

MODELING THE TRACE ELEMENT COMPOSITION OF THE MOON'S SECONDARY CRUST.

L. Allibert¹, S. Schwinger², I. Bernt², T. Wiesehofer³, C. Haupt³, J. Schmidt⁴ and A-C. Plesa². ¹ Museum für Naturkunde, Berlin, leibniz Institute (*Laetitia.allibert@mfn.berlin*), ²German Aerospace Center (DLR), Berlin, ³Institut für Geophysik/ Institut für Mineralogie, University of Muenster, ⁴Institute of Geological Sciences, Freie Universität Berlin.

Motivation: The Moon's formation is thought to have arisen from a giant collision between a Mars-sized body and the growing proto-Earth. The pieces of debris ejected during this large, energetic collision are considered to be the building blocks of the Moon as it is today. It is widely accepted nowadays that such a violent event may have led to large-scale melting so that the early Moon was fully covered by a global magma ocean. As a result, the Moon's primitive mantle may have differentiated into chemically distinct layers upon cooling. This has been suggested as soon as the first samples from the Apollo missions were returned, as it could explain many geological and geochemical features of the Moon (e.g. [1], [2], [3], [4]). Notably, the existence of both a feldspathic crust and mafic cumulate mantle could be the direct result of such a past lunar magma ocean (LMO). In particular, the mantle is seen as the result of the sinking of the cumulates of the first materials to crystallize when the LMO started cooling. These are mafic minerals such as Mg-rich olivines and pyroxenes. This left a magma ocean enriched in iron, from which aluminum- and calcium-rich minerals started crystallizing, forming plagioclase [5]. These are less dense than the surrounding melts and would have floated up to the Moon's surface and agglomerated to form the feldspathic Al-Ca-rich crust (ferroan anorthosite rock suite: FAN). The residual melt continued to crystallize and became accordingly more and more enriched in the more incompatible elements such as the KREEP (K, REE & P) and iron. There could have been a sufficient amount of heat-producing elements in this most recently formed layer to cause renewed melting of the lunar mantle. These younger magmas are thought to be responsible for the formation of the secondary crust lithologies (basalts), which is characterized by Mg-rich minerals as well as by an enrichment in alkali elements. This model suggests that this secondary crust formed the Mare basalts observed at the lunar surface. The Mare basalts chemical composition indeed suggests a post FAN formation (especially considering their large depletion in europium (Eu) compared to other trace elements (REEs) since Eu^{2+} fits perfectly into Ca-site)[4].

This LMO model is still the reference model today. However, in the light of new analyses of Apollo samples with improved analytical methods, the single floatation event has been challenged. The exact extent

of the Moon's differentiation and the physical processes responsible for forming the lunar crusts are still somewhat poorly constrained. Amongst them, the cause for the critical difference between rocks on the nearside and farside of the Moon is still unknown. Another unresolved question concerns the relationship between the depth of melting and melt compositions that are required to form the Mare basalts. Ultimately, the composition of lunar rocks from surface measurements and Apollo samples need to be combined with a model of the Moon's interior dynamics in order to gain further insight on the evolution of the lunar primitive mantle.

In this study, we explore the formation of the secondary crust from mantle melting events initiated during its solid-state convection. Selected rare earth elements are tracked during these melting events and their resulting abundances in the secondary crust are computed. The results are discussed with natural trace element contents of Mare basalts.

Modeling approach: An initial petrological and chemical mantle composition is assumed. We consider a heterogeneous lunar mantle as formed after fractional crystallization of the LMO [6] using the bulk lunar mantle composition of [7] with an FeO content of 10 wt% as suggested in [6]. In this setup, the mantle is described by four distinct layers of different densities and compositions. We used alphaMELTS to calculate solidus and liquidus temperatures of the four mantle layers, including their change in fertility with increasing degree of melting. However, for simplification, each layer itself is assumed to be homogeneous in bulk oxides composition and mineral phases.

A geodynamical thermal evolution model calculates the solid-state convection and secondary melting events as described in [8]. The code GAIA [9] is used to track the melting events over time. The code uses as inputs the layering and melting temperatures, and implements their changes according to the petrological model described above. For each melting event that occurs during the long term evolution of the lunar mantle, we record the melt fraction, the time at which it occurred, the mineral phases involved, as well as the melting pressure and temperature.

These melting event data are post-processed to determine the evolution of the secondary crust's chemical composition. A simple box-model is used to

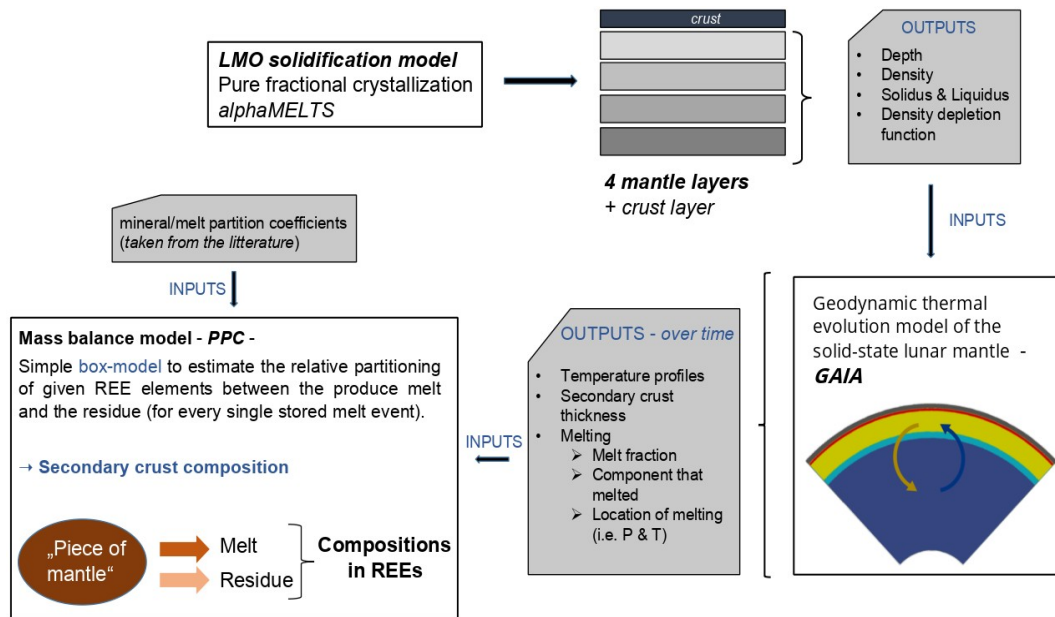


Figure 1. Flowchart illustrating the method used in this study. Different models are coupled to follow the partitioning of REEs between the different lunar crust/mantle layers as a function of time from the LMO solidification up to the secondary crust formation by further remelting induced during solid-state mantle convection.

provide the mass balance for the given compositions. Rare earth element partition coefficients of minerals and bulk layers implemented in the geodynamical thermal evolution model enable the modeling of REE abundances in the basalts (REE: La, Sm, Nd, Eu, Lu), which originate from these secondary melting processes. Suitable partition coefficients to describe the fractionation of the selected elements between minerals and remaining melt were chosen from literature (e.g., [10], [11], [12]).

Expected Outcome: We will present a unique framework to interpret the composition of REE in the Moon's secondary crust. Our approach is highly multidisciplinary and combines thermodynamic investigations to model the LMO crystallization sequence, modelling of the interior dynamics and partial melting of the solid state lunar mantle, and calculations of the REE abundances in secondary melts by employing appropriate partition coefficients.

We expect to enhance the current understanding of the petrogenesis of Mare basalt by combining current state of the art computational approaches. For instance, the REEs pattern of the secondary crust as acquired from the partial melting of the mantle at given depths will be compared to the known lunar samples REEs pattern. By doing this, we will be able to infer whether a chemical signature appears missing from the melt composition produced in our models with respect to natural Mare basalt samples. In particular, the discrepancy between the model-produced melt and the

Mare basalt samples could provide insights on the chemical contribution from individual mantle layers as inferred from their REEs pattern. According to the required contribution from different mantle layers to fit the data, the role of a mantle overturn or, of some degree of assimilation during melt extraction, as the melt rises from its source to the surface, can be discussed.

With our multidisciplinary approach we will contribute to the ongoing debate about long-lasting volcanic activity on the Moon and provide implications for melting processes in the lunar interior (e.g. [13]).

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References: [1] Smith J. A. et al. (1970) *GCA*, 1, 897-925. [2] Wood J. A. et al. (1970) *GCA*, 1, 965-988. [3] Hartmann W. K. and Davis D. R. (1975) *Icarus*, 24, 504-515. [4] Warren P. H. (1985) *Annual review of planet. Sciences*, 13, 201-240. [5] Snyder et al. (1992) *GCA*, 56, 3809. [6] Schwinger S. and Breuer D. (2022) *Physics of the Earth and Plan. Interiors*, 322, 106831. [7] O'Neil H. S. C. (1991) *GCA*, 55, 1135-1157. [8] Bernt I. et al. (2022) *EPSC*, Abstract #2022-646. [9] Hüttig C. et al. (2013) *Physics of the Earth and Planetary interiors*, 220, 11-18. [10] Dygert N. et al. (2014) *GCA*, 132, 170-184. [11] Sun C. and Liang Y. (2013a), *GCA*, 119, 340-358. [12] Klemme, S. et al. (2006), *Chemical Geology*, 234, 251-263. [13] Che X. et al. (2021) *Science*, 10.1126/science.abc17957