COMPARISON OF LUNAR AND TERRESTRIAL MAGMA OCEANS
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Introduction. The concept of formation of the Earth-Moon system via collision between a proto-Earth and a large planetesimal implies a subsequent formation of magma oceans (1-4). The magma oceans on the Earth and the Moon were formed and crystallized under different conditions: the depth and pressures of a magma ocean, gravity, surface conditions (atmosphere) and composition. We develop models of various physical processes involved into the evolution of magma oceans (5,6) and show that there are following fundamental differences between lunar and terrestrial magma oceans. Fractional and “near-solidus” crystal-liquid separation occur in different layers on the Earth and the Moon. A crust could be formed in the very beginning of the evolution of the lunar magma ocean but it can not be formed on the terrestrial magma ocean until the crystal fraction is very high. Plagioclastic crust on the Moon is formed later via Rayleigh-Taylor instabilities. A compositional convection remixes the terrestrial mantle but not the lunar mantle.

“Near-Liquidus” Versus “Near-Solidus” Differentiation. “Near-liquidus” differentiation (or fractional crystallization) means that liquid-solid separation occurs at small solid fractions. It is unavoidable, for example, if the gravitational energy release due to the differentiation is larger than the heat flux which can be removed from the system. “Near-solidus” differentiation implies that the differentiation is negligible until a high (possibly dense packing) crystal fraction is reached. In this case the main factor which determines the beginning of differentiation is the viscosity of the crystal-liquid mixture. Fractional differentiation results in a complete mineralogical stratification corresponding to the sequence of the liquidus phases. “Near-solidus” differentiation results in a differentiation of mixtures of liquidus phases: in the simplest case the stratification consists of only two different layers one of them is a squeezed and solidified residual melt. Because the rates of separation are different by several orders of magnitude fractional differentiation is essentially non-equilibrium process and “near-solidus” differentiation could be an equilibrium process. The criteria determining which kind of differentiation takes place depend on the melt viscosity, the crystal-melt suspension viscosity, the sign of crystal-liquid density difference, convective heat flux, depth of the magma ocean, gravity and crystal radius. The viscosity can be calculated from the melt composition, radiative heat flux was constrained in (7,8) and the crystal radius is estimated from the solution of kinetic problems of the convective multiphase system (5). The differentiation of the terrestrial lower mantle is almost certainly “near-solidus”. In the case of solidification of the upper mantle fractional differentiation becomes more possible because the crystal-liquid density difference is “normal” and the heat flux is much lower when the upper mantle undergoes freezing. Crystallization of the lunar magma ocean could occur mostly in the absence of any atmosphere and in the absence of volatiles. The first factor increases the heat flux from the Moon, causes earlier formation of the crust and significantly enhances the possibility of “near-solidus” differentiation in comparison with the upper mantle of the Earth. The second factor together with a possible effect of Ostwald ripening can influence the conclusion because they increase the crystals sizes and corresponding settling velocities.
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Solidification from the Bottom versus Solidification from the Top. Solidification starts at the level where temperature of the convective magma ocean intersects the liquidus temperature. It depends on the heat flux and on the relative variation of adiabatic and melting temperatures. In the case of the Earth the solidification can begin from the bottom or somewhere in the lower mantle but not from the surface: a steam atmosphere limits the heat flux from the surface of the magma ocean and the crust can not be formed until almost the entire magma ocean is solidified up to the dense packing crystal fraction. The absence of such atmosphere on the lunar magma ocean decreases the surface temperature below the solidus temperature even earlier than the solidification begins from the bottom of the magma ocean! Solidification (up to the dense packing crystal fraction) of the lunar magma ocean occurs simultaneously from the top and the bottom. The competition between a high negative buoyancy of this crust and its extremely high viscosity results in a stagnation of the crust. The convection effectively occurs under this crust but the crust is gravitationally unstable and continuously recycles. The crust defined as a rheological layer effectively non-participating in the main convective flow is a crystal-liquid mixture with a crystal fraction close to the dense packing value (0.6-0.7 and could be even higher). Differentiation of this two-phase crust continues together with the slowing recycling of the crust. The crust is growing, the convective region is thinning, the thermal convection becomes slower and ceases at most after ten(s) years (possibly much earlier). Fractional crystallization begins approximately at this time or earlier. It also helps to stop convection creating a stable density gradient. Fractional crystallization takes place mainly in the remaining (several hundred kilometers thickness) intermediate layer. Floatation of plagioclase and sinking of mafic cumulates occur at this time. Due to Rayleigh-Taylor instability plagioclase reaches the surface and forms a stable crust. A pronounced asymmetry of this process could result in the observed asymmetry of the lunar structure.

Compositional Convection. In the case of “near-solidus” differentiation compositional convection occurs in the presence of crystal-liquid density difference inversions. At the density cross-over levels (for crystal mixtures) double compositional boundary layers are formed by the crystal-liquid differentiation. These boundary layers are sources of gravitational instabilities and provide driving forces for the compositional convection. In the case of the Earth there could be 1-2 such boundary layers (in dependent on the thickness of the magma ocean) which provide a complicated mixing of the entire mantle.