Numerical convection modelling of a compositionally stratified lunar mantle

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Introduction

Full Moon convection models of lunar interior evolution are usually simplified in their compositional setup. They are often purely thermal convection-diffusion models, using a homogeneous mantle composition and a heat reservoir to model the core [1, 2].

Other models add only an ilmenite-rich layer at shallow depth [3, 4]. When this compositionally distinct and relatively dense layer is used, the focus is typically on the overturn of the lunar mantle, due to the gravitational instability which originated from the crystallisation of an early lunar magma ocean.

In this study, we investigate compositionally more complex models. The initial configuration of our models has a both mineralogically and geochemically layered composition, to determine the influence of a more realistic mantle stratification on mantle dynamics and the thermal evolution of the Moon.

Lunar Magma Ocean crystallisation

It is generally assumed that the Moon accreted as a hot planetary body (independent of which process led to Moon formation). The Moon then consisted of a global magma ocean, which crystallised upon cooling. Calculations and experiments on this crystallisation process show that the result was a layered mantle, covered by a plagioclase flotation crust [5, 6]. The last material to crystallise at shallow depth below this crust was a layer rich in high density ilmenite ($FeTiO_3$) [5]. Figure 1 schematically shows this layering due to magma ocean crystallisation. The high density ilmenite-rich layer at shallow depth was gravitationally unstable and this likely resulted in an overturn of the lunar mantle.

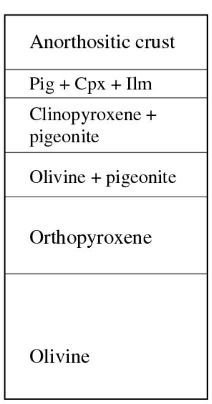


Figure 1: Layered mantle, resulting from the crystallisation of the Lunar Magma Ocean. (After Snyder et al. [5])

Another process which takes place during magma ocean crystallisation is fractionation of trace elements. Depending on their size and charge, elements will either fit well into a crystal lattice or prefer to remain in the coexisting melt. This process concentrates large and highly charged elements into the last remaining liquid. The heat producing elements thorium, uranium and potassium are examples of the socalled incompatible elements, resulting in a higher internal heat production in the later crystallising layers.

Ilmenite and mantle overturn

The dense ilmenite-rich layer, which crystallised at shallow depth beneath the crust, has previously been included when modelling the formation of the titanium-rich basalts found at the lunar surface [3] and to study the possible formation of an ilmenite-rich core in the lunar interior [4].

However, the compositional layering in the mantle underneath the ilmenite-rich layer is usually neglected and a constant background composition is used in the modelling instead. The deeper layering is likely to at least influence the timing of the overturn, but also the general dynamics. Therefore, this study investigates the influence of a more realistic mantle stratification on the overturn of the lunar mantle, using multi-component thermo-chemical convection models. Furthermore, the

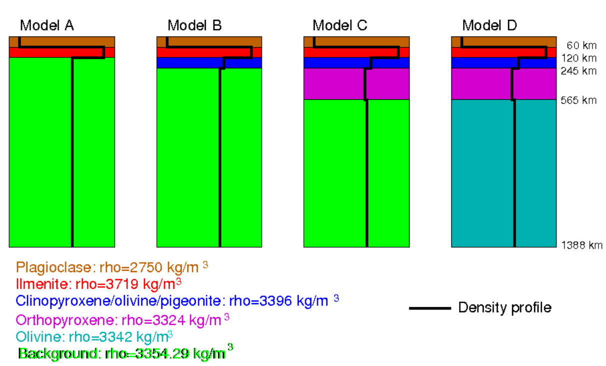


Figure 2: Initial setup of the models with different numbers of layers

influence of composition dependent heat production is studied, investigating the influence of trace element fractionation during magma ocean crystallisation on lunar mantle overturn.

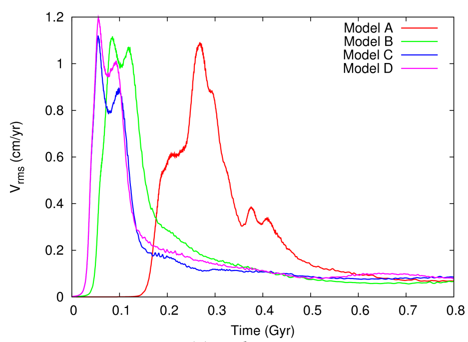
Modelling

Thermo-chemical convection modelling experiments were performed, using a 180° cylindrical finite element mesh. The convection equations for an incompressible, infinite Prandtl number fluid were solved using an extended Boussinesq approximation, which includes both viscous dissipation and adiabatic heating. Composition is described using tracer particles, advected by the flow.

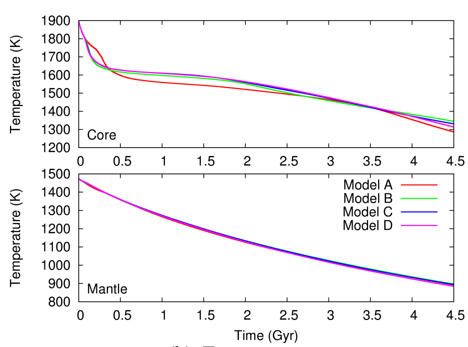
Four different initial setups are used in our compositionally layered models. These four initial setups, labeled A, B, C and D, are shown in figure 2. Starting from an initial model with only the crust and the ilmenite-rich layer, more compositionally distinct layers are added in the next models.

Results and discussion

The preliminary results in figure 3 show that mainly the relatively dense clinopyroxene-rich layer, directly underneath the ilmenite-rich layer, greatly influences the evolution of the overturn velocity of the mantle with time



(a) *Velocity*



(b) *Temperature*

Figure 3: Preliminary results, layered models with a homogeneous heat production

(fig. 3a). The main period of overturn shifts to earlier times upon the addition of each subsequent layer. In contrast, temperature evolutions of both core and mantle do not seem to be largely influenced by the compositional layering in these preliminary calculations (fig. 3b). However, including composition dependent heat production will very likely change this result.

Conclusions and outlook

We conclude from our initial modelling that the more realistic initial layering and the composition dependent heat production influence the timing and dynamics of lunar mantle overturn and associated basalt production.

At the meeting we will present results of the inclusion of composition-dependent heat production in the models. Heat production for each layer is calculated from a crystallisation sequence for the lunar magma ocean as calculated by Snyder et al. [5], crustal anorthite concentrations of Th, U and K [7] and literature partition coefficients for the radioactive elements between melt and lunar minerals.

Acknowledgements

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