CHEMICAL COMPOSITION OF LUNAR MAGMA OCEAN CONSTRAINED BY HIGH PRESSURE EXPERIMENTS.
R. Sakai[1], I. Kushiro[1], H. Nagahara[1], K. Ozawa[1] and S. Tachibana[1], [1]Department of Earth and Planetary Science, The University of Tokyo, 7-3-1 Hongo, Tokyo 113-0033, JAPAN (rsakai@eps.s.u-tokyo.ac.jp)

Introduction: It is widely accepted that lunar anorthosite crust was formed by flotation of anorthite in the magma ocean. However, there are large uncertainties in physical and chemical conditions of the lunar magma ocean (LMO) such as scale, composition, and cooling history. Here we report our attempts to constrain bulk chemical compositions of LMO based on critical conditions that anorthite can float in LMO, which are determined by experimental constraints for physical properties of magma combining with observations of lunar samples, and geophysical and geochemical data obtained by lunar explorations. The critical conditions for flotation of anorthite are: (1) there still remained enough fractionated melt to match the thickness of the crust, (2) the melt had larger density than anorthite, and (3) the viscosity of the melt was small enough to float anorthite even at the final stage of magma ocean crystallization. The critical observations are: (a) 45±10 km for the average thickness of lunar crust [1-5], (b) ~27±3 wt% for Al_2O_3 content in the crust [6-9], and (c) <1.8 cm for the grain size of plagioclase from the anorthosite 15415 [10-11]. In this study, in order to estimate plausible range of the bulk composition of the initial LMO under the constraints listed above, we experimentally determined the viscosity and density of melts derived from several compositions assumed for the initial magma ocean.

Initial LMO and its evolution: Initial bulk LMO compositions were assumed to be BSE (bulk silicate Earth) and to be the compositions which have BSE ratios of Si, Al, Mg, and Ca with varying Fe contents (BSE4, BSE6, and BSE13). BSE4, BSE6, and BSE13 were assumed to contain FeO of 4, 6, or 13 wt%, respectively. We assumed that the initial LMO differentiated at a low pressure (~0.5 GPa) and the evolution of magma composition due to maximum fractionation was evaluated using the MELTS algorithms[12] until the first appearance of anorthite. Note that we added minimal amounts of Na_2O and TiO_2 to the initial LMO compositions with which MELTS could calculate differentiation of LMO. We call each calculated composition of the melts at the first appearance of anorthite as BSE*, BSE4*, BSE6*, and BSE13* (Table 1). We also calculated the evolution of LMO as a result of separation of minerals at every 60% crystallization, for comparison.

Experiments: High pressure experiments were done with a piston-cylinder apparatus to determine magma properties. Synthetic glasses for BSE*, BSE4*, BSE6*, and BSE13* were used as starting materials.

The experimental conditions were within the plausible range of anorthite stability; the temperature is near or above the liquidus of anorthite (1275-1350°C), and the pressure (0.5-1.0 GPa) corresponds to the depth of 100-200 km from the surface of the moon.

We first carried out experiments for density comparison between anorthite and the melts at 0.5 and 1.0 GPa. A few chips of natural anorthite were placed at the middle of the Pt capsule, and the capsule was heated at 1300 or 1350°C at a certain pressure for 5 min. The run products were checked whether anorthite floated or sank from the original position.

The falling-sphere method [13] was applied to measure viscosities of BSE*, BSE6* and BSE13* melts. Spheres of San Carlos olivine (Fo~91), located near the top of a Pt capsule, was held at ~0.5-1.0 GPa and 1275-1350°C for 3-5 min. The sank distance of the sphere in a run product was measured under an optical microscope, from which the viscosity of the melt could be determined [13].

Results: Floatation experiments of anorthite showed that anorthite floated in BSE*, BSE6*, and BSE13* melts at 0.5 GPa and in all the melts at 1.0 GPa. For BSE4* at 0.5 GPa, anorthite did not float but stayed close to the original position, suggesting that the density of BSE4* at 0.5 GPa at a temperature close to the anorthite liquidus is close to the density of anorthite.

We found that viscosities of melts have little (or slightly negative) dependence on pressure (Fig. 1) and that the viscosity show a clear negative dependence on FeO contents (Fig. 1).

The activation energy of viscosity at 0.5 GPa was estimated to be 317 and 227 kJ/mol for BSE6* and BSE13*, respectively, at ~0.5 GPa (Fig. 2).

Discussion: The floatation experiments of anorthite indicates that anorthite does not float in the LMO of BSE4* at a depth of 100 km (~0.5 GPa). We thus conclude that BSE4, which has the lowest FeO content (4 wt%), is not a plausible composition for LMO because anorthotire crust of ~45 km in thickness cannot form from BSE4.

The LMO would have been highly convective even in the stage of anorthite crystallization. Thus the condition of anorthite flotation in the LMO should not be dependent only on density difference, but anorthite should have a terminal velocity large enough to float in a convective magma. Based on experimentally determined viscosities, we calculated both terminal velocities (v_{term}) of anorthite grains in the melts of BSE*,

BSE6*, and BSE13* and convective velocities (v_{conv}) of the melts at the temperature conditions where anorthite starts to crystallize. Separation of solid from the convective melt occurs effectively when v_{term} and v_{tconv} satisfies the relation of $S = b(v_{term}/v_{tconv}) > 1$, where S is called as the Rouse number and b is 42 [14]. Figure 3 shows the size of anorthite grains satisfying the condition of $S > 1$ in the melts with various FeO contents. Because the melt with higher FeO content has higher density and smaller viscosity (Fig. 1), the critical size of anorthite that can float in the LMO is smaller for the FeO-rich melts, i.e., anorthite could float easily. When we apply the maximum grain size of anorthite in the Apollo sample 15415 (1.8 cm), the LMO should have FeO higher than or similar to BSE* when anorthite started to crystallize. This implies that the initial magma ocean should have contained FeO comparable to or richer than BSE, i.e., the redox state of bulk silicate Moon should have been comparable to or more oxidizing than the bulk silicate Earth. If the LMO differentiates by separation of minerals after 60% crystallization, the LMO at the first appearance of anorthite tends to have less FeO than that for maximum fractionation (Table 1), which leads to less effective floatation of anorthite. The initial LMO should thus contain more FeO than BSE in this case.

References: [1] Ishihara Y. et al. (2009) *GRL 36,* L19202. [2] Hikida H. and Wieczorek M. A. (2007) *Icarus* 192, 150-166. [3] Wieczorek M. A. et al. (2006) *Rev. Mineral. Geochem. 60,* 221-364. [4] Lognonné P. et al. (2003) *EPSL 211,* 27-44. [5] Khan A. et al. (2000) *GRL 27,* 1591-1594. [6] Lucey P. G. (1998) *JGR 103,* 3679-3699. [7] Korotev R. L. (2000) *JGR 105,* 4317-4345. [8] Jolliff B. L. (2000) *JGR 105,* 4197-4216. [9] Wieczorek M. A. and Zuber M. T. (2001) *GRL 28,* 4023-4026. [10] James O. B. (1972) *Science 175,* 432-436. [11] Wilshire H. G. (1972) *Geol. Soc. Am. Bull. 83,* 1083-1092. [12] Ghiorso M. S. and Sack R. O. (1995) *Contr. Miner. Petrol,* 119, 197-212. [13] Kushiro I. (1976) *JGR 81,* 6347-6350. [14] Tonks W. B. and Melosh H. J. (1989) in *Origin of the Earth,* 151-174.

Table 1. Calculated composition of LMO at the first appearance of anorthite in each LMO model (wt%). See details in the text.

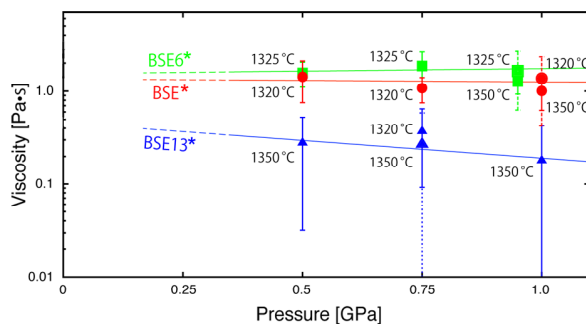|	BSE*	BSE4*	BSE6*	BSE13*
SiO$_2$	43.8	47.5	45.4	40.0
Al$_2$O$_3$	17.2	19.8	18.6	14.5
FeO	15.3	5.9	10.8	25.0
MgO	10.1	11.8	10.9	8.9
CaO	13.4	14.3	14.1	11.4
TiO$_2$	0.04	0.05	0.05	0.04
Na$_2$O	0.17	0.18	0.18	0.15

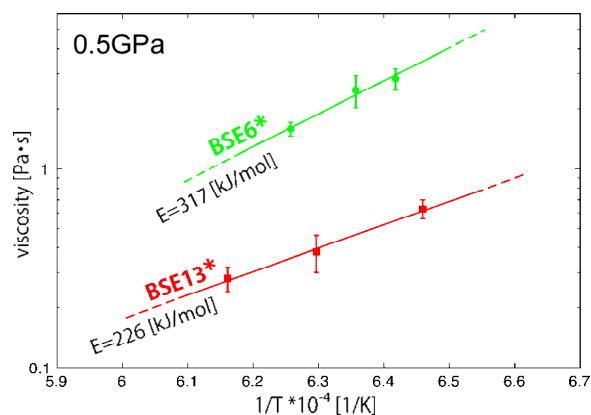**Fig. 1.** Viscosities of the melt BSE*, BSE6* and BSE13*plotted against pressure.

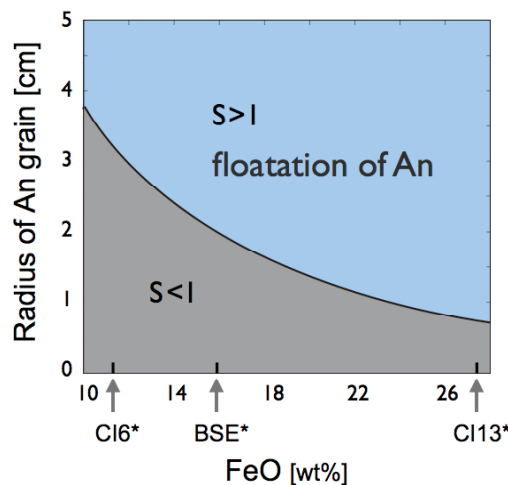**Fig. 2.** Temperature dependence of viscosity for the melt BSE6* and BSE13*.

Fig.3. The size of anorthite grains that can float in the convective LMO during the stage of anorthite crystallization. The critical size of anorthite requires for floatation (S=1; see details in the text) is smaller for the melt with higher FeO content.