REDISTRIBUTION OF TITANIUM IN THE LUNAR MANTLE BY GIANT IMPACT-INDUCED MELTING.
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Introduction: The compositional variations of the mare basalts on the Moon indicate that the mare basalts formed from compositionally distinct mantle reservoirs with different contents of Ti and other incompatible elements [1]. On the lunar surface, Ti-rich basalts are highly concentrated in the Procellarum region on the nearside, suggesting a local Ti enrichment of the underlying mantle. Although several scenarios have already been proposed to explain the high volume of observed Ti-rich mare basalts on the nearside of the Moon, the mechanism how to produce the Ti-enriched reservoirs within the mantle only on the nearside of the Moon is unclear. The nearside of the Moon was proposed to be a gigantic tectonomagmatic structure [2]. However, recent observations show that the farside has a layered crustal structure [3,4] and the nearside contains a large area of impact melt material (e.g., low-Ca pyroxene) [5], suggesting a giant impact occurred on the current nearside of the early Moon. A large impact event produces a thermal anomaly on the planetary scale [6] and changes the source depth and volume of magmatism [7]. Therefore, it might also induce local changes in the composition of the mantle by partial melting and heat induced mantle convection.

In this work we investigate the effects of a giant impact at the Procellarum region to test if the crystallization of an impact-induced melt pool could explain the apparent Ti-enrichment of the lunar mantle underneath the Procellarum region as a potential source for the Ti-rich mare basalts on the nearside of the Moon.

Methods: *Giant Impact Modeling.* We modeled the giant impact using iSALE [8], assuming an impactor with a diameter of 780 km hitting the nearside of the Moon with a velocity of 6.4 kms^{-1}. Such a giant impact could form a mega-basin on the Procellarum region and reproduce the characteristics of the crustal dichotomy and structures comparable to those observed on the current Moon, including the nearside lowlands and the farside thick mafic-rich layer on top of the primordial anorthositic crust [9]. Using the modeled impact peak pressures, we calculated the impact induced heating to investigate the degree of partial melting.

Material Properties. We assumed a differentiated projectile with a bulk H chondritic composition and a simplified thermal stratification with a 1350 K core and 850 K mantle. The lunar mantle and crust were assumed to have formed by fractional crystallization of a global lunar magma ocean (LMO) with main oxide contents as proposed by [10] but an elevated TiO_2 content of 0.4 wt% corresponding to the maximum estimates of other works (e.g. [11,12,13,14]). We modeled LMO crystallization with alphaMELTS [15,16,17], 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 [18]. We used this distribution of IBC in the mantle after convective overturn to calculate the TiO_2 concentrations in the lunar mantle. The mantle temperature was assumed to be at the solidus at the time of the giant impact.

Partial Melting and Melt Pool Crystallization Model. For each material considered in the impact model we determined the solidus and liquidus temperatures and the compositions of partial melts at different degrees of melting using alphaMELTS [15,16,17] and phase diagrams for iron and plagioclase. 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 with alphaMELTS [15,16,17].

Results and Discussion: As a consequence of shock compression and the subsequent unloading [19], the giant impact produces partially molten material that extends almost entirely over the impact hemisphere (Fig. 1). Partially molten material reaches down to the core and extends radially to a distance of 1600 km, corresponding to the size of the mare basalt region [20] and the putative Procellarum basin [21]. The impact leads to heating of large parts of the lunar mantle and to an average degree of melting of about 9% in the mantle below the Procellarum region. About 50% of the initially 38 km thick crust in the target area is molten and the remaining solid crust is largely pushed

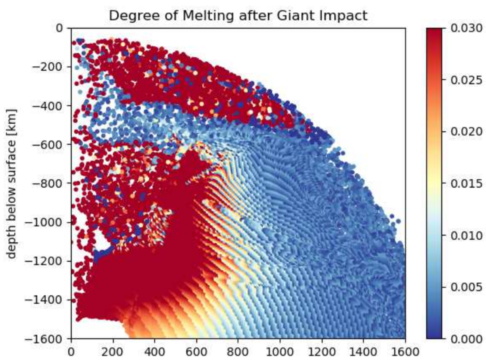

Fig. 1: Degree of melting after the giant impact. Red areas indicate the source areas of those partial melts that are assumed to form the melt pool (degree of melting ≥3%).

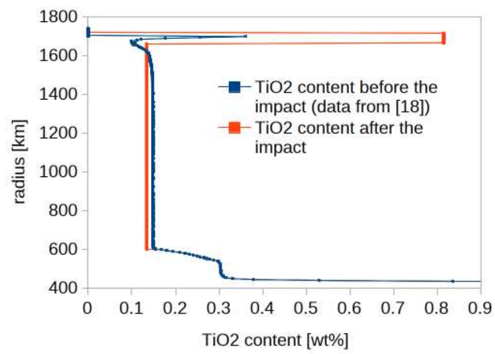

Fig. 2: TiO_2 contents of the lunar mantle below the Procellarum Basin. Blue: TiO_2 content before the impact (after overturn of the magma ocean cumulate pile as calculated by [18]). Red: Average TiO_2 contents of the depleted mantle and the solidified melt pool after the impact.

towards the basin rim or buried deeper in the mantle. Assuming that the partial melt rises vertically towards the surface and does not penetrate any remaining crust at the basin rim, the melt forms a pool with a diameter of ~2900 km and a thickness of 74 km. A melt pool of this depth can be expected to crystallize within 1-10 Ma, depending on the efficiency of convective cooling during different stages of crystallization. The crust forming from this magma pool has a thickness of 21.5 km, assuming that the crust consists of pure plagioclase and that no other minerals or parts of primary crust are mixed in. This value is comparable to the average crust thickness of 25 km in the Procellarum region derived from GRAIL data [22]. Before the giant impact TiO_2-rich materials are mostly located at the core-mantle boundary and at the base of the crust [18]. The TiO_2 contents in the upper mantle range from about 0.09 - 0.36 wt% (Fig. 2). These values are similar to the TiO_2 contents that have been estimated for the mantle sources of low Ti mare basalts, ranging from about 0.09 - 0.34 wt% [23]. Due to the giant impact, the mantle below the Procellarum region is partially molten and these partial melts accumulate in a melt pool at the surface. Thereby Ti is preferentially partitioned into the partial melts along with other incompatible elements, including heat producing isotopes of U, Th and K. This process results in a depletion of the mantle in incompatible elements and a complementary enrichment of that part of the upper mantle that formed by crystallization of the melt pool. Thus, the TiO_2 content in the upper 50 km of the mantle below the Procellarum region increases to an average of 0.82 wt% with local concentrations varying from 0 20 wt% TiO_2 if the cumulate layers are insufficiently mixed. These values are consistent with the range of TiO_2 contents up to ~1.5 wt% that have been estimated for the source regions of high-Ti mare basalts [23]. The TiO_2 content in the underlying mantle (depth > 50 km) decreases, respectively, from an average of about 0.15 wt% to an average of about 0.13 wt% in the region from which most of the partial melts originate (Fig. 2).

Conclusions: In this study we demonstrate that partial melting and re-solidification of the mantle after a large impact in the Procellarum region (1) is consistent with the observed crust thickness in the Procellarum region and (2) leads to local variations of mantle Ti contents of the same order as they have been inferred from mare basalt compositions.

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