Thermochemical modeling of the lunar mantle - Effects of an initially layered composition

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The Moon was initially covered by a global magma ocean as a consequence of the Moon-forming impact. Upon cooling, the magma ocean underwent fractional solidification, which led to an initially layered composition in the lunar mantle. The aim of our work is to investigate the effects of the layered initial mantle composition on the convection and the subsequent melting of the lunar mantle.

In our work we use the mantle convection code GAIA [1] to model the thermochemical evolution of the Moon. We consider a compositionally heterogeneous mantle and compare our results with a homogeneous lunar mantle scenario. For both scenarios (i.e., homogeneous and heterogeneous mantle), we use a petrological model [2] to calculate the initial density, solidus and liquidus curves, density change due to depletion, and, in case of a heterogeneous lunar mantle, the initial temperature profile and the initial layered structure. Our models use a 2D quarter cylinder geometry. We employ an Arrhenius law to calculate the temperature and depth dependent viscosity, and we account for core cooling, radioactive decay, and mechanical mixing. The mantle composition is tracked via a particle-in-cell method [3], where tracer particles carry information about material properties such as density, melting temperature, degree of depletion, and amount of heat producing elements. We account for latent heat consumption during melting and consider both the increase of solidus and the changes in density of the residual material due to mantle depletion. Our models track the timing of the melting events and how much of the components melted.

We calculate the amount of secondary crust produced during the evolution and require that successful models fit the present-day secondary crust thickness with values between 2 and 10 km. This range accounts for basaltic lava flows that comprise less than 1% of today's crust [4] and the Mg-suite rocks, that account for about 6% to 30 %, though recent findings show that at least some rocks of the Mg-suite originated from impact melts [5].

Our results show that a model with a homogeneous initial mantle composition either produces too much crust to match today's estimates, or needs a very cold initial temperature profile, which is unlikely to be established from a solidifying magma ocean, and then produces melt too late to match the ages of the Mg-suite rocks. The heterogeneous models can match the estimates when at least part of the IBC layer takes part in the mantle convection.

References [1] Hüttig C. et al. (2013) PEPI; [2] Schwinger S. and Breuer D. (2021) PEPI; [3] Plesa A.C. et al. (2013) IGI Global; [4] Head J.W. (1976) Rev. Geophys.; [5] White L. F. et al. (2020) Nature Astron.

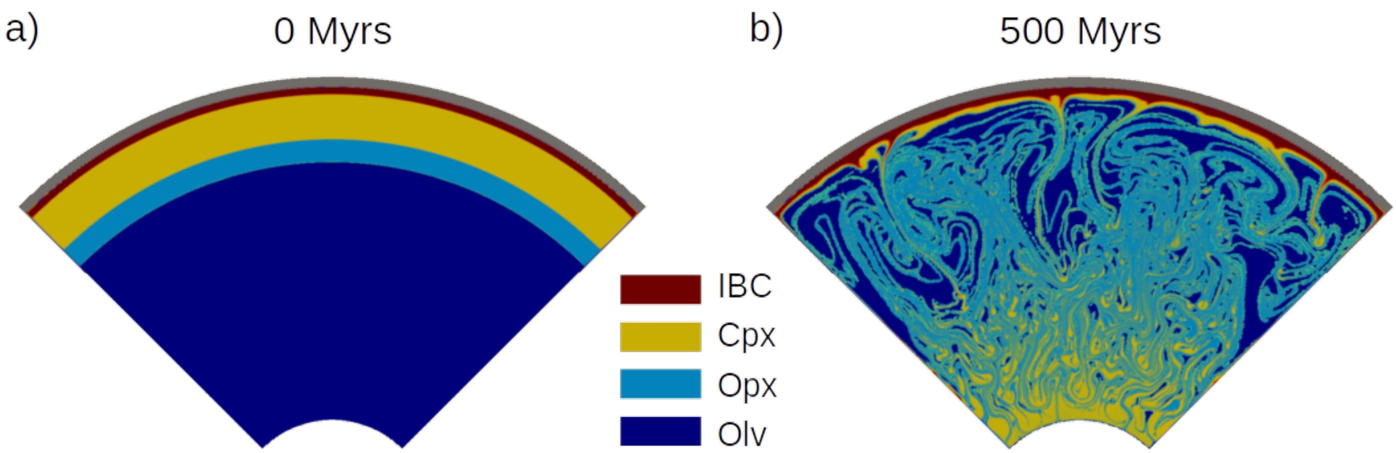

Figure 1: Convection in an initially layered lunar mantle. In panel a) the initial layered composition is shown (using the density field) directly after the solidification of the lunar magma ocean, whereas in panel b) the same case is shown 500 million years later. The models use an anorthositic crust with a low thermal conductivity of 2 $\mathrm{W\,m^{-1}K^{-1}}$ and four mantle compositional layers (top to bottom): IBC = ilmenite bearing cumulates; Cpx = clinopyroxene rich cumulates; Opx = orthopyroxene rich cumulates, Olv = Olivine rich cumulates. The figure is shown to illustrate the convection in a multilayered lunar mantle in a case where IBC takes part in the convection.