LUNAR SURFACE MG# DISTRIBUTION AND MAGMA OCEAN CRYSTALLIZATION. M. Laneuville[1], D. Breuer[2], A.-C. Plesa[2] and S. Schwinger[2]. [1]Earth Life Science Institute (ELSI), Tokyo Institute of Technology, Tokyo, Japan. [2]German Aerospace Center (DLR), Berlin, Germany.

Abstract. Recent results from the Japanese Kaguya (SELENE) mission [1], and analysis of lunar meteorites [2,3] suggest that the lunar highlands are much more heterogeneous than previously thought. Specifically, there is a longitudinal gradient in magnesium number (Mg#) that needs to be explained.

During magma ocean crystallization, the Mg# of anorthosite varies with time as iron and magnesium fractionate between liquid and solid phase. Understanding the observed hemispherical Mg# trend is thus linked to the problem of understanding the time evolution of near- and farside crustal thickness.

In this presentation, we review the petrological character of the Mg# variation trend and report possible scenarios to explain its existence.

Introduction. The lunar nearside and farside differ in terms of volcanic activity, crustal thickness, elemental abundances, but the highlands have long been thought to be homogeneous on both hemispheres.

Recent analysis using Kaguya (SELENE) spectral profiler showed that there is a significant difference in magnesium content relative to iron (Mg#) between the two hemispheres, as can be seen in Fig. 1 [1]. Iron is more incompatible than magnesium (i.e., stays preferentially in the melt), therefore a higher Mg# implies crystallization from a less evolved magma ocean. However, such an observation could be explained by different scenarios: (1) a homogeneous primordial magma ocean followed by an asymmetric crustal crystallization, (2) a poorly mixed magma ocean followed by a uniform crust formation, or (3) a symmetric crust composition, but an asymmetric mixing process that resurfaced different portions of the crust on each hemisphere.

We approach this problem from two perspectives. From petrological considerations, we study the link between magma ocean properties and anorthosite composition. On the other hand, we also consider an energy balance approach to understand which environmental conditions could produce a thermal evolution consistent with observations.

Magma ocean crystallization sequence. The sequence of crystallizing phases in a lunar magma ocean has been studied both through direct experiments and thermodynamic considerations. Here we use the software package MELTS to understand how the Mg# content of anorthosite evolves with magma ocean crystallization. Figure 2 (top) shows the anorthosite Mg# as a function of magma ocean crystallization state (in "percent solid", PCS, vol%) for different relative plagioclase fractions, defining anorthosite as a pure mixture of plagioclase and clinopyroxene. From these curves, it is possible to compute what PCS distribution is required to reproduce a given Mg# distribution (Fig. 2, bottom). We do this by inverting the functions in Fig. 2 (top) and asking which range of PCS would produce the Mg# distribution of Fig 1.

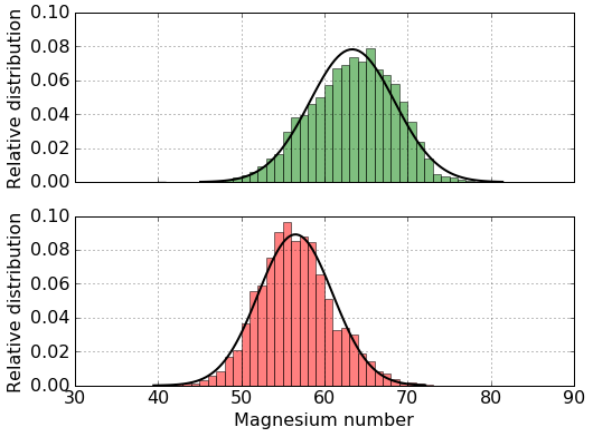

FIG. 1: Magnesium number (Mg# = Mg/(Mg+Fe) in mol%) distribution on the lunar far (top) and nearside (bottom) using data from Ohtake et al (2012). The distributions are normalized per hemisphere.

This result depends on a minimal amount of assumptions, namely a given crystallization sequence. We can therefore use this to get an insight into the timing of crystallization and depth of origin of the crust. It is important to stress here that we can only make statements about the part of the crust that is sampled by remote sensing. For example, the nearside Mg# distribution can be best explained by a narrow range of PCS, while the farside is explained by a broader, almost uniform distribution.

In this study, we focus on scenario (1), which can be explained either by asymmetric crystallization, where the early crust is formed first on the farside [3], or formed everywhere but transported preferentially to the farside [e.g., 4]. A scenario where the crust is formed symmetrically, but partly removed on the nearside is possible but not studied here. We now investigate models that can explain a crystallization sequence such as that in Fig. 2 (bottom).

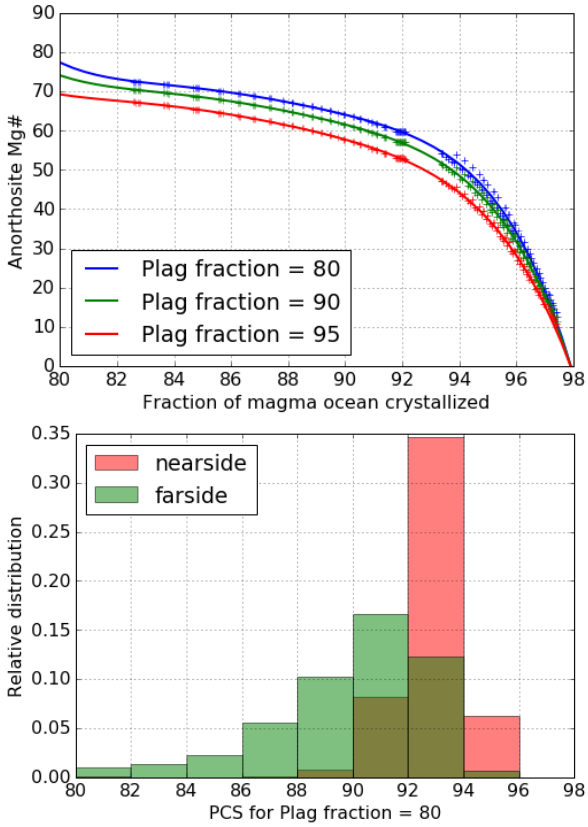

FIG. 2: (top) Anorthosite Mg# parameterization as a function of magma ocean crystallization (in "percent solid") using MELTS and Lunar Primitive Upper Mantle composition (LPUM). (bottom) PCS distribution required to match Mg# distribution from Fig 1 assuming a given parameterization from the top figure.

Thermal evolution. We run simple energy balance calculations in the magma ocean to track the evolution of the crustal thickness and composition. The thermal model is similar to [5], but we do not model orbital evolution:

$$E - Q = (Q_L + Q_s)\frac{dr}{dt}$$

Where E is the surface heat flow, Q heating due to radioactive decay, Q_L and Q_S the latent heat and secular cooling contribution terms, respectively, r the thickness of the crust and t is time. The surface heat flow is parameterized as $F_0 + (F_0 - F_1) \exp(-t/\tau)$, to take into account a possible asymmetry between near- and farside cooling rate, where F_0 and F_1 are the initial surface heat flows on the far- and nearside.

For a given crystallization sequence (as parameterized in Fig. 2, top), the free model parameters to generate Mg# distribution on both hemispheres are the different cooling rates between hemispheres (including potential delay), and the effective depth sampled by remote sensing (impact induced crustal mixing) which can be different between hemispheres.

Fig 3 shows an example of Mg# profile with depth in the crust on both hemispheres. The gradient is shallower on the farside, which crystallized from lower PCS than the nearside. Fig 2 (top) indeed shows that at low PCS, a given volume of crystallization leads to a smaller decrease in Mg# than at higher PCS values. Note that those curves can change depending on the crystallization model (i.e. trapped liquid at depth, remelting by decompression…). This will be investigated in the future.

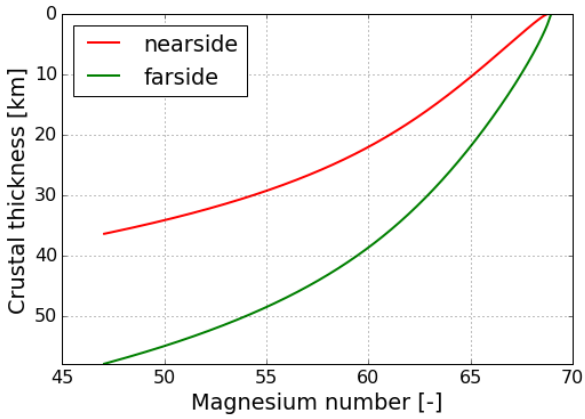

FIG. 3: Example crustal Mg# number obtained by a simulation using 5 Ma delay, τ is 10 Ma, F0 and F1 are 0.15 and 0.30 W/m^2, respectively and the parameterization with plagioclase fraction of 80 is used.

Conclusion: The crustal profile shown in Fig. 3 does not fit the observed Mg# distribution, as both hemispheres have a similar largest Mg# value. We plan to sample the model phase space through Monte-Carlo algorithm to find which type of evolution can best reproduce the data (i.e. observed nearside comes from a much smaller range of PCS than the observed farside). A critical point will be to understand which property of the distribution observed in Fig. 1 informs us most about the crust formation process.

Acknowledgements: This work benefited from discussions with M. Ohtake and was funded by the Japanese Grants-in-Aid for Scientific Research program and the Deutsche Forschungsgemeinschaft (SFB-TRR170).

References: [1] Ohtake, et al. *Nat. Geosci.* **5** (2012), [2] Russell, et al. *Phil. Trans. R. Soc. A.* **372** (2014), [3] Gross, et al. *Earth Planet. Sci. Lett.* **388** (2014), [4] Loper and Werner. *J. Geophys. Res.* **107** (2002), [5] Tian, et al. *Icarus.* **281** (2017).