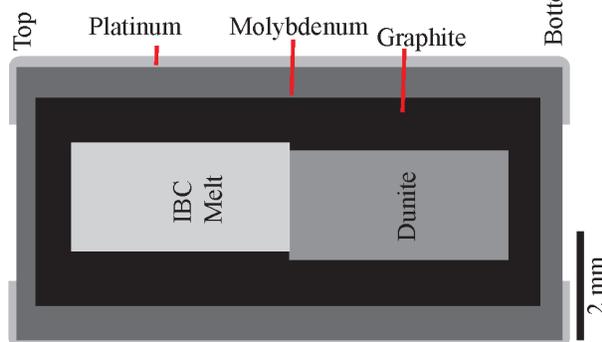


**Hybridization of the Lunar Mantle: Insights from Melt-Rock Reaction Experiments.** J. L. Scholpp and N. Dygert, Department of Earth and Planetary Sciences, University of Tennessee, Knoxville ([jscholpp@vol.utk.edu](mailto:jscholpp@vol.utk.edu))

**Introduction:** Cumulate mantle overturn is hypothesized to be a consequence of lunar magma ocean (LMO) solidification [1-5]. As dense ilmenite (ilm) bearing cumulates (IBC) sink through the lunar mantle and radiogenically heat, they will eventually pass their solidus and begin to melt. Melting the IBC would produce a Ti-rich ferrobasalt that reacts with the surrounding mantle peridotite to form hybridized lithologies, which are proposed sources for lunar basalts [e.g., 6,7]. The chemical reactions that occur during the hybridization process, the mineralogy of the reaction products and their chemistry are largely unknown. To investigate these reactions, we report results from experiments that juxtapose IBC melt against a lunar-relevant dunite. We find that the IBC dissolves the dunite to form a hybridized melt at temperatures above the IBC solidus, and precipitates clinopyroxene (cpx) and Fe-Ti oxides at the reaction interface. The IBC solidus lies between 1100 °C and 1150 °C at 2 GPa.

**Starting Materials:** The experiments were conducted in a piston cylinder apparatus at the University of Tennessee using reaction couples formed from starting materials preconditioned separately in graphite-lined Mo capsules. For the melt side of the reaction couple, a powder with the composition of an assumed IBC melt [1] (15% normative ilm and 85% normative hedenbergitic clinopyroxene (cpx)) was prepared from reagent oxides. The  $f_{O_2}$  of the powder was conditioned to IW at Brown University to approximate the lunar mantle. After grinding and conditioning, the powder was glassed at 1325°C and 1 GPa for 2 hours. The dunite side of the reaction couple was prepared using homogeneous ground terrestrial olivine (Mg# 91 [8]) annealed at 1200°C and 1 GPa for 24 hours. These presynthesis runs were cut in half latitudinally and polished to 1µm before being joined to form reaction couples wrapped in Pt foil (Fig. 1) [9].



**Figure 1.** Schematic illustration of experimental reaction couples (rotated 90° counterclockwise).

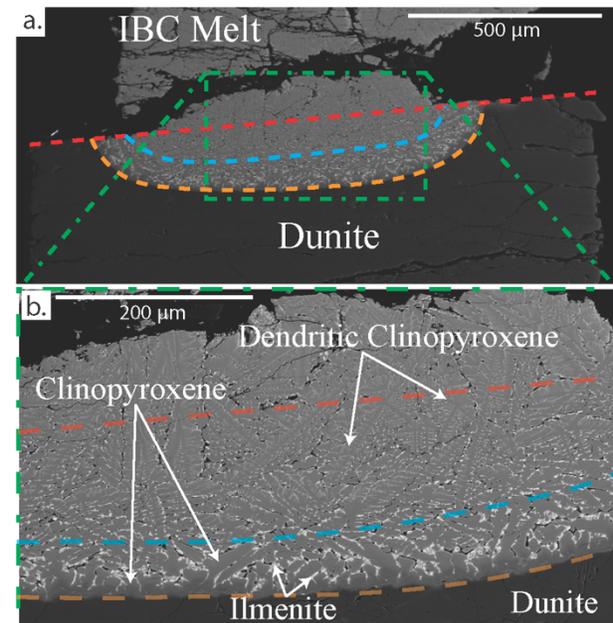
**Experimental Methods:** Experiments were run with the IBC melt half of the experiment above the dunite. Slight

offsets in the position of the sample charges on either side of the couple mark the initial interface between them. All reaction experiments were run for 6 hours. The products of reaction experiments were cut longitudinally to expose a cross-section of the experiment and microprobe polished for analysis.

**Experiments:** Experiments were conducted under conditions described in Table 1. These pressures simulate conditions in the deeper and shallow lunar mantle (i.e., ~400-100 km).

**Table 1.**

Experiment	T (°C)	P (GPa)	Duration (h)
Ex1150_2GPa	1150	2	6
Ex1100_2GPa	1100	2	6
Ex1150_5Kb	1150	0.5	6



**Figure 2.** BSE images of Ex1150\_2GPa. (a) Image of the reaction interface. Red dashed line represents the initial interface between the reaction couples. Orange dashed line represents the final reaction boundary. Blue dashed line represents the beginning of dendritic crystal growth which likely occurred during the quenching process. (b) Close up image of the reaction interface and crystals.

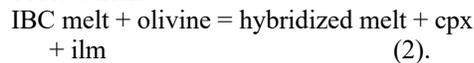
**Experiment Ex1150\_2GPa** exhibited evidence of dunite assimilation (dissolution) as the interface between the IBC melt and dunite migrated downward into the dunite side of the reaction couple (Fig. 2). The reaction boundary between the IBC melt and dunite is rimmed with cpx and ilm on the melt side of the boundary. These crystals exhibit anhedral growth textures indicating that they crystallized quickly but are large, such that they likely formed during the experiment rather than during quenching. Further into the melt side of the reaction boundary, cpx and ilm crystals with dendritic morphology

are present. The dendritic growth of the crystals indicates they likely formed rapidly during isobaric quench, nucleating on crystals at the dunite-IBC melt interface [10]. Dendritic cpx crystals formed from the edge of the anhedral growth zone to the top of the melt side of the reaction couple.

Cpx crystals closest to the melt rock reaction boundary have Mg#s of 63-52, while cpx crystals farther from the reaction boundary have Mg#s of 35-16. This indicates that assimilation of dunite at the reaction boundary enriched the IBC melt in normative olivine. Assuming that the cpx crystals were in equilibrium with the melt from which they crystallized, the equilibrium distribution coefficient for Fe-Mg in the cpx versus melt was used to determine the Mg# of the melts from which the cpx formed, where

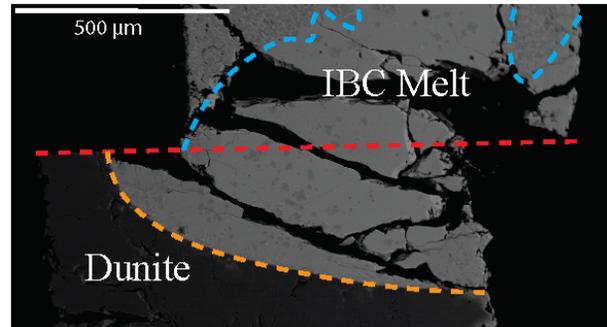
$$K_D^{Fe-Mg} = \frac{\left(\frac{FeO}{MgO}\right)_{Cpx}}{\left(\frac{FeO}{MgO}\right)_{Melt}} \approx 0.26 - 0.30 \quad (1),$$

[11-14]). These calculations indicate that the melt near the interface had an Mg# of ~31-22 while the melt farther from the interface had an Mg# of ~12-5. Since the Mg# of the initial IBC melt was ~5, these data demonstrate that the IBC melt assimilated the dunite. We envision a dissolution-precipitation reaction to describe our observations:



**Experiment Ex1100\_2GPa** crystallized completely and did not show evidence of assimilation. This indicates the IBC melt was below its solidus temperature during this run and suggests the solidus for our IBC melt falls between 1150°C and 1100°C at 2 GPa.

**Experiment Ex1150\_5Kb** (Fig. 3) exhibited similar evidence of dunite assimilation as Ex1150\_2GPa, but the dissolution interface protrudes deeper into the dunite than in Ex1150\_2GPa. Unlike Ex1150\_2GPa, the interface between the IBC melt and dunite is not rimmed with cpx and ilm on the melt side of the reaction boundary. Cpx crystals are present along the walls of the IBC side of the reaction couple, ilm is not observed. Cpx often exhibits sector and patchy zoning. Ex1150\_5Kb also contains a large region of uncrystallized melt (~40% of the melt side of the reaction couple). Cpx crystals throughout this 0.5 GPa experiment have elevated Mg#s from ~40-25 with no correlation between distance from the interface and the Mg#. The quenched melt closest to the dunite exhibits elevated Mg# (40-37) while melt farthest from the interface has lower Mg#s (30-27). We calculate that the Mg# of the melt in equilibrium with these cpxs is ~15-8. We infer that the IBC melt half of the reaction couple approached diffusive homogenization throughout the experiment, and that the cpx crystals in the IBC half of the reaction formed before and during quench.



**Figure 3.** BSE image of Ex1150\_5Kb. Red dashed line represents the original interface between the reaction couples before the experiment. Orange dashed line represents the new interface after the experiment. Blue dashed line represents the boundary between cpx cumulate growing from the wall and the melt.

**Implications:** The IBC melt is highly reactive with the lunar mantle material represented by the dunite. Reaction products are Mg enriched cpx ± ilm and a hybridized melt. The mineralogy of the reaction products may constitute part of an appropriate source for the lunar basalts [6-7], and future work will explore the similarity of the hybridized melt to lunar basalts. If the hybridized melt is negatively buoyant, it may form cpx-ilm reaction channels that extend downward. In the extreme case, these channels might extend all the way to the lunar core-mantle boundary. This melt would carry incompatible heat producing elements that were initially concentrated in the IBC to the core, as suggested by an inferred partially molten layer around the core based on seismic attenuation and tidal dissipation data [15-17].

**References:** [1] Hess and Parmentier (1995), *EPSL*, 134, 501-514. [2] Dygert et al. (2016), *GRL*, 43, 532-540. [3] Zhang et al. (2017),. [4] Dygert et al. (2019), *LPS L*, Abstract #2132. [5] Li et al. (2019), *JGR: Planets*, 124, 1357-1378. [6] Van Orman and Grove (2000), *MPS*, 35, 783-794. [7] Singletary and Grove (2008), *EPSL*, 268, 182-189. [8] Dygert et al. (2019), *G<sup>3</sup>*, 20, 1525-2027. [9] Wang et al. (2013), *CMP*, 166, 1469-1488. [10] Lofgren and Russell (1986), *GCA*, 50, 1715-1726. [11] Longhi et al. (1978), *GCA*, 42, 1545-1558. [12] Grove and Bryan (1983), *CMP*, 84, 293-309. [13] Sisson and Grove (1993), *CMP*, 113, 143-166. [14] Bedard (2010), *Chem. Geol.*, 274, 169-176. [15] Lognonne et al. (2003), *EPSL*, 211, 27-44. [16] Harada et al. (2014), *NGS*, 7, 569-572. [17] Kahn et al. (2014), *JGR: Planets*, 119, 2197-2221.