The formation and evolution of a lunar core from ilmenite-rich magma ocean cumulates.

J. de Vries[1,2], A.P. van den Berg[1], W. van Westrenen[2], [1]Faculty of Geosciences, Utrecht University, Budapestlaan 4, Utrecht, The Netherlands (jdevries@geo.uu.nl), [2] Faculty of Earth and Life Sciences, VU University Amsterdam, De Boelelaan 1085, Amsterdam, The Netherlands

Introduction: The size and composition of the lunar core are still debated. It has been suggested that a dense ilmenite-rich layer, which originally crystallized near the top of the lunar magma ocean, may have sunk to the center of the Moon to form either a complete lunar core or an outer core surrounding a metallic inner core[1].

The second model seems more likely since this model combines the requirements for a lunar magnetic field, caused by an early dynamo in the lunar interior (requiring a electrically conductive core) with the fact that ilmenite is too dense to remain at shallow depths after crystallization. However, it is difficult to explain how a dynamo could have existed in a small, quickly cooling body like the Moon. If the magnetic remanence in lunar samples is due to impact magnetism or to interaction of the lunar surface with the solar wind[2] no metallic core is needed and an ilmenite-rich (metal-free) core is a possibility. In this study the formation and stability of both options (ilmenite-rich core and outer core) have been investigated with thermo-chemical convection models.

Model description: A numerical thermo-chemical convection model with a 2D cylindrical geometry was used, in which the convection equations are solved on a finite element grid. The relevant compositions (ilmenite-rich material and homogeneous background material) are modelled using tracers, that are advected by the flow.

Most planetary convection models assume a constant gravity acceleration in the planetary mantles. However, in the Moon, gravity acceleration decreases quickly with depth (Figure 1) due to the much smaller core mass fraction for the Moon, $X_c \approx 0.01$–0.04 versus $X_c = 0.315$ for Earth. Initial model tests showed that the decrease of the gravity acceleration towards the centre of the model significantly altered the buoyancy of different materials. This becomes clear from the buoyancy term in the momentum equation, which is multiplied by the gravity acceleration. Since the buoyancy in the centre of the model is a crucial parameter in our core formation models, the low gravity acceleration in the centre was explicitly taken into account.

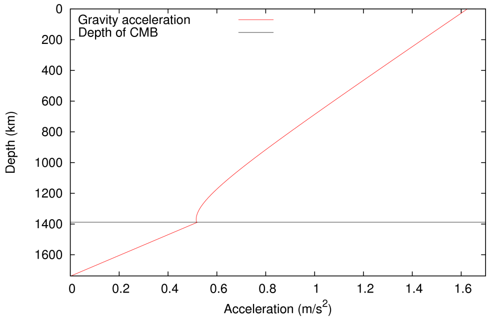


Figure 1: *Figure showing the decrease of the gravity acceleration with depth for a model with an Fe-FeS core with a radius of 350 km.*

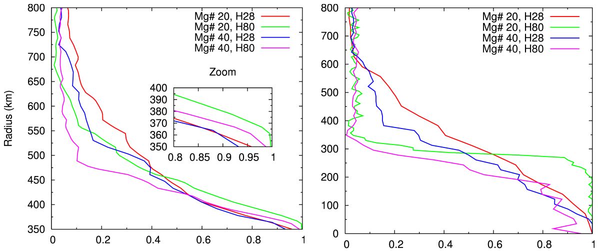
Models: We have investigated core stability by varying two parameters: density contrast and internal heat production. The density of the ilmenite-rich layer is varied, resulting in different density contrasts with the background material. The density of the ilmenite-rich layer depends largely on the Mg# (Mg#=100*Mg/(Mg+Fe)) of the minerals in this layer (mainly clinopyroxene and ~5 wt.% ilmenite). A lower Mg#, results in higher densities, since iron is heavier than magnesium. Snyder et al.[3] in their calculations of the crystallization of the lunar magma ocean showed that the Mg# varies between about 40 and zero during the crystallization of ilmenite. In our models, calculations are done for Mg# 20 and 40.

The internal heat production due to the decay of radioactive isotopes of K, U and Th is used as a free parameter. The concentration of radioactive elements as a function of depth in the Moon is not well constrained. During the crystallization of the magma ocean most radioactive elements must have concentrated in the last crystallizing layers, since they are incompatible in the earlier cumulates. Two different radioactive element distributions are used in our models. The concentration in the background material is preserved between models. The concentrations in the plagioclase-rich crust and the ilmenite-rich layer are varied. The bulk concentration is kept constant in all models.

Varying these two parameters changes the compositional and thermal buoyancy of the dense layer. These two effects counteract: a higher internal heating in the ilmenite-rich material results in a smaller density contrast, while a higher density results in a larger density contrast. Therefore these two parameters are studied seperately.

Results: Figure 2 shows the average composition as a function of radius for a model with and a model without a metallic inner core.

The final core density depends on the Mg# and the internal heating. A higher density (lower Mg#) of the ilmenite-rich layer results in a core density closer to the density of the ilmenite layer. If the ilmenite-rich layer is less dense, more mixing with background material takes place in the core and the relative density is lower.



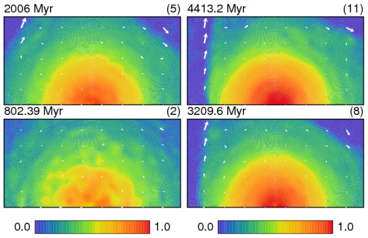
(a) *Metallic inner core* (b) *No inner core*

Figure 2: *Composition profiles of four models with varying Mg# and internal heating (H28 models have an initial heat production rate of 26×10^{-12} W/kg in the ilmenite-rich layer, in the H80 models this heat production is about 3 times larger). Composition is shown as a dimensionless density. Composition 1 corresponds to the density of the ilmenite-rich layer, composition 0 corresponds to the background density. This way the core density of models with different density for the ilmenite-rich layer can directly be compared. The increasing core density for higher ilmenite density or higher internal heating is shown in the zoomed in figure.*

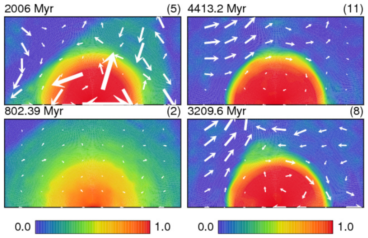
Interestingly, higher internal heating in the ilmenite-rich layer (models H80) also results in a relatively denser core. This is caused by the fact that the high internal heating results in high temperatures and therefore low viscosities. Due to these low viscosities, material moves faster and core formation takes less time. This means that there is less time for the ilmenite-rich material to mix with background material.

This same effect also influences the sharpness of the core-mantle boundary. Lower internal heating results in a more gradual core-mantle boundary. This can be seen from figures 2b and 3. Lower internal heating results in lower temperatures and higher viscosities. Therefore, slower sinking and more mixing, resulting in a gradual core-mantle boundary.

A further interesting result from these models is that the temperature of a metallic inner core between models varies about 700 degrees maximum (around 2 Gyr after the start of the models), but only about 300 degrees after 4.5 Gyr. This temperature difference is significant if one wants to determine whether the lunar core could be fluid at present day temperatures.



(a) *Low internal heating (H28)*



(b) *High internal heating (H80)*

Figure 3: *Compositional snapshots for models with contrasting heat production in the ilmenite-rich layer*

Conclusions: Results from this study show that a stable ilmenite-rich (outer) core may indeed have formed in the lunar interior. The size and density (relative to the density of the ilmenite-rich layer) of this core depend on the internal heating in and the Mg# of the ilmenite-rich layer. A summary of these results is shown in figure 2a. Furthermore, the sharpness of the core-mantle boundary depends on the internal heating in the ilmenite-rich material (Figures 2b and 3).

Future research: To further study the possibility of an ilmenite-rich core, stronger constraints on the distribution of radioactive elements are needed. This requires experimental measurements on the partition coefficients of these elements between lunar minerals and melts. Further narrowing of the range of internal heating values is important since it has a direct impact on the present day core temperature and (solid/liquid) phase.

References: [1] P.C. Hess and E.M. Parmentier. *Earth Planet. Sci. Lett.*, 134:501–514, 1995. [2] N.C. Richmond and L.L. Hood. *J. Geophys. Res.*, 113:E02010, 2008. [3] G.A. Snyder, L.A. Taylor, and C.R. Neal. *Geochim. Cosmochim. Acta*, 56:3809–3823, 1992.