

TRACE ELEMENT EVOLUTION OF THE LUNAR MAGMA OCEAN, THE ORIGIN OF KREEP, AND THE INFLUENCE OF GARNET C. R. Neal¹ and J. D. Davenport^{1,2}, ¹Dept. of Civil and Env. Eng. & Geological Sciences, University of Notre Dame, Notre Dame, IN 46556, USA; ²Centre de Recherches Petrographiques et Geochimiques, Vandoeuvre-les-Nancy, France 54501 (neal.1@nd.edu; jessedvnprt@gmail.com).

Introduction: The lunar magma ocean (LMO) hypothesis [1-3] forms the basis of our understanding of the initial differentiation of the Moon and the formation of the lunar crust and mare source region. The incompatible element rich component KREEP represents the last dregs of LMO crystallization ($\geq 99\%$ crystallization). However, there are still many questions regarding the LMO hypothesis that are unresolved: 1) what was the initial LMO composition? 2) How deep was the LMO? 3) How long did the LMO take to crystallize? In this presentation we assume the LMO was deep enough to stabilize garnet and we examine the effect of this phase on the REE evolution during crystallization and the production of KREEP.

Approach: We examine the rare earth element (REE) evolution of the LMO using the initial composition of [4] and an initial depth of 1000 km [5]. We examine LMO evolution initially using the crystallization sequence and bulk composition of [4]. This approach is expanded to the more aluminous Taylor Whole Moon (TWM) composition, and uses the SPICES programs [6,7] to define crystallization parameters for this and other LMO bulk compositions. The goal of this study was to examine the origin of KREEP and to explore the effect of garnet on the REE evolution of the LMO, assuming it was a primary crystallization phase of the LMO. Using a LMO depth of 1000 km will allow garnet to stabilize, assuming the bulk composition contains a high enough Al_2O_3 content to permit the stabilization of an Al-rich phase. The presence of garnet in the lunar mantle has been hypothesized on the basis of thermodynamic and seismic considerations [8-10] as well as inferred from sample data [11].

Model Parameters: The initial approach uses the partition coefficients reported by [4] in order to recreate the REE evolution of the LMO as presented by [4]. It is recognized that work on trace element partitioning has certainly advanced since the model of [4] was published. For example, the partitioning of trace elements into plagioclase is controlled by the Anorthite content (e.g., [12-14]). Predictive models have been produced to calculate partition coefficients for plagioclase based on An content (e.g., [15]).

Parameterized models for calculating REE partition coefficients have also been produced for low-Ca pyroxene [16,17] and clinopyroxene [18]. The SPICES programs produce the compositions of crystallizing phases that can be used to calculate partition coefficients for these phases. For olivine, the partition coefficients are so low those used in [4] are used here. A similar situation is assumed for ilmenite.

For garnet, predictive models and experimental data have been produced [19-23]. We use these partition coefficients here rather than those reported by [24], which were produced on high-Ti compositions.

Finally, garnet is the aluminous phase that is assumed to crystallize below 500 km and plagioclase is the shallow aluminous phase. Results are compared to the high-K KREEP composition [25]. As we do not crystallize garnet until after 78 PCS, the amount will be relatively minor compared to plagioclase due to the fact that the mantle below 500 km will be already dominated by the already crystallized olivine and orthopyroxene.

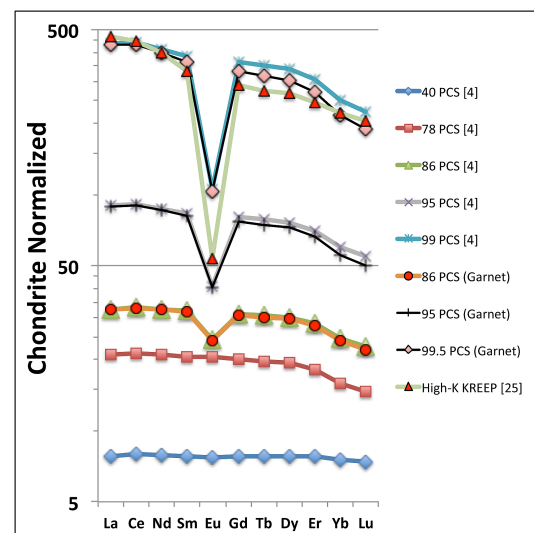


Figure 1: Chondrite normalized [27] REE plot recreating the LMO crystallization model of [4] and showing the effect of garnet on the latter stages when the aluminous phases are crystallizing. 1.5% garnet is used in the model presented here.

Results and Discussion: This work is based on the results presented at this conference by [26].

The modeling results are presented in Figure 1. These results use 1.5% garnet crystallizing beyond 78 PCS (i.e., when the aluminous phase is on the liquidus) for the model of [4]. The bulk composition of [4] contains 5.0 wt% Al_2O_3 . The TWM composition contains 6.0 wt% Al_2O_3 [28], whereas other estimates suggest 8.2 wt% Al_2O_3 in the initial LMO composition [3,29]. The more aluminous the initial LMO composition, the early aluminous phases would start to crystallize (as verified by SPICES). These observations have to be reconciled with the results of the recent GRAIL mission [30], where the results indicate that the Moon is not enriched in refractory elements. The GRAIL data support a bulk Moon Al_2O_3 abundance of ~4 wt%. However, while the Al_2O_3 content of the crust is reasonably well known, that of the middle and lower mantle are relatively unknown because estimates rely on Apollo seismic data and a mineralogic model to explain such data (e.g., [8-10]). The resolution of Apollo seismic data below 500 km is relatively poor, which produces to a variety of estimates of the Al_2O_3 content of the middle and lower lunar mantle. The required resolution of lunar seismic data will not be available until a global lunar seismic network is established. Fortunately, such a network is a named New Frontiers mission in the current Planetary Sciences Division Decadal Survey [31].

Summary & Conclusions: Crystallization of the LMO that encompasses garnet at relatively minor levels (1-5%) yields results that are consistent with hypothesized KREEP compositions produced after 99% crystallization. We have explored a number of bulk LMO compositions and garnet crystallizing at $\leq 5\%$ produces results consistent with KREEP. The lack of knowledge about the lunar interior severely hampers our understanding of lunar magma ocean evolution, as well as better understanding the mare source regions. The next major advance in our understanding of lunar differentiation and the evolution of the LMO will only come from establishing a long-lived (decadal) and global lunar seismic network.

Future Work: Modeling and experimental crystallization studies continue to make progress in our understanding of LMO evolution (e.g., [32-34]). However, in order to take modeling efforts to the next level, detailed knowledge of element partitioning under lunar conditions is a necessity. In particular, understanding the partitioning behavior of Fe-rich systems,

particularly for pyroxenes, will be essential to understand the nuances of magma evolution and element distribution within the Moon. The effects of crystallization with pressure also need to be better quantified.

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