub-chondritic ($(Ti/Sm)_C \approx 1700$; $(Ti/Y)_C \approx 300$) in KREEP

$((\text{Ti}/\text{Sm})_{\text{KREEP}} \approx 200\text{-}250; (\text{Ti}/\text{Y})_{\text{KREEP}} \approx 35\text{-}45)$. Ti/Sm and Ti/Y for KREEP basaltic lithologies are substantially lower than mare basalts suggesting prior removal of ilmenite was important in their petrogenesis. Yet, these rocks all crystallized from basalts that were far removed from ilmenite saturation. [10] and [11] suggested that the low Ti/Sm (and Ti/Y) for KREEP is a characteristic of their mantle source and denotes extensive differentiation, presumably the late-stages of LMO evolution that followed ilmenite crystallization. These ratios do not reflect simply a high abundance of intercumulus melt in the LMO cumulate pile.

The overall abundance of Y and presumably other incompatible elements is higher in the olivine from NWA 773 (0.7 – 3.3 ppm) than in very low-Ti and low-Ti mare basalts (<0.25 ppm). A similar Y enrichment in olivine is observed in Mg-suite lithologies [9]. This enrichment in Y implies that the olivine in NWA773 initially crystallized from an incompatible element-rich basaltic magma (relative to mare basalts). This simple enrichment in Y is not necessarily a result of KREEP. Alternatively, this enrichment could reflect the reequilibration between the early olivine and late-stage intercumulus melt.

The Ti/Y in the olivine in NWA773 increases with decreasing Ni (Fig. 2), overlapping with values found in the Mg-suite (10-500), and is substantially lower than measured in mare basalts (>1100). These observations indicate that the KREEP signature (low Ti/Y) was a characteristic of the basaltic magma prior to olivine (Fo_{70}) appearing on the liquidus. It also indicates that the KREEP signature inherent in the olivine was not a product of olivine-intercumulus melt interaction. If this was the case the Ti/Y value would decrease with decreasing Ni.

Based on the observations that there are compositionally diverse basaltic magmas with a KREEP signature, the KREEP component was added to the basaltic magma prior to the crystallization of the most magnesian olivine in the cumulate, and that 20% KREEP must be assimilated by the parental magma to the olivine cumulate to account for the substantial KREEP signature [5,6] it would appear most likely that the KREEP component was introduced into the basaltic magma during melting. Having the KREEP component in the source regions of the basalts provides less thermal constraints than assimilation and provides a heat source for melting in the deep lunar mantle. This is consistent with the spatial relationship between mare magmatism and KREEP enrichment on the near-side of the Moon. In this scenario, the termination of both mare and KREEP-rich magmatism may result from the exhaustion of KREEP-rich horizons. This would imply that if KREEP is the driving thermal mechanism

behind the production of Mg-suite and other KREEP-rich magmatism, this style of magmatism would only occur on the near-side of the Moon associated with the PKT and that during the duration of KREEPy magmatism (4.46 to 2.8 Ga) the degrees of partial melting and the proportions of a KREEP component should decrease with time.

References: [1] Shih et al. (1993) *GCA*, 57, 915-931. [2] Nyquist and Shih (1992) *GCA* 56, 2213-2234. [3] Schultz and Spudis (1979) *Proc. 10th LPSC*, 2899-2918. [4] Hiesinger (2002) *GRL* 29, 10.29/2002GL014847. [5] Borg et al. (2005) *LPSC XXXVI*, in press. [6] Borg et al. (2004) *Nature* [7] Jolliff et al., (2003) *GCA* 67, 4857-4879. [8] Fagan et al. (2003) *MAPS* 38, 529-554. [9] Shearer and Papike (2005) *GCA*, in press. [10] McKay et al. (1978) *Proc. 9th Lunar Planet. Sci. Conf.*, 661-687. [11] Longhi and Boudreau (1979) *Proc. 10th Lunar Planet. Sci. Conf.*, 2085-2105.

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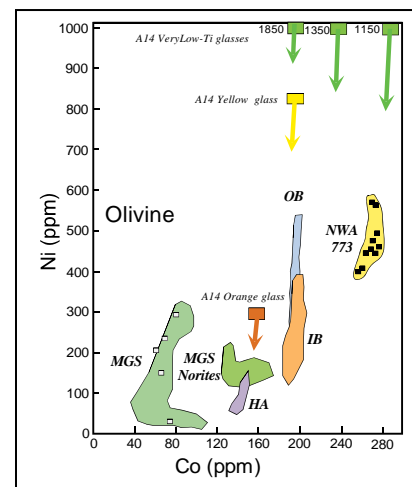


Figure 1. Ni and Co measured in olivine for a wide-range of KREEPy basalts (NWA 773, Mg-suite, high-Al basalts) and mare basalts (A12 olivine basalts OB, A15 Ilmenite basalts IB). Ni and Co calculated for olivine that would be in equilibrium with pyroclastic glasses with a KREEPy signature.

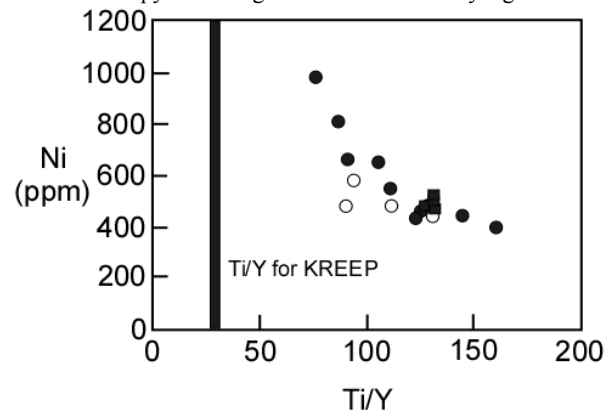


Figure 2. Ti/Y versus Ni in three different olivine crystals. Ti/Y for CHUR = 300.