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Forming a Lunar Dichotomy by Giant Impact Melting

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Abstract

An impact on the lunar nearside can potentially explain several aspects of the lunar dichotomy, including differences in crustal thickness, the lateral extent of the lunar lowlands and a high concentration of thorium and other incompatible elements (KREEP) in the Procellarum KREEP Terrane (PKT) on the lunar nearside. We employ a multi-step modeling approach to simulate the compositional evolution of the lunar interior and explore, which aspects of the lunar dichotomy can be explained by a giant impact on the lunar nearside.

1. Introduction

The Moon is characterized by a global asymmetry comprising distinct differences in crust thickness, crater density, surface compositions and heat flow between the lunar nearside and farside [1, 2, 3]. The lunar farside is covered by an old, heavily cratered anorthositic crust, while the lunar nearside is dominated by mare basalts. Recent GRAIL data [4] indicate a dichotomy in crustal thickness with up to 60 km on the lunar farside and about 25km in the Procellarum region on the lunar nearside. Heat flow measurements indicate an increased heat flow in the Procellarum region [5] that coincides with high amounts of Fe, Ti, Th and KREEP [2]. Multiple models have been proposed to explain different aspects of the lunar dichotomy, including asymmetric crystallization of the lunar crust [6] and asymmetries in mantle convection [7]. In this study we explore, which aspects of the lunar dichotomy can be explained by a giant impact and subsequent partial melting of the mantle on the lunar nearside.

2. Model

1.1 Impact

We use iSALE [8] to model the impact of a projectile with a diameter of 780 km on he nearside of the Moon with an impact velocity of 6.4 kms^{-1}. The projectile was assumed to be differentiated into a FeS core and a silicate mantle from a bulk H chondritic composition. The lunar mantle and crust constituting the target were assumed to have formed by fractional crystallization of a global lunar magma ocean (LMO) with main oxide contents as proposed by [9]. We modeled LMO crystallization with alphaMELTS [10, 11,12], assuming that all crystallizing plagioclase floats to the surface to form an anorthositic crust and the remaining mantle cumulate was mixed by solid state convection. It has been shown that dense, Ti-rich, ilmenite bearing cumulates (IBC) can be partially entrained in the deeper mantle, resulting in elevated IBC concentrations both at the core mantle boundary and at the base of the crust [13]. We used this distribution of IBC in the mantle after convective overturn to calculate the composition of the lunar mantle. The mantle temperature was assumed to be at the solidus at the time of the giant impact.

1.1 Partial melting

For each material considered in the impact model we assumed specific solidus and liquidus functions and determined the compositions of partial melts at different degrees of melting using alphaMELTS [10, 11,12] and experimental data for FeS and anorthosite compositions. Using this information, we calculated the degree of melting and the respective composition of the partial melts in different regions of the lunar mantle depending on the local post impact temperature. We assumed that above a minimum degree of melting of 3% the partial melts could migrate to the surface and form a melt pool. The composition and volume of this melt pool was calculated by mixing the compositions of all partial melts. In order to determine the thickness of the secondary plagioclase floatation crust formed by melt pool solidification and the composition of the newly formed upper mantle, we modeled the fractional crystallization of the melt pool using alphaMELTS [10, 11,12].

3. Results and Discussion

Assuming that the partial melts rise radially to the surface and form a melt pool of homogeneous thickness, the melt pool has a radius of ~1600km and a depth of ~80km. The dimension of the melt pool is consistent with size of the mare basalt region [14]. The thickness of the secondary crust crystallizing from the melt pool is in the order of 20 km, which is consistent with the average crust thickness of about 25 km in the Procellarum region inferred from GRAIL data [4]. The post impact melting process leads to a local enrichment of heat producing radioactive isotopes of Th, U and K. Compared to the upper mantle at the lunar farside, the Th concentrations at the impact site are elevated by a factor of about 2.5 in the upper 80km of the mantle. This local Th enrichment is about 6 times lower than the one assumed by [15] to explain the different durations of volcanic activity on the lunar nearside and farside. The Th content of the melt pool strongly depends on the composition of the mantle at the time of the impact, which in turn depends on the current distribution of KREEP bearing IBC material in the lunar mantle. Thus a different timing of the impact with respect to the onset of IBC crystallization and entrainment might lead to differences in the melt pool composition and thus the distribution of radiogenic heat sources.

4. Conclusions

A large impact on the Procellarum region at the lunar nearside can reproduce several aspects of the lunar dichotomy including the extent and crustal thickness of the nearside lowlands and the presence of a local enrichment of the uppermost mantle below the impact site. However, the modeled degree of enrichment is probably too low to explain the different durations of volcanic activity on the lunar nearside and farside. Thus, further refinement of the model is required to obtain results that are quantitatively consistent with the distribution and formation ages of mare basalts.

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