

**EXPERIMENTAL CONSTRAINTS ON COMPOSITION OF LUNAR MAGMA OCEAN FROM PHYSICAL PROPERTIES OF MAGMA.** R. Sakai<sup>1</sup>, I. Kushiro<sup>1</sup>, H. Nagahara<sup>1</sup>, K. Ozawa<sup>1</sup> and S. Tachibana<sup>1</sup>, <sup>1</sup> Department of Earth and Planetary Science, The University of Tokyo, 7-3-1 Hongo, Tokyo 113-0033, JAPAN (lotilyx131@gmail.com)

**Introduction:** It has been widely accepted that the lunar anorthosite crust formed by floatation of anorthite in the magma ocean at the time of a giant impact of the Earth-Moon system formation. The positive Eu-anomaly in lunar anorthosites and the absence of mafic components in the lunar crust that contain complementary negative Eu-anomalies can also be the evidence of formation of the anorthosite crust by large-scale differentiation. It is thus important to understand the formation process of the anorthosite crust in order to reveal the nature of large-scale differentiation in the cooling lunar magma ocean (LMO). Here we report our attempts to understand differentiation in LMO processes based on experimental constraints from physical properties of magma ocean.

**Lunar magma ocean:** Many attempts have been made to estimate geophysical and/or geochemical conditions of the lunar magma ocean, and several models for differentiation of the moon in the cooling LMO have been proposed [e.g., references in [1] and references therein]. However, there are large disparities in the scale, composition, and cooling history of LMO.

Fractional crystallization in the large-scale magma ocean occurs as a result of combination of several physical and chemical processes such as convection of magma that transports heat and mass, floatation/settling of minerals, formation of viscous boundary layer, nucleation/growth/dissolution of minerals, and so on. Many of key processes in the magma ocean depend on physical and chemical properties of minerals and silicate melts, but some have not yet been precisely determined. Thus, even with a proper model of the magma ocean, it may not necessarily be realistic modeling of LMO. The most critical but poorly constrained parameter is the bulk composition of LMO ( $\approx$  the bulk silicate composition of the moon). For instance, there have been a wide range of estimates for concentrations of  $Al_2O_3$  and FeO that have been inferred from lunar rocks or seismic data [e.g., 2-5]. The  $Al_2O_3$  and FeO concentrations in the melt, however, change the liquidus temperature of anorthite and the density and viscosity of the melt, which should affect the floatation of anorthite in LMO.

**Concept of this study:** We have started working to constrain the composition of LMO by combining the physical modeling of LMO and experimental

determination of physical properties of silicate melts. We expect to find the most plausible compositional range of LMO, which can form the anorthosite crust in the cooling LMO with satisfying other geophysical and geochemical constraints of the moon as well. The critical condition is that anorthite can float from the melt that has already fractionated mafic phases at higher temperatures, which requires that (1) there still remains residual melt, (2) the melt has larger density than anorthite, and (3) the viscosity of the melt is small enough to float anorthite even at the final stage of magma ocean crystallization near the surface. Thus, it is crucial to investigate the density and viscosity of melt with the residual melt composition coexisting with anorthite as a function of pressure and bulk composition of LMO.

Here we report preliminary experimental results to determine densities and viscosities of possible LMO melts at plausible temperature and pressure conditions.

**Experiments:** We first carried out floatation experiments of anorthite in silicate melts [6] with various compositions using a piston cylinder apparatus. We further performed piston-cylinder experiments to determine the pressure effect on viscosity.

The chemical compositions of the starting glasses (Table 1) were determined as follows; (1) Initial bulk LMO compositions were assumed to be BSE (bulk silicate Earth) or to have solar elemental ratios of Si, Al, Mg, and Ca with varying Fe contents (CI4 and CI6). The CI4 and CI6 were assumed to contain FeO of 4 or 6 wt%, respectively. The former corresponds to the existence of 400-km metallic core for the moon with the bulk CI composition. However, the depletion of siderophile elements for the bulk moon has been widely known, and thus 400 km is the maximum core size for the composition of CI6. The FeO content in the latter case was taken from [5]. (2) The initial bulk LMO was differentiated at an experimental pressure using the MELTS [7] or pMELTS [8] algorithms until the first appearance of anorthite. (3) The amounts of  $Na_2O$  and  $TiO_2$  for CI4 and CI6 were determined as minimum concentrations, with which MELTS/pMELTS could calculate the liquidus of anorthite at an experimental pressure.

The starting glass, prepared by fusing and quenching of reagents of metallic oxides under controlled oxygen fugacity, was put in a Pt capsule (4.4 mm in inner diameter and 10 mm in height). A few

chips of anorthite, which is a natural almost pure  $\text{CaAl}_2\text{Si}_2\text{O}_8$ , were placed at the middle of the capsule. The capsule surrounded by pressure media (talc and pyrex glass) and a graphite heater was compressed uni-axially at  $\sim 0.5$  GPa and 1300 and 1350°C for 5 min. The pressure of  $\sim 0.5$  GPa corresponds to the depth of  $\sim 100$  km in LMO. The heating temperatures were  $\sim 40$ -52°C above the liquidus of the starting glasses.

The experiments to determine the pressure effect on viscosity were carried out using the starting glass of CI6 with the technique developed by Kushiro [9]. The Pt capsule with CI6 glass and a San Carlos olivine ( $\text{Fo}_{91}$ ) sphere, located near top of the capsule, was run at  $\sim 0.5$  and  $\sim 0.75$  GPa at 1350°C for 3 min.

**Results and Implication to LMO:** Anorthite floated in the melts of all the compositions in the present study at 0.5 GPa although MELTS predicts that the glass of CI4 has a smaller density than anorthite. This is the first that floatation of anorthite in silicate melt with a plausible compositional range of LMO that can coexist with anorthite is experimentally proved.

In the experiments for the viscosity measurement, the crystals sank from their original positions in the CI6 melt both at 0.5 and 0.75 GPa. The viscosity at 0.5 GPa estimated from the descent distance and the Stokes law with correction of the wall effect from the capsule was found to be smaller than that at 0.75 GPa. The positive pressure dependence of the residual melt of LMO is opposite to common terrestrial basalts.

Although further systematic experiments and quantitative evaluation on physics of differentiation during cooling of the magma ocean should be made, the present results indicate that the viscosity of LMO at the stage of anorthosite crust formation increases with depth and that floatation of anorthite in LMO may be less effective in deep LMO compared to shallow LMO.

**References:** [1] Bradley L. et al. eds., *New Views of the Moon*, *Rev. Min. and Geochem*, 60 (2006). [2] Taylor S. R. (1982) *Planetary Science: A New Perspective*, 2<sup>nd</sup> ed., Cambridge Univ. Press, New York. [3] Warren P. H. (1986) *Origin of the Moon*, Hartmann, W. K. et al. eds, 279-310. [4] Khan A. et al. *JGR*, 111, E05005. [5] Smith J. V. and Steele, I. M. (1975) *Lunar Science*, VI, 853-755. [6] Wakjer D. and Hays J. F. (1977) *Geology*, 5, 425-428. [7] Kushiro I. (1976) *JGR*, 81, 6347-6350. [8] Ghiorso M. S. and Sack R. O. (1995) *Contrib. Mineral. Petrol.*, 119, 197-212. [9] Ghiorso, M. S. et al., (2002) *Geochem. Geophys. Geosys.*, 3, 2001GC000217.

TABLE 1. Composition of starting glasses at the first appearance of anorthite in each model (wt%). BSE: bulk silicate Earth. See the text for CI4 and CI6

	BSE	CI4	CI6
$\text{SiO}_2$	43.6	48.1	45.9
$\text{Al}_2\text{O}_3$	17.0	19.3	17.9
CaO	13.2	13.2	14.41
MgO	10.0	11.0	10.2
FeO	15.9	6.3	11.4
$\text{TiO}_2$	0.04	0.06	0.05
$\text{Na}_2\text{O}$	0.17	0.16	0.15