

## ORIGIN OF LUNAR MARE HIGH-TITANIUM BASALTS. MELTING OF A DEEP HYBRIDIZED SOURCE OR SHALLOW ASSIMILATION OF HIGH-TI CUMULATES?

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**Introduction:** The high-titanium lunar basalts exhibit a wide range of  $\text{TiO}_2$  ( $\approx 8$  to 17 wt. percent) that make them fairly unusual compared with terrestrial basalts. Although the origin of high-Ti mare basalts has long been a point of debate, shallow assimilation and source hybridization models have been favored by many lunar petrologists. These two models for the generation of high-Ti basalts are mechanically different, yet their final products are surprisingly similar. Both assimilation and hybridization models require that the high-Ti basalts are produced from early- and late-stage magma ocean (MO) cumulates. Assimilation models require modal [1,2] to mineralogically selective [3,4] absorption of late-stage, ilmenite-bearing MO cumulates by low-Ti magmas produced by melting in the deep lunar mantle ( $>400$  km). Source hybridization models require that late-stage, ilmenite-bearing cumulates were transported to the deep lunar mantle where they mixed with earlier, MO cumulates [5,6,7,8,9]. Subsequent melting of these mixed cumulate sources, perhaps initiated by the incompatible element enriched late-stage cumulates [8,10], produced the high-Ti mare basalts. In this study, we conclude that modal assimilation of a late-stage MO cumulate by a primitive, low-Ti magma is not consistent with data for the high-Ti basalts. Although a selective assimilation mechanism [3,4] is compatible with major element composition and can be rationalized with regards to experimental studies and thermal requirements for assimilation, it does not fit trace element or isotopic constraints.

**Major and Trace Element Composition:** The high-Ti basalts exhibit a wide range in major element and trace element composition that is attributed to both mantle source composition and shallow fractional crystallization [8,9,11,12]. Many of the crystalline mare basalts represent fractionation products of primary melts, whereas the high-Ti picritic glasses are closer approximations of primary basalts. Therefore, major and trace element compositions of the picritic glasses and experimental studies of these compositions provide the best insight into evaluating pre-eruptive processes. Modal assimilation of ilmenite-bearing cumulate by very low-Ti picritic basalt is not consistent with major element mass balance calculations [3,12]. However, selective assimilation of ilmenite and clinopyroxene in a  $\approx 3:1$  ratio appears to be consistent with major element mass balance calculations

[3]. Experimental studies demonstrate that ilmenite dissolves incongruently in a very low-Ti basalt to Cr-spinel and a high-Ti melt [3]. Mass balance of trace element is less successfully explained by selective assimilation. None of the assimilation models are compatible with Nb, Zr, and Ce characteristics of the picritic glasses. Comparisons of MO trajectories and glass compositions, illustrate that the high-Ti picritic magmas do not fall on a mixing line equivalent to assimilation of late-stage MO cumulates by very low-Ti magmas (FIGURE 1). Selective assimilation of ilmenite makes the model even worse. Cumulate ilmenite should have higher Nb/Ce and Nb/Zr than calculated MO cumulates. On the other hand, mixing of late- and early-stage cumulates should produce a source which upon melting (and consuming ilmenite) should produce Nb/Ce and Nb/Zr similar to the high-Ti mare basalts (FIGURE 1).

**Experimental Studies:** Several types of experimental studies are relevant to the origin of the high-Ti basalts. First, the high- and very-low Ti glasses are co-saturated with olivine and orthopyroxene at depths of between 300 and 500 km, with no relationship between  $\text{TiO}_2$  and pressure of multiple saturation [13,14]. There is a correlation between  $\text{TiO}_2$  and temperature of liquidus of cosaturation. The depth of cosaturation has been interpreted as a minimum [6,9,10,13,14] or average [9] depth of melting for hybridization models. Although the temperature –  $\text{TiO}_2$  correlation may imply a negative depth versus temperature profile in the lunar mantle assuming a hybridization model, it may also be interpreted as indicating melting is localized and partially driven by the decay of radioactive elements associated with late-stage MO components. For assimilation models, the depth of cosaturation is either meaningless or could be interpreted as a minimum depth of origin for pre-assimilation parent magmas. Experiments also indicate that the high-Ti glasses are not saturated with ilmenite [3,13,14]. This can be interpreted as indicating that ilmenite either was consumed during melting or selectively assimilated by ilmenite undersaturated magmas. As predicted by Delano [15] and confirmed by Agee and Circone [16], the high-Ti melts become denser than their olivine-orthopyroxene source at moderate mantle depths (200-300 km). Contrasts in densities between high-Ti basalt and its source at moderate depths indicates that if the high-Ti magmas

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were produced by melting of a hybridized source, they would have difficulty separating from their source and may in fact sink into the deep lunar mantle [15,16]. Entrainment of high-Ti basalts in ascending diapirs would overcome this serious problem [17]. High-Ti basalts produced by assimilation would not have a similar problem because they are produced at lower pressure regimes. Early critics rejected assimilation models for the origin of the high-Ti basalts based on the tentative assumptions of the assimilation reaction stoichiometry and thermal energy constrains [5]. More recent studies [2,3,4] of the kinetics of ilmenite dissolution in very low-Ti melts illustrate a assimilation mechanism that is chemically and thermally plausible.

**Isotopic Systematics:** A wide range of isotopic systematics clearly show a difference between the cumulate sources for the very low-Ti basalts and the high-Ti basalts. This is particularly true for isotopic systematics that are dependent upon the crystal chemical behavior of ilmenite (Lu-Hf, W-Hf). For example, large fractionations of Lu/Hf relative to Sm/Nd (i.e. low-Ti basalts) are attributed to a source region dominated by olivine and orthopyroxene, whereas subequal fractionation of Lu/Hf relative to Sm/Nd (i.e. high-Ti basalts) is attributed to ilmenite-bearing source region [18]. Beard et al. [18] demonstrated that the Lu/Hf and Sm/Nd ratios for the high-Ti basalt sources can be produced by the assimilation of 10 to 30% assimilant with a ilmenite to clinopyroxene ratio of 3:1. However, they suggested that this type of assimilation would also produce magmas with intermediate  $TiO_2$ , large variations in  $\epsilon_{Hf}$  and moderate variations in  $\epsilon_{Nd}$ . They discounted assimilation as an important mechanism because of the lack of correlation between  $\epsilon_{Hf}$  and  $\epsilon_{Nd}$ .

**Conclusions:** Experimental results relevant to the generation of high-Ti basalts while predicting conditions of assimilation or hybridization-melting also illustrate the plausibility of either model. Isotopic and trace element characteristics of the high-Ti basalts, however, are more consistent with these magmas being generated by small to moderate degrees of melting of an initially deep, hybridized mantle source. Serious problems with a deep, hybridized source for the high-Ti magmas are primarily related to the separation from their source and their migration to the lunar surface.

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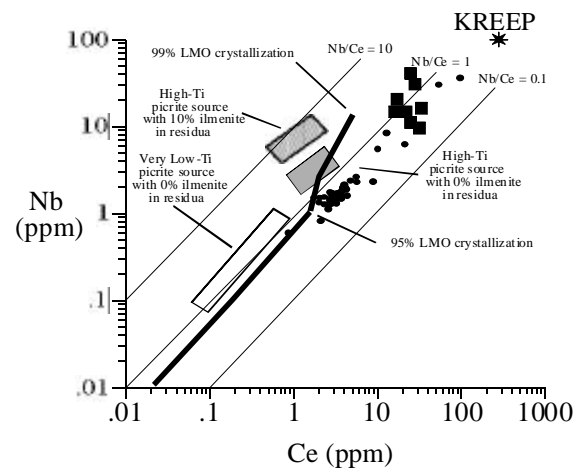


FIGURE 1. Plot of Nb versus Ce for the picritic glasses. The high-Ti glasses are represented by solid square symbols. Superimposed on the plot are (1) the fields of calculated mantle sources for the picritic glasses assuming 10% partial melting and a residual assemblage of olivine + orthopyroxene  $\pm$  ilmenite, (2) MO cumulate crystallization trajectory taken or calculated from Snyder et al. [19], (3) contours of constant Nb/Ce, and (4) KREEP. Ilmenite and ilmenite-clinopyroxene (3:1) assemblages plot at Nb values higher than Nb/Ce = 10.