EPSC Abstracts
Vol. 13, EPSC-DPS2019-1745-1, 2019
EPSC-DPS Joint Meeting 2019


EPSC
EPSC-DPS Joint Meeting 2019
15–20 September 2019 | Geneva, Switzerland

# Numerical simulations of the thermo-chemical evolution of the solid mantle bounded by magma oceans

**Daniela Bolrão** (1), Maxim Ballmer (2), Adrien Morison (3), Antoine Rozel (1), Patrick Sanan (1), Stéphane Labrosse (3) and Paul Tackley (1)
(1) ETH Zurich, Switzerland (2) University College London, United Kingdom (3) ENS Lyon, France
(daniela.bolrao@erdw.ethz.ch)

## Abstract

The idea that our planet had at least one episode of magma ocean during its formation is well accepted nowadays. When the magma ocean starts to crystallise, solid mantle appears. Several studies suggest different crystallisation scenarios, placing the solid mantle below, above or below and above a magma ocean. In this work we are interested in understanding how magma oceans affect dynamics and chemical evolution of the solid mantle. In order to do that, we use a numerical model with the convection code StagYY, with a phase change boundary condition that allows parameterisation of phase changes at the boundary between solid and liquid parts. Our results show that by allowing phase changes at the boundaries, the extreme case of degree-1 mode of convection in the solid part arises, and 50% of chemical equilibration between solid and liquid parts can be reached in few kyrs to 1 Myr.

## 1. Introduction

After accretion and formation of the Earth, our planet went through at least one episode of magma ocean. When the magma ocean cools down and its temperature decreases below the liquidus and then solidus curves, liquid starts to solidify and the solid mantle appears. Classical view for magma ocean solidification suggests that crystals start to form at the Core-Mantle Boundary (CMB) and that solid mantle grows from the bottom-up. Other studies suggest that magma ocean solidification starts at mid-mantle depths and two crystallisation fronts move in opposite directions: the surface magma ocean front upwards and the basal magma ocean front downwards (e.g. (1)). Regardless of the crystallisation scenario, the solid mantle appears from the crystallisation of at least one magma ocean, and its evolution is dependent on the interactions with a magma ocean on top, bottom, or top and bottom.

A direct interaction between solid and liquid layers occurs at the boundaries, when the convection in the solid mantle builds dynamic topography, $h_t$, by viscous forces. If melting and crystallisation processes occur at the boundary, this topography can be eroded or simply it is not developed. Although it is expected that exchange of material through phase changes occur at the interface between solid and liquid layers, numerical models of mantle convection often do not account for it. The boundary condition applied to the solid domain is often no-slip or free-slip, which implies that normal velocities of the flow tend to zero at the solid boundary and flux of material through the boundary cannot occur.

In this work we are interested in taking a more realist scenario by studying how phase changes and exchange of material between magma oceans and solid mantle affects the thermo-chemical evolution of the solid part.

### 1.1. Phase change boundary condition

The boundary condition applied to the solid part is the phase change boundary condition, introduced by (2). This phase change boundary condition allows material to flow through solid domain, which allows parameterisation of melting and crystallisation processes at the boundaries. This boundary condition is given in dimensionless form by:

$$2\frac{\partial u_r}{\partial r} - p \pm \Phi^{\pm} u_r = 0 \quad (1)$$

with $u_r$ the vertical component of the velocity in the solid part, $p$ the pressure in the solid part and $\Phi^{\pm}$ the phase change number at top (+) or bottom (-) boundaries. The phase change number, $\Phi$, is defined as the ratio between the timescale for phase changes to occur, $\tau_\phi = \frac{h_t}{u_r}$, and the timescale to build dynamic topography by viscous relaxation, $\tau_\eta = \frac{\eta}{|\Delta\rho| gR}$ (with $\eta$ the viscosity in the solid part, $\Delta\rho$ the variation of density between solid and liquid layers, $g$ gravity acceleration and $R$ the thickness of solid mantle):

$$\Phi = \frac{\tau_\phi}{\tau_\eta} \quad (2)$$

In the limit when the timescale to build the topography is faster than the timescale of phase changes, $\tau_\eta \ll \tau_\phi$ (then $\Phi \gg 1$ and $u_r \to 0$), vertical velocities tend to zero at the boundary: material cannot cross the boundary and the classical free-slip boundary condition is recovered. On the other hand, in the limit when phase changes occur faster than building the topography, $\tau_\phi \ll \tau_\eta$ (then $\Phi \ll 1$ and $u_r \neq 0$), a flux of material is allowed to cross the boundary and melt or crystallise. In this case, Equation (1) acts as a phase change boundary condition.

# 2. Methods

To understand how dynamics and chemical evolution of solid part varies with magma oceans, we use a numerical model with the convection code StagYY (3), where mass, momentum and energy equations are solved. We take into account three possible evolution scenarios: solid mantle bounded by a magma ocean on top, bottom or top and bottom. Our setup is a solid mantle represented by 2D spherical annulus geometry and magma oceans are parameterised as 0D objects at top, bottom or top and bottom boundaries. We test different thicknesses for magma oceans (100 km, 500 km and 1000 km), different values of $\Phi$ $(10^{-1}, 1, 10, 100)$ and different Ra numbers ($10^2$ Ra$_c$ $-$ $10^5$ Ra$_c$). We make use of the phase change boundary condition that allows material to flow through the boundaries. Thus, it is possible to parameterise fractional crystallisation and melting processes at the boundaries between solid and liquid domain. Because iron partitioning occurs preferentially in the oceans, the continuous melting/refreezing of material at the boundaries changes composition of solid and liquid parts with time.

# 3. Results

Our results show that the thermal evolution of solid part is strongly controlled by the presence of magma oceans above and below. Because material can now flow through the boundaries, different patterns of convection arise depending on the $\Phi$. If the timescale for melting/crystallisation is short, $\Phi \ll 1$, we show that the extreme case of degree-1 mode of convection (translation) happens. Regarding compositional evolution, we show that solid part gets iron depleted, while both magma oceans get enriched in iron. With time, iron content in both solid and liquid layers reach a steady state. We also show that $\Phi$ has a strong impact in the chemical equilibration between solid and liquid layers. When $\Phi \ll 1$, 50% of chemical equilibration can be reached in few kyr to 1 Myr. If $\Phi \gg 1$, 50% of chemical equilibration is reached in $10^2 - 10^3$ Myr.

# References

[1] Labrosse, S., Hernlund, J. W. and Coltice, N., A crystallizing dense magma ocean at the base of the Earth's mantle. Nature, 450(7171):866–869, 2007.

[2] Deguen, R., Thermal convection in a spherical shell with melting/freezing at either or both of its boundaries. Journal of Earth Science, Vol. 24, No. 5, p. 669–682, 2013.

[3] Tackley, P. J. Modelling compressible mantle convection with large viscosity contrasts in a three-dimensional spherical shell using the yin-yang grid. Phys. Earth Planet. Inter., 171(1-4): 7–18, 2008.