

MELT MIGRATION IN THE EARLY LUNAR CRUST: FORMATION OF THE PRIMITIVE, PURE LUNAR FERROAN ANORTHOSITES. D. Piskorz and D. J. Stevenson, California Institute of Technology, Division of Geological and Planetary Sciences, Pasadena, CA 91125

Introduction: Over the years, there have been many proposed mechanisms for moon formation, including fission, capture, and coaccretion, but the most popular and ever-evolving model at present is the giant impact origin [1]. The impact origin points to the existence of a hot, young moon, likely with a global magma ocean [2]. The next logical step, based on the mantle cumulate crystallization sequence [3], would be a resultant flotation crust made of plagioclase. Early calculations of the expected anorthosite content of the Moon [4] did not match initial measurements of Apollo samples [5], and more recently have not matched Clementine measurements [6] or SELENE measurements [7] because they assumed interstitial melt would freeze. By considering a physical model of a magma ocean with an accumulating flotation lid, we find that significant escape of melt can take place for reasonable physical parameters and timescales of melt migration, thus allowing for more nearly pure lunar anorthosites, consistent with observations.

Compositions of Ferroan Anorthosites:

Measured plagioclase contents of lunar anorthosites. Generally, anorthosites are 80-100% plagioclase feldspar with the remaining interstitial volume consisting of mafic minerals like pyroxene, ilmenite, magnetite, and olivine. Plagioclase is a type of feldspar ranging from albite (100% $\text{NaAlSi}_3\text{O}_8$) to anorthite (100% $\text{CaAl}_2\text{Si}_2\text{O}_8$). Unique properties of lunar ferroan anorthosites include high Al_2O_3 , high CaO, low Mg number, low levels of incompatible elements, a large Eu anomaly, and rare earth element abundances less than chondritic [8].

The bulk of the Apollo anorthosite samples contain up to 95% plagioclase by volume [5]. Recent data taken by SELENE (Selenological and Engineering Explorer) on the Moon Mineralogy Mapper suggest that plagioclase percentages of crustal anorthosite may be as high as 98%, if not 100% [7].

The lunar magma ocean model would predict that the anorthosites were formed early as a flotation crust with later intrusions by the rocks known as the Mg-suite. Mg-suite rocks are characterized by their high Mg/Fe ratios for their mafic components and are usually found in the lunar highlands. This hypothesis is thrown into question with the dating of lunar anorthosites and Mg-suite rocks; Sm-Nd dating predicts that lunar anorthosites are between

4.29 and 4.56 Ga, the youngest of which overlap the oldest of the Mg-suite rocks in time [9].

Initial calculations for lunar anorthosites. [4] carried out a mass-balance calculation of plagioclase and the interstitial melt remaining in the lunar crust. Assuming the density of the moon's flotation crust was equivalent to that of the underlying magma ocean, then using accepted values for the densities of plagioclase, mafic mineral, and melt, the volume of plagioclase in the lunar crust should be at least 81%. See figure 1 for a summary of these measurements and calculations.

Proposed formation models for lunar ferroan anorthosites. There exist many hypotheses for the formation of the lunar ferroan anorthosites (LFA). The high plagioclase content may suggest that some secondary process occurred which enriched primitive, perhaps less pure, anorthosite. [12] suggested that the lunar ferroan anorthosites are consistent with the post-cumulus removal of pyroxene through multiple melting episodes. [13] suggested that diapirism may enrich the LFA in anorthosite, eliminating the need altogether for the primary LFA to be exceptionally pure. During this process, pyroxene-rich extract would sink out of the anorthosite, and maybe could even be lost by the crust to return to the active magma ocean. This pluton model predicts anorthosite with 85% plagioclase by volume.

[14] proposes a formation process via adcumulus growth at the base of the lunar crust. We take this idea as the starting point of our model.

Methods and Calculations: We propose to revisit the idea of a primary mechanism for the formation of the lunar anorthosites to explain the disparity between measurements and predictions of their purities. We apply the concepts of Darcy flow and thermal diffusion to a region of early lunar flotation crust, squeezing mafic melt out and leaving behind the buoyant plagioclase crystals to freeze in place.

The process of the formation of the lunar anorthosite

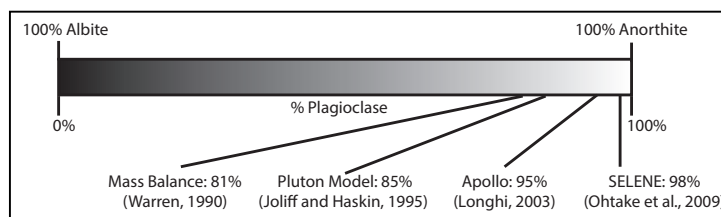


Figure 1: Spectrum of plagioclase concentrations in measurements and models of lunar anorthosites.

site crust is dominated by three rates: (1) the rate of the growth of the crust as light plagioclase crystals rise to the top of the magma ocean, (2) the rate of cooling of the lunar crust from the surface downwards, and (3) the rate at which interstitial melt is able to percolate downwards out of the plagioclase matrix, ie Darcy flow. The first and second rates are approximately the same due to the conductive temperature profile of the crust.

In order to carry out our model, we allow for Darcy flow with compaction at the locations where the plagioclase crystals have already formed and the interstitial mafic minerals are still liquid. Assuming a conductive thermal profile in the crust, a magma ocean temperature of $\sim 1500\text{K}$, a surface temperature of $\sim 300\text{K}$, a crystallization temperature of $\sim 1200\text{K}$ for the mafic minerals, we find that the bottom fifth of the crust is not completely frozen and the interstitial mafic melt may escape downwards. The efficiency depends on the particular epoch of the calculation and the thickness of the crust at that point in time. For example, [15] determines the moon's crustal thickness to be 34-43 km according to GRAIL data. This implies that a typical crustal thickness would be about 20 km (about half), and so the region where Darcy flow and compaction may occur is about 4 km thick at that epoch.

The permeability k is assumed to be $k_0 a^2 f^2$, where k_0 is a constant, a is the grain size, and f is the melt fraction [16]. We use a critical melt fraction of 0.2, above which the system is completely in the liquid phase. Even at small melt fraction, the Darcy velocity is large compared to the rate at which the crust thickens, suggesting efficient melt escape. However, we must consider the compaction process: We require that the deformation of the crystal matrix is fast enough such that compaction can compete with the rate at which the crust thickens. This is guaranteed provided the relevant compaction length is small compared to the thickness of the partial melt region [16]. Using a compaction viscosity of $10^{20}\text{Pa}\cdot\text{s}$, a gravitational acceleration of 1.67 m/s^2 , a density difference between plagioclase crystals and mafic melt of 150 kg/m^3 [4 and references therein], and a crustal growth rate of 0.3 cm/yr [14], we find that the compaction length is approximately 2 km. The presence of melt may make the viscosity smaller than this minimal choice. Terrestrial analogs have been suggested to have much lower values of compaction length [17].

Results and Discussion: In performing these calculations, we find our computed compaction length is less than the size of the region of the crust where melt may escape, at least for a crust that is already $\sim 20\text{ km}$ thick. In this case and with the aforementioned values,

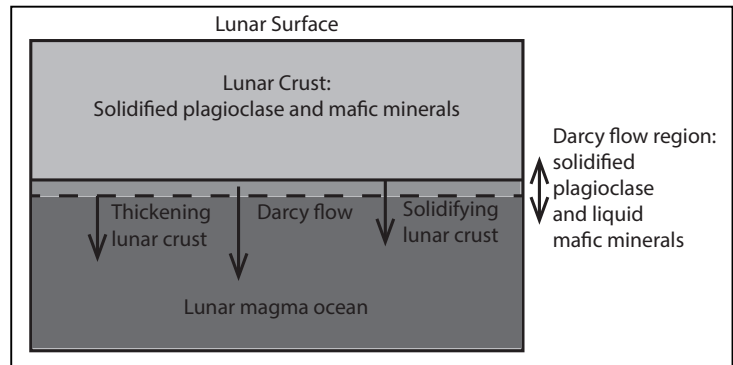


Figure 2: Schematic diagram of the model setup. At a given point in time, there is a region of the interior where mafic melt is capable of dripping out of the mesh of plagioclase crystals.

it is reasonable to create anorthosites with a minimum trapped interstitial melt fraction of 2%. The Darcy flux for this melt fraction is $\sim 0.05\text{ cm/yr}$ for a grain size of 5 mm and the Darcy velocity (flux/melt fraction) well exceeds the crustal growth rate.

Conclusions and Further Work: Thus far, we have been able to show that Darcy flow calculations model the rough compositions of the lunar ferroan anorthosites. The model may however encounter difficulty in explaining the expulsion of melt for the near-surface crust that presumably dominates the Apollo samples. We plan to also include considerations for tidal heating, volatilization and loss of alkalis, and varying rates of crustal growth, grain ripening, and viscosity thickening.

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