A SHALLOW MANTLE SOURCE FOR THE CHANG'E 5 BASALTS INDICATES PROLONGED INDIRECT HEATING OF THE UPPER MANTLE BY KREEP.

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Introduction: The initial studies of the samples returned by the China National Space Agency's Chang'e 5 mission reveal that the terrain at the landing site is dominated by a basalt that dates to ~1.96 Ga [1-4]. As the youngest dated igneous rocks from the Moon, surpassing the previously youngest known basalts by ~1 billion years [e.g., 5-7], these samples offer an unprecedented opportunity to examine the thermal and magmatic evolution the Moon though time.

The Chang'e 5 basalt is geochemically evolved, with samples that are in Fe-Mg equilibrium with their coexisting olivine having an Mg# of ~34 [4], an intermediate TiO_2 content of ~5 - 7 wt.%, and a LREE-enriched REE pattern. However, their Nd and Sr isotopic compositions are depleted [4], indicating the melt is derived from a source region that does not contain more than ~1 to 1.5% KREEP [8]. These compositional observations led to the interpretation that the Chang'e 5 basalts were formed through extensive fractional crystallization of a much more primitive melt derived from a dry source region that experienced previous melting, and that KREEP was not involved in the petrogenesis of the basalt, even indirectly [1-4].

However, by 2 Ga, the Moon had cooled significantly and the quantity of melt generated, as evidence by the ages of surface flows [e.g., 9], had diminished. Magmatism at 2 Ga or younger is primarily confined to Procellarum KREEP Terrane (PKT) [9], which strongly suggests a linkage between the enrichment of heat-producing elements in KREEP and sustained lunar magmatism [e.g., 10-12]. The mantle source region(s) of the Chang'5 basalts potentially offers a key constraint on the temperature at a certain depth in the lunar mantle at ~2 Ga. Therefore, we have investigated the high-pressure and -temperature phase relations of the Chang'e 5 basalt using experimental petrology and phase equilibrium modeling to examine its petrogenetic history and, potentially, the P-T conditions of melting.

Experimental Methods: We synthesized an experimental starting composition based on Chang'5 sample 103-001,005 using reagent grade oxides and fayalite. Synthetic fayalite was used as an Fe reagent to ensure that all Fe in the mix was divalent. The mixture was homogenized under ethanol in an agate mortar and pestle, and dried at 700 °C at IW in a Deltech furnace. Piston cylinder experiments were conducted in the Florida Planets Lab at UF using graphite capsules and $BaCO_3$ pressure media in a Rockland Research Corp. end-loaded piston cylinder. Experiments have been conducted between 0.5 and 1.5 GPa, and each run utilized a super-liquidus step for 20 minutes to ensure melting and homogeneity. Ambient pressure experiments were conducted in a Deltech gas-mixing furnace using mixtures of CO-CO_2 to control the fO_2 at IW. Samples were suspended in the hotspot using Re wire loops. Run durations were ~24 hours. Run products were then mounted in epoxy and polished flat for analyses.

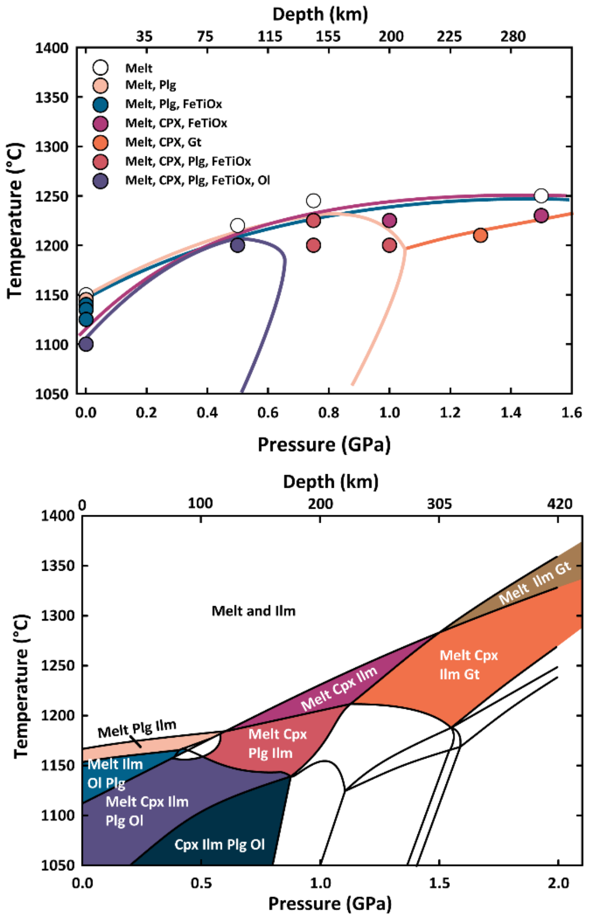

Figure 1: Pressure-temperature phase diagrams of the composition of the basaltic sample 103-001,005 returned by Chang'e 5, which is likely a liquid composition. Top: Experimentally determined phase diagram. Bottom: Phase diagram calculated with Perple_X. Ilmenite saturation is over-predicted by Perple_X. Note the different pressure scales in the figures.

Modeling: The equilibrium P-T phase diagram for Chang'e 5 basalt 103-001,005 was predicted using Gibbs free energy minimizations via Perple_X [12] for comparison to the experimental results. Calculations were performed in the KNCFMASTCr system at the IW buffer using appropriate solid solution models and a suitable thermodynamic dataset [13-15].

Phase Relations of the Chang'e 5 Basalt: The liquidus phases for the Chang'e 5 basalt (Fig. 1) at ~1 bar are plagioclase closely followed a few degrees down temperature by an FeTi oxide (both ilmenite and ülvospinel are observed in our experiments, but not together). Neither pyroxene nor olivine are observed to crystallize within ~40 °C of the 1 bar liquidus. At elevated pressure, a complex multiple saturation point (perhaps better described as a multi-phase region) that includes plagioclase, FeTi oxide, olivine, and clinopyroxene is observed at roughly 0.5 GPa, ± approximately 0.2 GPa, at temperatures close to 1200 °C. Olivine is not found in the assemblage at 1200 °C and 0.75 GPa, but plagioclase, CPX, and FeTi oxide are all found to saturate within 25 °C at that pressure. By 1 GPa, CPX and FeTi oxide overtake plagioclase as the near liquidus phases. Our experiments and the Perple_X calculations both imply the presence of another CPX + garnet ± FeTi oxide multiple saturation point at ≥1.5 GPa (Fig. 1).

A Shallow Origin for the Chang'e 5 Basalt: Based on the phase relations above, we conclude that the four-mineral multiple saturation point (or region) near 0.5 GPa (~100 km depth) and 1200 °C may roughly reflect the conditions of melting. The lack of olivine and/or pyroxene within ~40 °C of the 1 bar liquidus argues against the interpretation that this basalt underwent extensive fractional crystallization after derivation from a deeper source, as argued by [1-4]. If it had, those minerals would be expected to be at the low-pressure liquidus of the composition. Prior fractional crystallization of plagioclase at low pressure is possible, but would act to lessen the LREE enrichment in the melt, which runs contrary to the observed LREE-enriched nature of the basalt and would require a more Al-rich source than is already implied. Conversely, a shallow source is consistent with multiple observations. Firstly, the source region ^{147}Sm/^{144}Nd and ^{87}Rb/^{86}Sr are more consistent with a plagioclase-bearing source region [4] than a one without, suggesting a relatively shallow source where plagioclase is stable. Additionally, without the need to invoke extensive fractional crystallization, the inferred water content of the Chang'e 5 basalt is consist with that of other mare basalts and obviates the need for a previous source melting event that would make the enriched REE pattern more difficult to explain. Therefore, a shallow source consisting of a hybridized cumulate mantle containing CPX, olivine, plagioclase, and ilmenite is more consistent with current constraints [also see 8].

Indirect Heating from KREEP: A shallow origin for the Chang'e 5 basalts naturally eliminates a hot, deep mantle as the heat source for melting. Lunar thermal evolution models [10-12] suggest that by 2 Ga, regions of the mantle away from the heat-producing PKT are not capable of generating significant melt. Therefore, given the proximity of the Chang'e 5 site to high Th regions and the broader PKT (Fig. 2), the most likely heat source for melting is indirect heating of the nearside upper mantle from KREEP. The Fe-rich nature of the basalt also suggests a low-melting temperature source composition, which would promote melting.

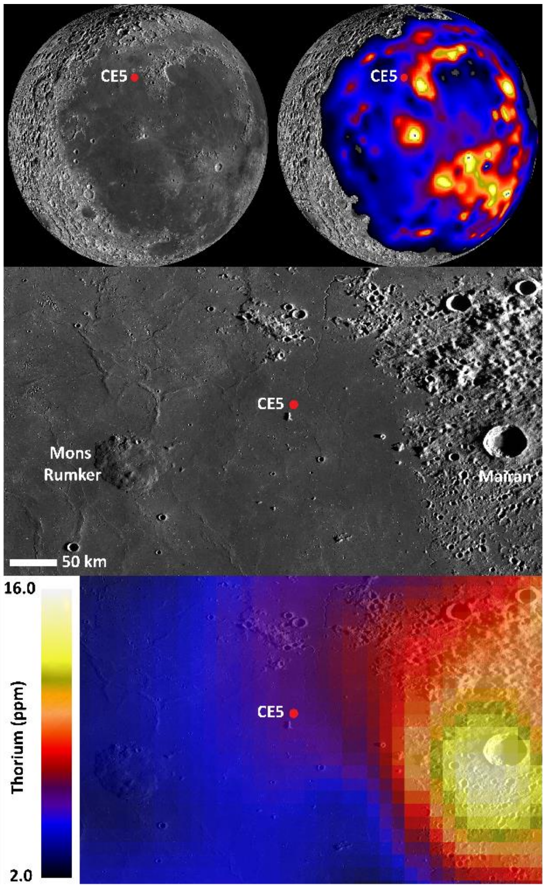

Figure 2: Maps showing the location of the Chang'e 5 landing site and the regional and local distribution of Th. Maps produced with LROC Quickmap.

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