INSIGHTS INTO THE MANTLE SOURCE OF THE CHANG'E 5 BASALTS FROM EXPERIMENTS AND MODELLING. S. M. Elardo[1], K. A. Cone[1,2], and R. M. Palin[3]. [1]The Florida Planets Lab, Department of Geological Sciences, University of Florida, Gainesville, FL 32611, USA. [2]Geology and Geological Engineering Department, Colorado School of Mines, Golden, CO 80401, USA. [3]Department of Earth Sciences, University of Oxford, Oxford, OX1 3AN, UK. selardo@ufl.edu.

Introduction: In December 2020, the China National Space Administration's Chang'e 5 mission returned ~1.73 kg of regolith from the northern Oceanus Procellarum region of the lunar nearside, marking the first return of new samples of the Moon since 1976. The first studies of these samples [1-4] reveal that the terrain at the landing site is dominated by basalts that date to ~1.96 Ga [1]. This makes the Chang'e 5 samples now the youngest dated igneous rocks from the Moon and surpass the previously youngest known basalts by ~1 billion years [e.g., 5-7]. Therefore, these samples offer an unprecedented opportunity to examine the thermal and magmatic evolution the Moon though time.

One of the myriad questions that can and will be addressed by studying the Chang'e 5 basalts is, what are the conditions of melting in their mantle source? By 2 Ga, the Moon had cooled significantly and the quantity of melt generated, as evidence by the ages of surface flows [e.g., 8], had diminished significantly. Magmatism at 2 Ga or younger is primarily confined to Procellarum KREEP Terrane (PKT) [8], which strongly suggests a linkage between the enrichment of heat-producing elements in KREEP and sustained lunar magmatism [e.g., 9-11]. Secular cooling of the Moon would presumably favor the melting of mantle lithologies with lower melting temperatures, such as Fe-Ti-rich cumulates produced late in lunar magma ocean (LMO) crystallization, but this has yet to be supported with sample data. 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, as well as insight into the composition of LMO cumulate, or hybridized cumulate, that melted to produce the basalts.

High pressure and temperature experiments on near-primary melt compositions (i.e., melts that have experienced little compositional alteration post-extraction from their source) have long been used to examine the P-T-X conditions of planetary mantles, including for the Moon [e.g., 12]. For such melts, the P-T of multiple saturation on the liquidus reveals the conditions of melting and the phases in the residual mantle (assuming there was more than one). Traditionally, the Chang'e 5 basalts would be thought to make poor candidates for such experiments, as they are Fe- and Ti-rich, which is usually interpreted as the product of fractional crystallization after source extraction. This is indeed one of the preliminary interpretations for the Chang'e 5 basalts [4]. However, at 2 Ga, melting of an evolved, Fe- and Ti-rich

source region is equally plausible given the Moon's waning heat sources and melt production [11, 12]. We have undertaken high P-T experiments on a potential liquid composition for the Chang'e 5 basalts in order to determine potential source region characteristics, conditions of melting, and petrogenetic history.

Determining a Liquid Composition: Experiments investigating the high-P-T liquidus mineralogy of a basalt with the goal of assessing the characteristics of its source region and/or the conditions of melting rely on the accurate determination of the parental melt composition to a suite of basalts. To determine the composition that best approximates a parental liquid for the Chang'e 5 basalt suite, we first calculated an appropriate olivine-melt Fe-Mg exchange K_D for each of the basalt compositions reported by Tian et al. [4] using the expression from Toplis [13]. The K_D values ranged from 0.28 – 0.35. We then compared the Fe-Mg exchange K_D calculated using the composition of each basalt fragment and the highest Mg# olivine composition reported for that sample and compared it to the K_D from Toplis [13]. Two samples, 103-001,005 and 103-011,011, produced K_D values in agreement with their calculated K_D. Next, we took the most magnesian olivine composition from any sample reported by Tian et al. [4], $Fo_{59.4}$, and calculated the Mg# of a liquid in equilibrium with that olivine. The Mg# of 29.4 for sample 103-001,005 is in excellent agreement with this olivine. Therefore, we selected the composition of 103-001,005 for our experimental and numerical modelling starting composition.

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 once dry, was stored in a desiccator. 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. Future experiments will utilize pure Fe capsules to better constrain the effects of fO_2 on the liquidus phase relations of this composition [14]. Preliminary runs have been conducted at 0.5 and 1 GPa, and each run utilized a super-liquidus step for 20 minutes to ensure melting and homogeneity. Run durations were ~24 hours. Run products were then mounted in epoxy and polished flat for microbeam analyses.
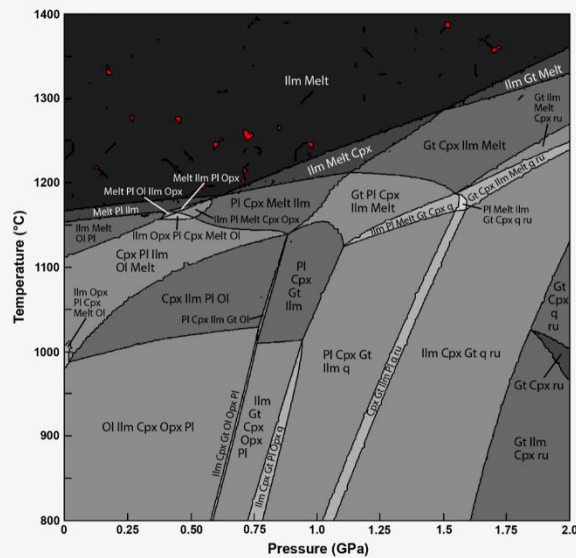
Figure 1: An equilibrium P-T phase diagram for the composition of the 103-001,005 basalt returned by Chang'e 5 calculated using Perple_X.. Ilmenite saturation is over-predicted in this model. Small red areas are calculation errors that do not affect the results.

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 [15] for comparison to the experimental results, and as part of a more expansive study of phase equilibrium software and multiple saturation point (MSP) conditions [see 16]. Calculations were performed in the KNCFMASTCr system at the IW buffer using appropriate solid solution models and a suitable thermodynamic dataset [17-19].

Preliminary Results and Interpretations: The equilibrium phase diagram for sample 103-001,005 predicted by Perple_X (Fig. 1) is in good agreement with the preliminary results of our experiments (Fig. 2), with the exception ilmenite stability. Perple_X greatly over estimates the temperature of ilmenite saturation; however, it is broadly successful at estimating silicate phase relations for planetary basalts [see 16].

Our preliminary results suggest a number of possibilities for the mantle origin of the Chang'e 5 basalts. The phase diagram predicted by Perple_X (Fig. 1) shows a region near the silicate liquidus (exclusive of ilmenite) where multiple phases, namely olivine, OPX, CPX, and plagioclase saturate over a small P-T space. The experimental results suggest ilmenite saturates near the liquidus as well (Fig. 2). This phase assemblage is in broad agreement with the mineralogy produced by late-stage LMO crystallization. The approximate depth of this region is ~80-130 km in the lunar mantle, and this could be interpreted as the depth of origin for the Chang'e basalts if an evolved, Fe- and Ti-rich source with a low melting point is favored. The retention of
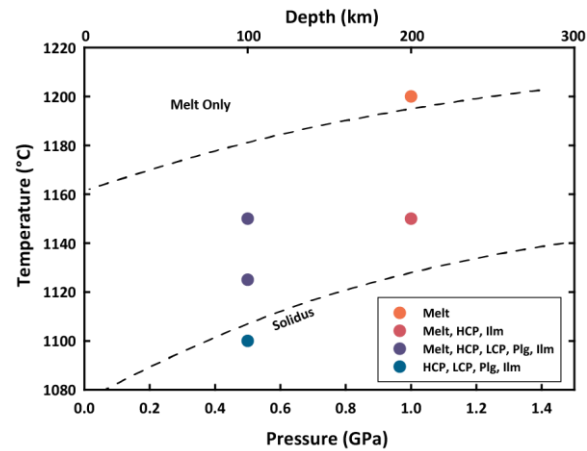

Figure 2: A preliminary equilibrium P-T phase diagram for the composition of the 103-001,005 basalt returned by Chang'e 5 determined with piston cylinder experiments. An estimated solidus and liquidus are included. HCP and LCP: High and low-Ca pyroxene. Plg: Plagioclase. Ilm: Ilmenite.

more than two minerals in the mantle source would also point toward a low degree of partial melting. Alternatively, the saturation of multiple phases near the liquidus at relatively low pressure could indicate the effects of fractional crystallization post-extraction from the source [e.g., 4]. In the latter case, a more mafic source region at deeper depths would represent the Chang'e 5 basalt source. The former model, however, would point to the effects of heat from the PKT in melting the relatively shallow mantle without mass transfer from KREEP [9-11], as the trace element and isotopic systematics of the Chang'e 5 basalts do not suggest direct involvement from KREEP in the melt [4]. Further experimentation and trace element modelling will aide in our interpretation of the mantle source for the Chang'e 5 basalts, the conditions of its melting, and the extent to which fractional crystallization has played a role.

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