COMPOSITION OF THE LUNAR MARIA; G. Jeffrey Taylor[1], P. G. Lucey[1], B. Ray Hawke[1], and P. D. Spudis[2]. [1]Hawai'i Inst.of Geophys. and Planetology, University of Hawai'i, 2525 Correa Rd., Honolulu, HI 96822. [2] Lunar and Planetary Institute, Houston, TX 77058.

We have developed analytical techniques to accurately determine the FeO [1] and TiO_2 contents [2] from reflectance spectra, and applied these to a global data set (35-km spatial resolution) obtained by the Clementine mission. The data show that lunar mare basalts vary continuously in composition from very low-Ti to high-Ti basalts. Basalts with TiO_2 contents in the range 2-4 wt.% are most abundant, though basalts with lower TiO_2 are significant. Abundance decreases with increasing TiO_2: only 5% of the mare surfaces contain >7.5 wt.% TiO_2. This is consistent with the relative abundances of very-low to high-Ti cumulates produced in a magma ocean. Some maria have notably lower FeO (by at least 5 wt.%) than typical; these include Nectaris, Frigoris, and Orientale. These maria may be composed of basalts richer in Al_2O_3 than aluminous mare basalts in the sample collection.

TiO_2 contents of the lunar maria. TiO_2 contents of the maria vary continuously from 0.5 to 13 wt.% (Figs. 1,2), in contrast to our biased sampling of the Moon, which suggests a significant gap between low- and high-Ti basalts. The most abundant mare basalts contain 2-4 wt.% TiO_2, similar to those from Apollo 12 and 15. Very-low Ti basalts are less common, but significant. The abundance of mare basalts decreases as TiO_2 increases from the peak at 2-4 wt.%. Only 10 % of mare surfaces contain > 6 wt.% TiO_2, and only 5% of the mare surfaces contain > 7.5 wt.%. Of course, high-Ti basalts would be diluted by vertical mixing of highlands material from beneath the maria or lateral mixing from nearby highlands. Comparison of average basalts collected at Apollo sites with associated regolith samples suggests that TiO_2 values could be 20% lower in regolith than rocks. If so, the percentage of mare surfaces with high-Ti basalts (>7.5 wt.% TiO_2) rises to 10%, but the relative abundances are unchanged. One might argue that the intermediate Ti-contents (4 to 7 wt.%) are caused by mixing of high-Ti and low-Ti mare basalts that overlie one another. This is certainly possible, and we intend to test this with high-resolution Clementine data by mapping, for example, the TiO_2 contents of flows with intermediate TiO_2, and testing whether variations are observed that could be ascribed to vertical mixing. Another test is to look in detail at the borders between high-and low-Ti flows, such as that between Mare Tranquillitatis and Mare Serenitatis, and to determine the relative abundances of high- to low-Ti basalts. The distribution of basalt Ti contents may also reflect a combination of the Ti content of the lunar mantle, the ease of melting of mantle sources at various Ti contents, and the efficacy of magma transport in the mantle and through the crust. These factors require detailed examination, but we suggest that to first order the low abundance of high-Ti mare basalts reflects the low abundance of Ti-rich, ilmenite-bearing mantle sources.

Implications for formation and evolution of the lunar mantle. The distribution of the TiO_2 contents of mare basalts depicted in Fig. 2 is consistent with models of the formation of their source regions as cumulates from the lunar magma ocean [e.g., 3,4], coupled with dynamic mixing of sinking, dense, Ti-rich late-stage cumulates and rising Mg-rich early cumulates or undifferentiated rock [*5-10*]. The mare basalts with < 4 wt.% TiO_2 formed by partial melting of olivine and orthopyroxene cumulates with low abundances of TiO_2. Such cumulates would have been the most abundant product by far of the lunar magma ocean, accounting for at least 70 vol.% of the cumulate pile [e.g., 3,11]. Thus, the fact that about 70% of mare basalts contain < 4 wt.% TiO_2 is consistent with their origin as partial melts from cumulates formed in the lunar magma ocean. Formation of mare basalts with > 4 wt.% probably involved dynamic mixing of these early cumulates with late-stage cumulates rich in clinopyroxene and ilmenite. The abundance of ilmenite-bearing cumulates would be only 5-10 vol% of the cumulate pile (ilmenite would not have reached saturation in the magma ocean until > 90% of the magma ocean had solidified), thus accounting for the rarity of high-Ti mare basalts. The extent to which a hybrid source contained the ilmenite-rich cumulates was a major factor in determining the final TiO_2 content of the mare basalt magma produced. This model predicts that basalts with intermediate TiO_2 contents ought to be more abundant than those with high-Ti, in accord with our observations (Fig. 2). It is likely that even the low-Ti basalts (2-4 wt.% TiO_2) formed from hybrid sources, though with less ilmenite; otherwise, it is difficult to explain their Mg/Fe ratios and europium anomalies [9].

Low-FeO mare basalts. The Clementine data show a startling abundance of mare basalts low in FeO compared to others. Although some of the low FeO points in Fig. 1 are caused by mixing near the borders of maria, many are from three maria: Nectaris, Frigoris, and Orientale. Detailed study awaits higher resolution data, but we can estimate from the present data set that these maria have FeO contents of 10-15 wt.%, at least 5 wt.% below those of most maria. Even aluminous mare basalts, such as those from Apollo 14 and Luna 16, have FeO contents > 16 wt.%. The uniqueness of Mare Oriental was reported previously by [12,13]. TiO_2 content varies among the maria: Frigoris has about 1 wt.%, Nectaris has 1.5-2.5 wt.%, and Orientale has 2-3.5 wt.%. If the basalts in these maria follow the linear trend of FeO and Al_2O_3 as other mare basalts (Fig. 8.3a in *Lunar Sourcebook*), then they contain 14-18 wt.% Al_2O_3, not very different from terrestrial basalts. Alternatively, they might simply have higher Mg/Fe than other basalts, implying a very magnesian mantle source or high percentages of partial melting. Present data cannot distinguish these possibilities. These maria are relatively thin, however, so it is possible that their surfaces reflect a mixture of highlands and mare basalts with normal FeO contents; this will be tested with high-resolution data.

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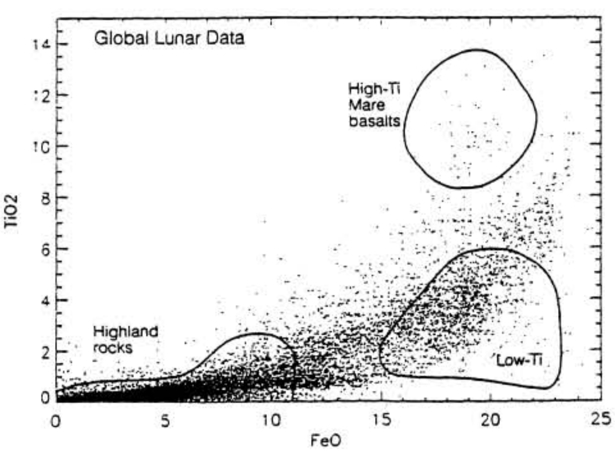

Fig. 1. Global data set with fields for highland rocks, low-Ti, and high-Ti basalts.

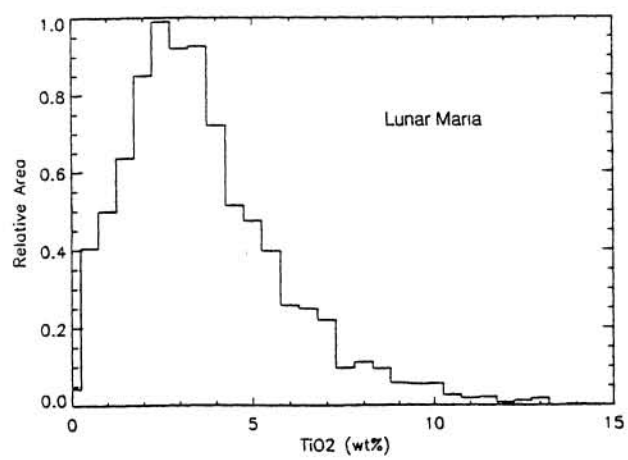

Fig. 2. Histogram of TiO_2 contents in the lunar maria. Note the continuous decrease from low- to high-Ti compositions, in contrast to the bimodal distribution shown by the sample collection.