EFFECT OF TIDAL DISSIPATION ON LUNAR CRUST FORMATION.

M. Laneuville[1]
[1]Earth Life Science Institute (ELSI), Tokyo Institute of Technology, Tokyo, Japan.

Abstract. The asymmetric character of the Moon has long been recognized. Over the years many scenarios have been invoked to explain it, but no consensus exist to date. Recent results from the Japanese Kaguya (SELENE) mission [1], and analysis of lunar meteorites [2,3] suggest that the lunar anorthosites are much more heterogeneous than previously thought. This prompt a new investigation of the magma ocean hypothesis. In particular, we will study the potential for asymmetric crustal growth due to temperature-dependent tidal heating.

Introduction. Earth's Moon possesses a clear dichotomy between its nearside and farside hemisphere. This asymmetry is both compositional and structural. The most important features are the volcanic activity and radioactive heat sources concentration on the nearside [4]. Though the case for the causal relationship between the two has been made [5,6], the origin of the concentration of radiogenic elements is still unclear, despite numerous studies. Over the years, many hypotheses have been suggested such as impact driven processes [7,8], asymmetrical crystallization of the early lunar magma ocean [9,10] and degree-1 Rayleigh-Taylor instabilities in the crystallized magma ocean [11,12].

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 [1]. Iron is more incompatible than magnesium therefore a higher Mg# implies crystallization from a less evolved magma ocean. This observation strongly favors an asymmetric crystallization of the magma ocean as the cause for the present day observations. In addition, analysis of lunar meteorites show that different rock families follow different compositional trends [2,3]. This also points to notable heterogeneities in the magma source of the lunar crust, in contradiction to the global magma ocean hypothesis.

It therefore is timely to study what processes could have generated such heterogeneities, and what their implications for the present day composition would be. In this paper, we will specifically study the influence of temperature-dependent tidal dissipation on sustaining an initial hemispheric temperature different, due for instance to radiation of the terrestrial magma ocean.

Temperature difference: The Moon becomes tidally locked to the Earth early in its history, therefore earthshine could be a cause of asymmetry between the hemispheres. Asymmetric crystallization due to earthshine alone has been investigated by Wasson and Warren (1980) [9], but was deemed implausible due to the low radiative temperature of the Earth. However if a surface magma ocean can be sustained on the Earth for several million years, as previously shown [e.g. 13], its radiative heat flux may have been enough to generate a significant temperature difference between the lunar hemispheres.

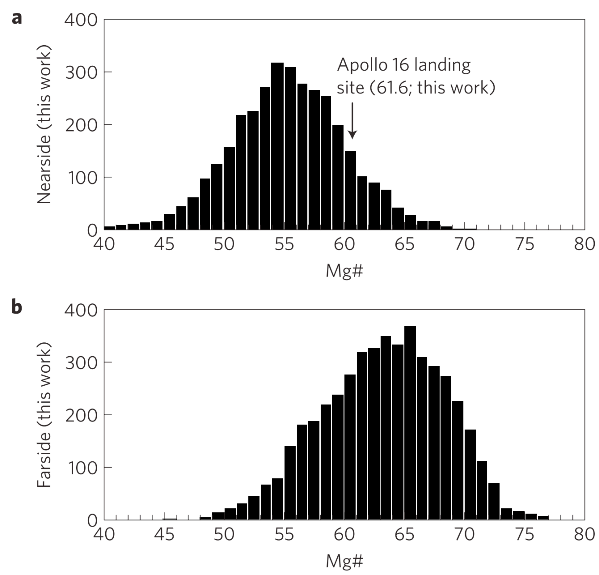

FIG. 1: Magnesium number distribution on the lunar near (top) and farside (bottom) from Ohtake et al (2012). This suggests that the lunar farside crystallized from a less evolved magma ocean (Ohtake et al. 2012).

Temperature difference. We consider first the potential hemispheric temperature difference for a tidally locked Moon as a function of Earth's radiative heat flux and Earth-Moon distance. The former is estimated from [13] and parameterized as an exponential decay with initial value F_0 and decay constant τ_f. The initial value and decay time are linked to the global water content, and thus the thickness of the steam atmosphere. We model the timing of orbital evolution as

$$d(t) = A_0 + (A_1 - A_0)(1 - \exp^{-t/\tau})$$

A value for τ can be found in [14] and is set at 20,000 years. A_0 and A_1 are set to 5 and 60 Earth radii, respectively. The rate of recession of the lunar orbit depends on tidal dissipation on the Earth, which is largely unknown. The time over which this effect is important is therefore likely to change. Figure 2 shows the enveloppe of potential temperature differences for a range of parameters. We can see that a temperature difference much larger than what has been considered previously can be obtained for about 100,000 years.

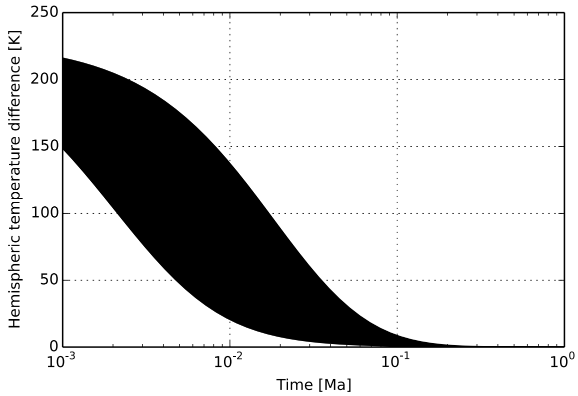

FIG. 2: Range of possible temperature difference between the near and farside during the early stages of lunar evolution. The lower part of the enveloppe corresponds to a case with $\tau = 2\ 10^4$ years, while the upper part if for $\tau = 4\ 10^5$ years. In both cases, $F_0 = 10^4$ W/m^2 and $\tau_f = 10^5$ years.

Tidal dissipation: Tidal dissipation being strongly temperature-dependent, even an initially small temperature difference between hemispheres could be amplified with time. Initially hotter material on the nearside will tend to dissipate more heat and remain hotter while the farside is allowed to cool faster.

Once this range of potential temperature differences is obtained, we can thus estimate the potential tidal dissipation difference between hemispheres. We consider here the temperature dependence of the quality factor Q proposed by [15]

$$\frac{1}{Q} = \frac{1}{Q_{max}} + \left(\frac{1}{Q_{min}} - \frac{1}{Q_{max}}\right)\left(\frac{T}{T_m}\right)^n$$

where n = 20 and T_m = 1600 K. The tidal heating rate is then linear in Q. Figure 3 shows the relative dissipation rate between the two hemispheres for various temperature differences and as a function of local temperature. The difference is maximal at higher temperatures closer to the solidus, but relative differences of a few percents can still locally be found at 1000 K.

To understand the potential effect on crust formation we need to integrate this effect over the crustal thickness. The crust of both hemispheres have is a T = T_m at the crust/magma ocean interface. We assume here for simplicity that it follows a linear profile down to the surface temperature, which differs by ΔT between the hemispheres. At a given time, if the hemispheric temperature difference is about 50 K, then the hotter side will experience about 4% more tidal dissipation.

Conclusion: This study shows that while the effect is not particularly large, a difference in tidal dissipation rate of a few percents between the two hemispheres can be obtained. The influence of tidal dissipation integrated over the crust formation time can be calculated by coupling the present considerations to a 1-dimensional evolution model. The main uncertainty on the result is the recession rate of the lunar orbit. Better constraints on this rate is required to obtain a better undestanding of the influence of tidal dissipation on lunar crust formation.

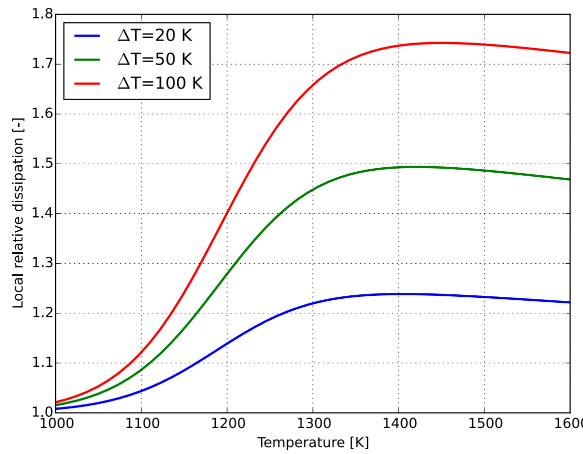

FIG. 3: Relative tidal dissipation rate as a function of temperature for different hemispheric temperature differences. This takes into account the temperature dependence of the quality factor from [15] as the only temperature dependent parameter of the tidal dissipation rate.

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