MARE BASALT FRAGMENTS IN LUNAR HIGHLANDS METEORITES: CONNECTING MEASURED TI ABUNDANCES WITH ORBITAL REMOTE SENSING.

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Lunar highland meteorites contain small proportions of mare basalt fragments, which are important for defining lunar basalts in areas not visited by Apollo/Luna. We analyzed seven mare basalt fragments from three highland meteorites, and retrieved the Ti contents of their parent magmas from core pyroxene compositions. The analyzed clasts span the range of VLT and low-Ti, basalts in Apollo & Luna samples. A histogram of inferred TiO_2 contents of their parent magmas is much like that inferred from global remote sensing, and not like that of the Apollo mare basalts.

Introduction: Many lunar meteorites are from areas that were not sampled by the Apollo or Luna missions, and so provide information on lunar rock types outside the explored areas. In particular, lunar highlands meteorites provide samples from regions (like the far side) that are not obviously represented in the Apollo samples [1]. Many highlands meteorites contain fragments of mare basalts, which have not been well characterized. Our study focuses on basalt clasts in the highlands meteorites ALH81005, MAC88105, and QUE 93069. A few mare clasts from these meteorites have been described or mentioned previously [2].

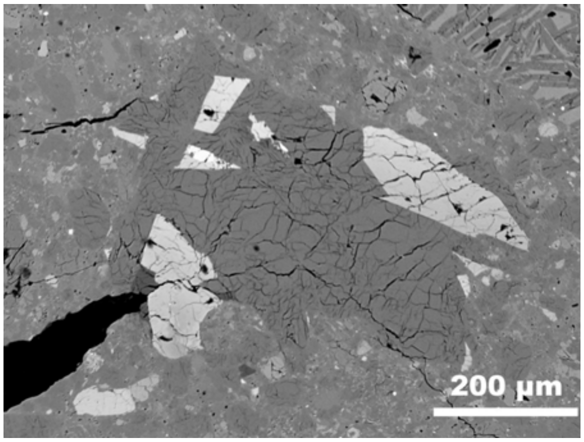

Figure 1. BSE image of LB2, ALH81005 (Clast G of [2]). Darker is plagioclase; lighter is pyroxene, note zoning.

Samples and Methods*:* We investigated these thin sections of lunar highlands meteorites: ALH81005,9; MAC88105,164; and QUE93069,36. Sections were analyzed with optical microscopy, backscattered electron imagery, and quantitative EMPA.

Basalt fragments were identified and as crystalline clasts with ophitic or subophitic textures, near equal proportions of feldspar and pyroxene, and chemically zoned pyroxenes that were more ferroan than Fe*=0.2 (Fig. 2). Partially melted or impact melt clasts were excluded. Chemical analyses were obtained at Johnson Space Center-ARES on their Cameca SX-100 electron microprobe with: accelerating potential of 15kV, beam current of 20 nA, Na and K analyzed first to reduce losses through volatility, and count times of 60 seconds for Ti and Cr, and 20-30 seconds for other elements. Standards were well-characterized natural and synthetic oxide compounds. Raw data were reduced using Cameca PAP software, and further processed with Microsoft Excel.

Results: We found basaltic fragments in the three lunar highlands meteorites we investigated. Chemical analyses of pyroxenes in the fragments showed that two of the meteorites contain two or more types of basalt. We found several previously unclassified basalt fragments that fall between the categories defined by Apollo samples.

To classify the basalts we use a (Fe*) [i.e., Fe/(Fe+Mg)] vs. Ti/(Cr+Ti) plot (Fig. 2) after Nielsen and Drake (1978) [3]. This plot shows how less compatible Fe and Ti increase in the melt as more compatible Mg and Cr are incorporated into crystallizing pyroxene. The initial composition of the parent magma determines the evolving pyroxene crystallization trend, and when coupled with the distribution coefficient for Ti, the Ti content of the pyroxene [3, 4].

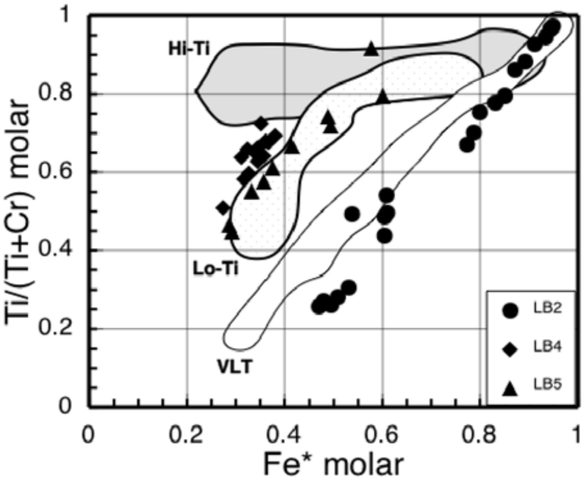

Figure 2. Molar Fe* (Fe/(Fe+Mg)) versus molar Ti/(Ti+Cr) for pyroxenes in three basalt fragments in ALH81005. At least two distinct Ti trends are clear, indicating that there are at least two types of basalt in ALH81005,9. Apollo data is from [5-7].

ALH 81005. Treiman and Drake (1983) described a VLT clast (their ‘G’) in this thin section [2]. We confirm that this clast (here named LB2) is of VLT basalt. We also analyzed two previously unrecognized basalt fragments, LB4 and LB5, with pyroxenes significantly richer in Ti than those of LB2. These clasts' pyroxenes are shown in Figure 2, compared to the trends of composition trends for Apollo mare basalts. LB4 and LB5 plot between the high- and low-Ti basalt fields.

MAC88105. We found three basalt fragments in MAC88105 (Fig. 3). One appears to fall in the high Ti field, while the other two plot between the high and low Ti fields. Other basalt fragments with possible high-Ti and VLT composition in MAC88105 are described [8, 9, 10]. MAC88105 could thus contain the entire range of mare basalt compositions (Fig. 3).

Other meteorites. Pyroxene compositions in the single analyzed basalt fragment in QUE93069 plot between the low and very low Ti basalt fields.

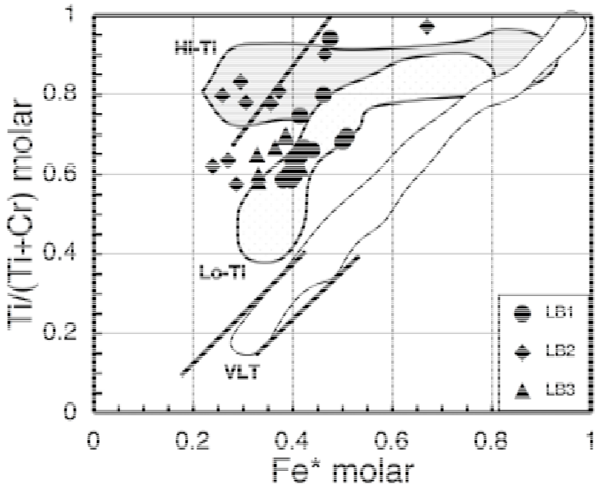

Figure 3. Molar Fe* (Fe/(Fe+Mg)) versus molar Ti/(Ti+Cr) plot of pyroxenes in different basalt fragments in MAC88105. Points are our analyses, while the three fields represent trends from Apollo mare basalts. The lines represent analyses from the literature corresponding to two possible VLTs [9, 10] and a possible high-Ti basalt [8] in MAC88105.

Parent Magma Compositions: Using the pyroxene compositions from these mare basalts, one can calculate the TiO_2 contents of their parental magmas using distribution coefficients. We estimated a distribution coefficient for TiO_2, $D^{TiO_2}_{(px/basalt)} \approx 0.25$, based on compositions of Apollo mare basalts and their first-crystallized pyroxenes [5], and on experimental data [12, 13]. Literature D values range from 0.15-0.35, with the variation ascribed to Ca contents of the pyroxenes and cooling rates [14, 15]. Figure 4 shows the calculated TiO_2 contents for the clasts' parental magmas for a constant pyroxene Fe*≈0.35.

Conclusion: The range of magma Ti contents inferred from our basalt fragments does not resemble the bimodal distribution of Ti abundances in the Apollo mare basalts. Instead, the distribution of inferred magma composition resembles the unimodal continuum of Ti abundances inferred from orbital remote-sensing data (Fig. 4; [16, 17]). Thus, our observations confirm the remote sensing data with sample analyses, and show again that the high-Ti basalts are over-represented in the Apollo collections.

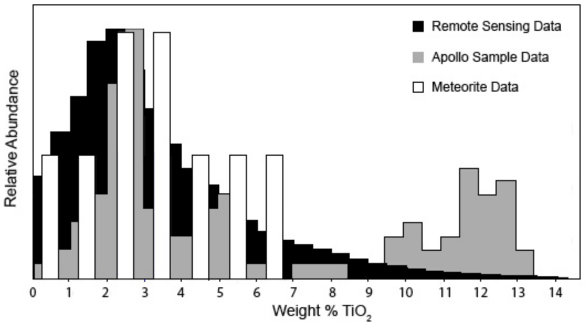

Figure 4. Histograms of TiO_2 content of lunar basalts. White bars are compositions calculated here for a pyroxene Fe* = 0.35, a glass fragment in QUE93069, and a glass bead from [18]. The distribution is unimodal. Gray data is bulk Apollo mare basalts (from [16]). Note bimodal distribution, with both low- and high-Ti basalts. Black data are inferred TiO_2 abundances, based on Clementine and Galileo reflectance spectra (from [16]). Note unimodal distribution, similar to white bars.

The identification of different types of mare basalts in individual meteorites may also help constrain their possible source craters. TiO_2 maps of the Moon are available [16,17]. If several types of basalt can be identified in a particular meteorite, a fresh crater with nearby basalt deposits of those compositions could theoretically be found. Using this method, it may be possible to locate the source craters of some lunar highlands meteorites..

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