Thermodynamic Constraints on Mantle Melting and Magma Ocean Crystallization

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The early formation history of rocky planets is dominated by the interplay between thermodynamics and fluid dynamics as planetary-scale magma oceans cool and crystallize. The transition from rapid to sluggish convection is sensitive to the details of silicate crystallization at extreme pressures. Together, depth of crystallization and crystal bouyancy help determine the evolutionary path of the cooling planet. Two competing endmember hypotheses argue that the magma ocean crystallizes primarily from the bottom-up (e.g. Andrault et al., 2011) or the center-outwards (e.g. Stixrude et al. 2009). We explore this issue using an integrated exploration of the thermodynamics of silicate melting and the fluid dynamic consequences of cooling a deep magma ocean.

The crystallization depth depends on the properties of both chondritic melt and the liquidus solid phase ($MgSiO_3$ bridgmanite), and is controlled by the relative slope of the liquid adiabat compared to the liquidus. Determination of the mantle liquidus is particularly difficult due to complex mantle chemistry and extreme P-T conditions. The disagreement between previous experimental and theoretical studies is understandable, given that the crystalization depth is strongly senstitive to the curvature of the mantle liquidus, and this higher-order derivative property is difficult to constrain with high confidence. We adopt a new fully themodynamic approach, independent of past studies, to help discern between these two endmember scenarios. Our method is based on the theory of multi-component fusion curves, derived by Walker et al. (1988), which extends the Clausius-Claperon approach by focusing on the volume and entropy of fusion for just the crystallizing component $MgSiO_3$, defined by the liquidus phase bridgmanite. We explore the non-ideal contributions to both partial molar entropy and volume of fusion introduced by a realistic chondritic mantle composition. These are dominated by changes to the entropy, arising from volume-dependent configurational entropy and coordination-dependent entropies of mixing (Wolf et al., 2015). These calculations provide adjustments to the pure $MgSiO_3$ melting curve that are determined directly for a chondritic mantle composition. The non-negligible curvature of the resulting liquidus is shown to favor center-outwards crystallization, and the corresponding magma ocean cooling evolution is explored with a one-dimensional energy-conserving numerical model.