

A 3D Numerical Model of the Solidification and Differentiation of a Mushy Lunar Magma Ocean

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Returned samples of the lunar crust show an anorthite-rich feature, which leads to the hypothesis of lunar magma ocean (LMO) in which olivine/pyroxene fractionally crystallized and sunk to form cumulates, whereas late-stage plagioclase precipitated and floated up to form the anorthositic crust. Such a conventional thinking, however, does not agree with the data-derived, ~ 200 Ma lunar crust formation timescale which the fractional crystallization model would predict to be on the order of tens of Ma. One possible avenue to sustaining the lifetime of the LMO is to consider the weakened convective cooling of the mushy-state LMO. To systematically account for this process, we devise a 3D numerical model based on CitcomS, where we consider melt segregation in the mushy magma ocean, melt extraction via near-surface dikeing, thermal and chemical convection, as well as a parameterized partial melting model involving anorthite and olivine. The two chemical components---anorthite and olivine---are employed to represent the fertile and refractory constituents during partial melting/freezing, and their chemical buoyancy is also consistently accounted for. With this 3D model, we find that melt segregation and subsequent extraction to the surface expedite the cooling of the LMO; however, the lunar crust formation timescale can still last for ~ 200 Ma given the high viscosities of the convecting solids. Furthermore, due to the differential buoyancy between the anorthite and olivine components, a new mechanism of overturn is found during the Moon's mushy stage, potentially reconciling the magma ocean theory with the age data that show a temporal overlap between the lunar Mg-suite and ferroan anorthosites. This potential overturn mechanism is subject to future test because the current model does not consider iron-bearing components which strongly affect chemical buoyancy.