AN EXPERIMENTAL STUDY OF THE SOLIDUS OF A HYBRID LUNAR CUMULATE MANTLE: IMPLICATIONS FOR THE TEMPERATURE AT THE CORE-MANTLE BOUNDARY OF THE MOON.

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Introduction: Recent seismic studies suggest that there is a partially molten boundary layer between the cumulated lunar mantle and the fluid outer core [1-3]. This partially molten boundary layer may provide important constraints on the thermal structure of the Moon, in particular the temperature at the core-mantle boundary. One way to estimate temperature at the core-mantle boundary of the Moon is from solidus of the lunar lower mantle where ilmenite may present. According to the cumulate overturn model, a globally distributed ilmenite-rich layer (composed of ilmenite and clinopyroxene (cpx) with the proportion of 1:3~1:5, and a small amount of plagioclase [4-5]) formed near the end of solidification of a lunar magma ocean (LMO) was gravitationally unstable and sank into the lunar mantle. Convective mixing between the late and early cumulates results in a hybrid lunar mantle [4-9]. The depth at which ilmenite-bearing cumulates sunk into the lunar interior is not well constrained. According to Hess and Parmentier [6], at least part of the late cumulates might settle at the core-mantle boundary. Mixtures of ilmenite-rich late cumulate and early harzburgite cumulate mantle have often been attributed as sources for high-Ti basalts and picritic glass melts [10]. The goal of the present study is to determine the solidi of ilmenite-bearing cumulates at pressures and temperatures relevant to lunar lower mantle conditions.

Solidi of ilmenite-bearing mafic and ultramafic lithologies relevant to lunar magma genesis were reported in a number of experimental studies [11-13]. Wyatt [11] first determined the melting relations of cpx + ilmenite pair between 2 and 4.7 GPa. The solidus of cpx + ilmenite is about 1440°C at 4.2 GPa [11]. Van Orman and Grove [12] measured the solidus of late ilmenite-rich cumulate (referred to as TiCum) at pressures from 1 atm to 1.8 GPa (blue line in Fig. 1). Their TiCum starting composition was modeled after [4] at about 95% crystallization of the lunar magma ocean. Figure 1 shows that solidus of TiCum follows the extension of cpx + ilmenite solidus reported in [11]. Recently, Thacker et al. [13] investigated the stability of ilmenite in the earlier lunar cumulated dunite and harzburgite mantle (Fig. 1). Their ilmenite-bearing harzburgite starting composition is cpx-free and hence has a higher solidus than those of [11] and [12], especially at pressure higher than 1.4 GPa. In this study, we expand the work of [11-13] by examining solidus and phase relations of a hybrid lunar cumulate mantle that consists of a mixture of late ilmenite- and cpx-bearing cumulate and early harzburgite mantle.

Experiments: To investigate the solidus of the hybrid lunar mantle, phase equilibrium experiments were conducted. With reference to previous studies, we selected a starting composition that consists of a mixture of 14% ilmenite-rich late cumulate and 86% harzburgite lunar mantle. The ilmenite-rich late cumulate consists of 73% cpx + 24% ilmenite + 3% anorthite (An_{100}); the harzburgite lunar mantle is composed of 50% orthopyroxene (opx) and 50% olivine (ol), according to [4-5]. Experiments were carried out at 1270-1350°C and 1.18-2.64 GPa using a 19.1 mm piston-cylinder apparatus, and higher pressure experiments using a 12.7 mm piston-cylinder apparatus will also be conducted. The furnace assembly for the 19.1 mm apparatus consists of a molybdenum lined graphite inner capsule (~ 5mm long) and crushable MgO spacers in a graphite, Pyrex®, and salt sleeve. Oxygen fugacity is believed at C-CO, and the experiments are nominally anhydrous. Sample preparation and experimental procedures are similar as those described in [13]. All the experiments were held at target temperature for 22-26 hours. After each run, the molybdenum lined graphite capsule was sectioned along a surface parallel to the cylindrical axis of the capsule, mounted in epoxy and polished for analysis.

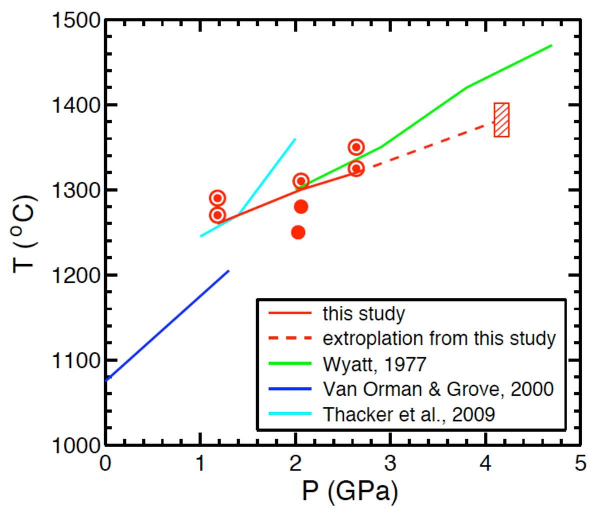

Figure. 1. Preliminary phase diagram derived from experiments using the starting composition of the mixture of ilmenite-rich cumulate and harzburgite lunar mantle. Solid dots represent experiments that only solid phases are present in the run products; dot filled

circles represent run products with both solid phases and melt or dendritic quenched melt. Solidus of a silicates (ol + opx + cpx ± plagioclase ± garnet) + Fe-Ti oxides (ilmenite or armalcolite) mixture between 1.18 and 2.64 GPa is shown as red solid line, and its extrapolation to 4.2 GPa is shown as red dashed line and hatched rectangular box (4.2 GPa, 1360-1400°C). For reference, solidi for a 71% cpx + 21% ilmenite mixture from the higher-pressure study of [11] (green solid line), a cpx + ilmenite + plagioclase mixture [12] (blue solid line), and an ilmenite + ol + opx mixture [13] (cyan solid line) are also shown.

Run products were identified using optical microscopic technique. The first appearance of dendritic quenched ilmenite was taken as the beginning of melting [11], and a representative charge close to solidus (2.64 GPa and 1325°C) is shown in Fig. 2b, based on which the melting temperature is estimated as 1320°C at 2.64 GPa. For comparison, a charge well below the solidus (2.06 GPa and 1250°C) is shown in Fig. 2a, where dendritic ilmenite is absent.

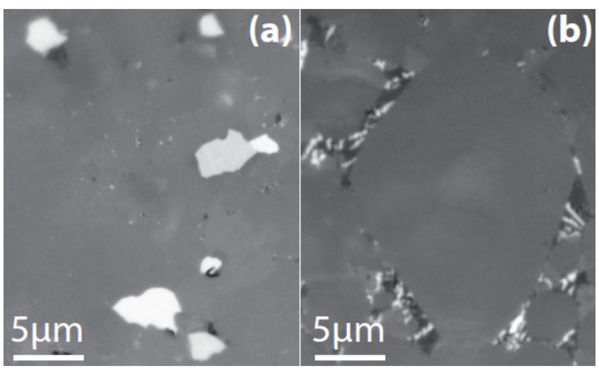

Fig. 2. Photomicrographs in reflected light of representative experimental charges. (a) Charge CMTC-4, in which ilmenite has not begun to melt yet. (b) Charge CMTC-10 showing the distribution of dendritic quenched ilmenite (white) among intersects of other silicate minerals (darker gray).

Results: Figure 1 shows the solidus of our starting composition to date, which is a mixture of ilmenite-cpx rich late cumulate and high Mg harzburgite (Mg# ~ 91) which may serve as an analogy for early lunar cumulate mantle. The beginning of melting temperature is 1260°C at 1.18 GPa and increases to 1320°C at 2.64 GPa, defining a slope for the solidus of 4.1°C/kb. Melting temperature at 4.2 GPa, which corresponds to the pressure close to lunar core-mantle boundary, is extrapolated based on the slope constrained from this study, with the value of 1360-1400°C (hatched rectangular box in Fig. 1). The solidus defined by higher-pressure ilmenite + cpx phase equilibrium experiments gives a slope of 6°C/kb [11]. The interpolated melting temperature at 4.2 GPa is ~1440°C, which is 40-80°C above our result. The low pressure ilmenite-rich cumulate phase equilibrium study indicated a slope of the solidus nearly 10°C/kb [12], and a melting temperature of 1490°C at 4.2 GPa can be extrapolated. Phase equilibrium studies of Fe-Ti oxide + ol + opx concluded a solidus with the slope overlapping with this study at 1-1.4 GPa and much steeper at pressure above 1.4 GPa, accompanied with the break down of armalcolite [13].

Discussion: Overall, solidus slope for the hybrid lunar cumulate mantle determined in this study is the smallest compared with previous phase equilibrium studies of the lunar mantle cumulate. Based on the solidus slope of this study, melting temperature at lunar core-mantle boundary is extrapolated as 1360-1400°C, which is also lower than previous studies. It is possible that solidus of the hybrid lunar cumulate mantle is not linear, as such our estimated temperatures above set a lower bound. Phase equilibrium studies at higher pressures are needed to pinpoint the solidus.

Future work includes higher-pressure experiments under deeper lunar mantle conditions to pinpoint the solidus of our starting composition, so that a more accurate melting temperature at core-mantle boundary can be determined. Mineral proportion of the ilmenite-bearing late cumulate and the percentage of ilmenite-bearing cumulate in the hybrid mantle affect the solidus and chemical composition of the melt. For example, the fraction of plagioclase plays an important role on the bulk Al_2O_3 abundance of the ilmenite-bearing cumulate. The proportion of ilmenite-bearing cumulate in the hybrid mantle will affect the TiO_2 content in the melt. These first order effects will be examined in this study.

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