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Chemical Composition of Lunar Magma Ocean Constrained from Condition of Lunar Crust Formation

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The internal structure and the bulk composition of Moon have not yet been clarified in spite of numerous studies based on lunar rocks and explorations. In this study we attempt to constrain the chemical composition of the initial magma ocean from determining the condition required for the formation of the observed anorthosite crust.
The conditions for the formation of the anorthosite crust are: (1) the magma ocean crystallizing anorthite should be deep enough to match the observed thickness of the crust, (2) the magma should have a higher density than that of anorthite, and (3) the viscosity of the magma should be low enough for effective flotation of anorthite in the last stage of the cooling magma ocean. The later two conditions relate to the physical property of magma should be determined by high-pressure experiments.
We assumed several compositions for the initial lunar magma ocean, and calculated the evolution of chemical composition of magma due to crystallization and fractionation of minerals using MELTS and /or pMELTS [Ghiorso and Sack, 1995] to determinethe composition of the magma ocean at the first appearance of anorthite. We considered several different ways of crystal fractionation, which are maximum fractionation and batch crystallization at a shallow depth of magma ocean, and repeated batch crystallization up to 40% crystal fraction followed by instantaneous and complete crystal separation at deep magma ocean. The calculated magma composition at the appearance of anorthite tend to have more SiO2 and Al2O3 and less FeO in the order of maximum fractionation, incremental fractionation, and batch crystallization.
We then synthesized glasses with chemical compositions covering the range estimated in various fractionation models, and carried out piston-cylinder experiments to determine the viscosity and density of the magmas that crystallize anorthite in the last stage of magma ocean evolution. We found that viscosities of melts have little (or slightly negative) dependence on pressure, and that the viscosity and density show clear negative dependences on FeO contents.
We applied the experimentally determined viscosity and density of the magma to the condition of mineral separation in a convective magma [Tonks and Melosh, 1990], which indicates that the initial magma ocean could have the FeO content similar to or more than the bulk silicate Earth in the case of maxmum fractionation and that is should be enriched in FeO than the bulk silicate Earth in the cases of incremental fractionation and batch crystallization.

Keywords: Moon, Magma Ocean, Anorthosite crust, High-pressure experiments, Piston-Cylinder, Physical property of Magma