Core cooling and lower mantle crystallisation in the thermal evolution of the Earth

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Models for the thermal evolution of the Earth have traditionnally assumed that the core cools at the same pace as the mantle or more slowly. The latter assumption comes from the idea that the heat flow across the core mantle boundary (CMB) is low, of order 3TW, and given by the buoyancy flux sustaining hotspot swells. The present heat imbalance of the Earth, quantified by the Urey number being lower than 0.5, and the positive feedback between mantle temperature and heat flow through temperature-dependence of the viscosity, typically lead to a thermal catastrophe less than 2 Byr ago in standard parameterised models of thermal evolution. This has pushed many authors to propose non-classical scalings of heat transfer by mantle convection.

The thermal conductivity of core material has been recently revised to values larger than 90W/m/K at the CMB and increasing with depth in the core [1]. With such values, the low CMB heat flow assumed previously would not sustain a geodynamo, even taking into account compositionnal buoyancy released upon inner core growth. A CMB heat flow larger than 10 TW is required, which can effectively solve the thermal evolution for the Earth. Indeed, when considering the CMB heat flow as a source for the mantle, its effective Urey number is in excess of 0.65, a value much easier to accommodate with standard scalings.

For the low amount of potasium usually considered as possible in the core, a large CMB heat flow implies a large cooling rate, more than 750 K in 4.5 Gyr. Dense partially molten regions at the bottom of the mantle provide the best explanations to the seismic observations of ultra low velocity zones. The large cooling of the core implies a thicker molten lowermost mantle in the past [2]. The slow fractionnal crystallisation of this basal magma ocean brings in latent heat, helping to solve the thermal evolution problem. In addition, assuming that heat producing elements partition in the melt at the pressure of the lowermost mantle, a significant fraction of the Earth budget can be stored there.

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Modes of formation of the basal magma ocean

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The classical view of magma ocean crystallization is based on the assumption that the liquidus gradient is steeper than the isentropic temperature gradient, leading to crystallisation from the bottom upward. In addition, it was usually assumed that the solid thereby formed is denser than the liquid. Recent results on the phase diagram of deep mantle minerals prompt a reconsideration of these assumptions.

Some recent studies propose that crystallization of the magma ocean could start from mid-mantle and produce neutrally buoyant crystals at the same depth. This would naturally lead to a surface magma ocean and a basal magma ocean. On the other hand, some recent results [1] suggest that crystallisation should start at the bottom of the mantle and make dense solids. However, the gradual enrichment of the solid in Fe by fractional crystallization causes an unstable density increase with height and eventually overturn following a Rayleigh-Taylor instability. This would bring down highly fusible Fe-rich solid and the gravitational energy released by viscous friction would remelt it. The Fe-rich formed liquid would then be dense enough to remain at the bottom of the mantle as a basal magma ocean.

Alternatively, the formation of the core could result in a largely superheated core that would melt the mantle from below. The liquid produced could be less dense than the solid despite being enriched in iron. Its rise and subsequent freezing would be a means of rapidly transporting core superheat to the mantle as well as producing an unstably stratified solid mantle whose overturn would also create a basal magma ocean.

We explored quantitatively the outcome of these different scenarios in terms of the thickness of the basal magma ocean produced and the implied geochemical signatures, in particular regarding rare gases [2].

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DOI:10.1180/minmag.2013.077.5.12