EPSC Abstracts
Vol. 6, EPSC-DPS2011-798-1, 2011
EPSC-DPS Joint Meeting 2011

Cooling of an early Earth magma ocean in interaction with the atmosphere

T. Lebrun (1), H. Massol (1), E. Marcq (2), F. Leblanc (2), G. Brandeis (3), A. Davaille (4), P. Sarda (1) and E. Chassefière (1)
(1) IDES/CNRS/Univ. Paris-Sud, France (2) LATMOS/CNRS/Univ. of Versailles St-Quentin, France (3) IPGP, Univ. Paris 7, France (4) FAST/CNRS Univ. Paris-Sud, France
(Thomas.lebrun@u-psud.fr / Fax: +33 (0)1-69-15-49-05)

Abstract

We developed a 1D convective model of a cooling magma ocean that we coupled with a 1D radiative-convective model of a primitive atmosphere [4]. Our main objective is to estimate the cooling time when the retroaction with the atmosphere is taken into account. We first describe our model and present some preliminary results of the coupled magma ocean / atmospheric model. We show that cooling time depends on the amount of volatiles released from the interior and is of order of 1 to 2 million years.

1. Introduction

It is likely that a magma ocean has formed early in the Earth history and in particular just after the big impact that is thought to have formed the Moon 4.48 Ga ago [3]. This magma ocean interacts with the atmosphere through degassing upon crystallization. Hence a strong coupling should exist between the two envelopes (atmosphere and cooling magma ocean). Our objective is to build a coupled model of a cooling magma ocean interacting with a primitive atmosphere, in turn, allowing for an estimation of the cooling time of the magma ocean. The model will be coupled in the near future with an impact and hydrodynamic escape model. Subsequently, this will enable us to determine the time required for the primitive atmosphere to condense its water vapor thus determining the period during which the water oceans may have formed.

2. Model

2.1 Model of the magma ocean

We consider that the magma ocean is in a soft turbulence regime [5] above a liquid mass fraction~0.4. Potential and surface temperatures evolve with time according to experimental parameterization of the heat flux released [5]. At the initial stage we assume a completely molten magma ocean with a potential temperature of about 3000K [1]. We consider that the magma ocean crystallizes from the bottom [2]. We are aware that a solid lid may form at the surface but we neglect it at present, considering that strong convective motions below the lid prevent its formation. Magma ocean is divided into three zones: a zone completely solidified, a transition zone of liquid mass fraction above 40% and a liquid zone [5]. The last two zones undergo of convective motions, whose intensity is considered the same. Indeed, we ignore the effect of solid particles on convection in the transition zone. As crystallization proceeds, the magma gets enriched in dissolved volatiles. Considering the relative time scales of degassing and cooling we assume that degassing is almost instantaneous regarding solidification time scale (~1Ma) [2].

2.1 Coupling

Our model is coupled with the atmospheric model presented in [4] that takes into account several layers and convection. Convective heat flux from the magma ocean must be in balance with heat loss through the atmosphere. We developed an iterative scheme with surface temperature and volatile content being the input for the atmospheric model and with the outgoing heat flux from [4] being a boundary condition for the magma ocean part of the model. Partial pressures depend on the mass fractions of volatiles dissolved in the magma ocean.

3. Preliminary Results

The cooling time scale of the magma ocean up to a melt fraction of 0.4 is about 1 million years (Figure1) with an initial amount of volatile of 0.02 wt% CO_2 and 0.1 wt% H_2O. This result is similar

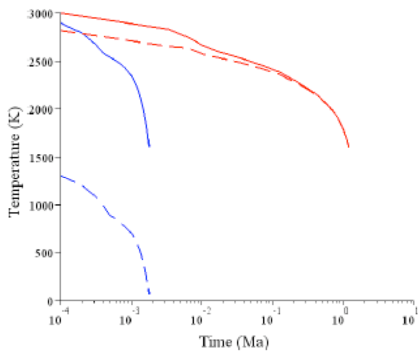

Figure 1: Temporal evolution of potential (Solid line) and surface (Dash line) temperature of the magma ocean with (red line) or without (blue line) interaction with the atmosphere.

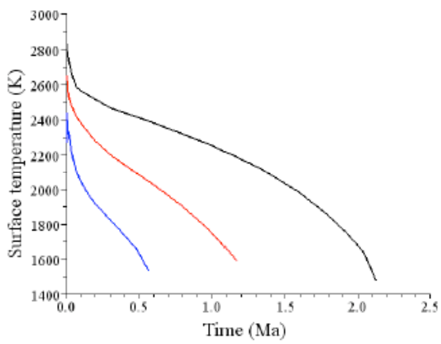

Figure 2: Temporal evolution of surface temperature of the ocean magma in interaction with the atmosphere for different amount of initial volatile. (Blue line) 0.01 wt% CO_2 and 0.05 wt% H_2O. (Red line) 0.02 wt% CO_2 and 0.1 wt% H_2O. (Black line) 0.04 wt% CO_2 and 0.2 wt% H_2O.

to the results obtained by Elkins-Tanton (about 3 million years to solidify 98% of the magma ocean) [2]. Without atmosphere (blackbody heat flux), the magma ocean cools about 1000 times more quickly. Also an increase of initial volatile dissolved in the magma ocean leads to increase the cooling time (Figure 2). For instance, if one doubles the amount of initial volatile the cooling time is almost twice as long. During cooling, crystallization enriches the melt phase in volatiles. This in turn leads to enrich the early atmosphere in volatiles thus reducing the cooling time.

4. Perspectives

We presented a first coupling between our simple model and the 1D convective radiative atmospheric model [4]. In the near future, improvements coming from the laboratory heat fluxes scaling laws and crystallization dynamics are expected. In addition, a coupling with a hydrodynamic escape and impact model is envisioned in order to take into account the escape of some part of the volatiles into space, and the contribution of volatiles and heat deposition by impacts. Ultimately, this coupled model will be able to be applied to other planets that the early Earth and thus allow the understanding of phenomena hitherto unexplained.

Acknowledgements

The authors acknowledge PNP 2011 for financial support.

References

[1] Abe Y 1997 Thermal and chemical evolution of the terrestrial magma ocean. Phys. Earth Planet. Int. 100, 27-39.

[2] Elkins-Tanton, L.T., Parmentier, E.M., Hess, P.C., 2003. Magma ocean fractional crystallization and cumulate overturn in terrestrial planets: implications for Mars. Meteorit. Planet. Sci., 38, 1753–1771.

[3] Halliday, A., N., 2008. A young Moon-forming giant impact at 70–110 million years accompanied by late-stage mixing, core formation and degassing of the Earth. Phil. Trans. R. Soc. A (2008) 366, 4163–4181.

[4] Marcq. E and al., An atmospheric model designed for integration into coupled models of magma ocean planets, this conference

[5] Solomatov, V.S., 2000. Fluid dynamics of magma oceans. In: Canup, R., Righter, K. (Eds.), Origin of the Earth and Moon. Univ. of Arizona Press, Tucson, pp. 323–338.