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Distribution of heat producing elements during crystallisation of the Lunar Magma Ocean

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Abstract

The spatial and temporal distribution of the main heat producing elements (K, U, Th) in the lunar mantle and crust strongly influence the thermo-chemical evolution of the lunar interior. Combining surface measurements of Th, U and K concentrations with petrological models of the crystallisation of the Lunar Magma Ocean and mineral-melt partition coefficients for these elements can give more information about their interior distribution. We have performed high-temperature and high-pressure experiments to constrain the partitioning of U, Th and K between plagioclase and co-existing melt to fill a significant gap in available data. Our data can be used to model the spatial and temporal distribution of heat producing elements in the lunar interior, which in turn improves numerical models on lunar thermal and chemical evolution.

1. Introduction

It has been shown that the thermo-chemical evolution of the lunar interior is strongly influenced by the internal distribution of heat producing elements in the lunar mantle and crust[1]. The concentrations of the main heat producing elements (K, U and Th) in the Moon are relatively poorly constrained. As detailed below, data from surface measurements of Th, U and K abundances, combined with a crystallisation sequence of the Lunar Magma Ocean (LMO) and mineral-melt partition coefficients of the radioactive elements between magma and the different lunar minerals, can in principle be used to model the total amount and distribution of Th, U and K. To date this approach has been hampered by the lack of accurate mineral-melt partition coefficients for most of the main minerals involved in LMO crystallisation. Here we present new experimental data for the partitioning of heat producing elements between plagioclase (the main lunar surface mineral) and co-existing melt, allowing for a new estimate of the Moon's thermal budget.

2. LMO crystallisation

Petrological modelling of the crystallisation of the LMO shows that this proces resulted in a layered mantle[2]. This sequence is shown in figure 1. During fractionation of minerals from the magma ocean, trace elements were partitioned between the different layers, depending on their constituent mineral-melt partition coefficients. Elements with generally low partition coefficients (so-called incompatible elements) will preferentially concentrate in the melt and end up being enriched in the last crystallising layers. The heat producing elements Th and U are generally very incompatible, whereas K usually has a higher partition coefficient, but is still incompatible in most minerals[3].

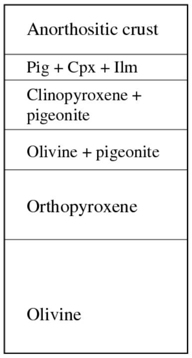

Figure 1: Compositionally layered mantle after crystallisation of the LMO. (After [2])

3. From surface measurements to interior distribution

Once the crystallisation sequence of the LMO and partition coefficients for the heat producing elements into the lunar minerals are known, the last parameter needed for the calculation of the distribution of each specific element is the concentration of this element in one of the layers. This is where surface measurements come into play. The distribution of Th, U and K concentrations on the lunar surface have been measured by the Lunar Prospector and Kaguya missions (e.g. [4, 5]). Using these concentrations in the plagioclase-rich highland areas as concentrations for the top layer in the crystallisation sequence (Figure 1), concentrations for the other layers can in principle be calculated.

Unfortunately, plagioclase-melt partition coefficients for these elements are either very scattered or scarce[3], largely due to the fact that plagioclase is not considered as a significant reservoir of heat producing element in terrestrial systems.

4. Experiments

To fill the gap of missing partition coefficients of radioactive elements between plagioclase and melt, high-temperature and high-pressure partitioning experiments have been performed. Starting compositions in the simple system Na_2O-CaO-MgO-Al_2O_3-SiO_2 (NCMAS) were synthesised from oxides and carbonates, and can be described as different mixtures of plagioclase and diopside. Adding a diopside component makes it possible to independently vary temperature, pressure and crystal composition to study the influence of each of these parameters on partition coefficients separately. K, U and Th were added in trace amounts in the form of 1000 ppm AAS standard solutions.

The experimental setup consists of a 2 mm OD platinum capsule, filled with sample material, which was dried for 10 minutes at 850 K and subsequently welded closed in and attempt to prevent sodium loss.

In our initial experiments, we focus on the effect of crystal composition. To this end, four start compositions were prepared, resulting in crystal compositions anorthite$_{56}$albite$_{44}$ (An56), An66, An76 and An86.

Figure 2 shows an example of a succesful experiment at a run temperature of 1500 K, showing two clearly visible An86 crystals. Ongoing experiments study the effects of temperature and pressure as well.

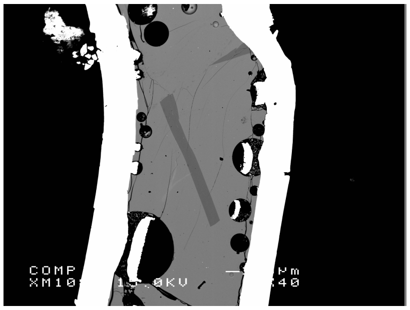

Figure 2: A BSE picture of a sample charge at 1500 K

Concentrations of Th and U in both crystals and melt will be measured by laser ablation ICP-MS at Utrecht University, while K will be measured by electron microprobe. At the meeting we will present our new partition coefficients and use them to provide a new estimate of the Moon's heat budget through time.

5. Summary

We will determine partition coefficients of radioactive elements between plagioclase and melt for several well-controlled plagioclase compositions. Combining these data with partition coefficients of Th, U and K for the other lunar minerals, calculations on the crystallisation of the LMO and surface measurements of Th, U and K concentrations, the distribution of heat producing elements in the lunar interior can be determined. These results can greatly improve models of lunar interior evolution.

Acknowledgements

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