Japan Geoscience Union Meeting 2015
(May 24th - 28th at Makuhari, Chiba, Japan)

PPS23-15 Room:A02 Time:May 26 09:30-09:45

Formation of anorthosite on the Moon through magma ocean fractional crystallization

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Geological records of the moon have a potential to reveal early evolution of the earth. 4.4Ga anorthosite on the Moon formed as by fractional crystallization of the lunar magma ocean (LMO). It has been generally accepted that the lunar bulk composition is enriched in FeO compared with the bulk silicate earth, which is critical to make large plagioclase/melt density difference enough to form the anorthosite. However, the bulk moon composition likely has the same composition of the earth, which is supported by isotopic similarities for the two bodies and recent giant impact modeling. In this study, critical condition of fractional crystallization of plagioclase is assessed for the BSE composition by taking into account crystal/melt density difference, viscosity of melt, crystal size, and Rayleigh number of the magma ocean. This study modeled solidification process of the LMO and calculated change of melt composition by use of MELTS/pMELTS. Density and viscosity of melt were calculated by use of first-principles simulations.

Results of thermodynamic calculations indicate that melt is basaltic (Mg# = 0.59) when plagioclase starts to crystalize. Viscosity of the basaltic melt ranges 20 - 10 Pa s whereas density ranges 2.60 - 2.71 g/cc for 0 - 1 GPa where plagioclase crystallizes. Comparison between critical crystal diameter calculated from the viscosity and density and crystal diameter of plagioclase (5 - 18mm) of anorthosite suggests that crystal fraction of magma, $\varphi = 0.55$ is required to make convection of magma ocean moderate enough that plagioclase could separate from the melt. Results of critical crystal diameter for olivine/pyroxene indicate that the crystallized mafic minerals would also be entrained in the viscous basaltic melt until $\varphi = 0.55$ is attained. In that case, large amount of mafic minerals are entrained in the magma along with plagioclase, which is enough to account for the $\varphi = 0.55$ in the magma. For the melt composition when crystal fraction $\varphi = 0.55$ is attained, the basaltic melt is enriched in FeO enough that plagioclase could float to the surface of the moon. Application of the discussion to the terrestrial magma ocean has insight into the surface evolution of the Hadean Earth, which would be related to the evolution of life.

Keywords: Moon, Anorthosite, Magma ocean, Density and viscosity of melt, Hadean Earth