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Consequences of an unstable chemical stratification on mantle dynamics

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Early in the history of terrestrial planets, the fractional crystallization of primordial magma oceans may have led to the formation of large scale chemical heterogeneities. These may have been preserved over the entire planetary evolution as suggested for Mars by the isotopic analysis of the so-called SNC meteorites. The fractional crystallization of a magma ocean leads to a chemical stratification characterized by a progressive enrichment in heavy elements from the core-mantle boundary to the surface. This results in an unstable configuration that causes the overturn of the mantle and the subsequent formation of a stable chemical layering.

Assuming scaling parameters appropriate for Mars, we first performed simulations of 2D thermo-chemical convection in Cartesian geometry with the numerical code YACC [1]. We investigated systems heated either solely from below or from within by varying systematically the buoyancy ratio B, which measures the relative importance of chemical to thermal buoyancy, and the mantle rheology, by considering systems with constant, strongly temperature-dependent and plastic viscosity. We ran a large set of simulations spanning a wide parameter space in order to understand the basic physics governing the magma ocean cumulate overturn and its consequence on mantle dynamics. Moreover, we derived scaling laws that relate the time over which chemical heterogeneities can be preserved (mixing time) and the critical yield stress (maximal yield stress that allows the lithosphere to undergo brittle failure) to the buoyancy ratio. We have found that the mixing time increases exponentially with B, while the critical yield stress shows a linear dependence.

We investigated then Mars' early thermo-chemical evolution using the code GAIA in a 2D cylindrical geometry [2] and assuming a detailed magma ocean crystallization sequence as obtained from geochemical modeling [3]. We used an initial composition profile adapted from [3], accounted for an exothermic phase transition between lower and upper mantle and assumed all radiogenic heat sources to be enriched during the freezing-phase of the magma ocean in the uppermost 50 km [4]. A stagnant lid forms rapidly because of the strong temperature dependence of the viscosity. This prevents the uppermost dense cumulates to sink, even when allowing for a plastic yielding mechanism. Below this dense stagnant lid, the mantle chemical gradient settles to a stable configuration. The convection pattern is dominated by small-scale structures, which are difficult to reconcile with the large-scale volcanic features observed over Mars' surface. Assuming that the stagnant lid will break, a stable density gradient is obtained, with the densest material and the entire amount of heat sources lying above the core-mantle-boundary. This leads to a strong overheating of the lowermost mantle, whose temperature increases to values that exceed the liquidus. Therefore a fractionated global and deep magma ocean is difficult to reconcile with observations. Different scenarios assuming, for instance, a hemispherical or shallow magma ocean will have to be considered.

References

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