FORMING THE MOON'S NEARSIDE-FARSIDE DICHOTOMIES VIA GIANT IMPACT.
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Introduction: The Moon exhibits striking dichotomies in elevation, crustal thickness, and composition between its nearside and farside. Although several scenarios [1-6] have been proposed to explain these dichotomies, their origin remains debated. Recent observations from the GRAIL mission indicate a crustal thickness of ~ 30-40 km on the nearside lowlands and ~ 50-60 km on the farside highlands [7]. The highland crust is composed of two layers, consisting of a 30-50 km-thick primary anorthositic crust, overlain by an ~ 10 km-thick mafic-rich layer [8]. Based on this layered crustal structure on the farside, together with the observational evidence for impact melts distributed over a large area of the nearside [9], here we propose a giant impact event on the nearside to account for the observed dichotomies.

Giant impacts are thought to have happened frequently in the early solar system. The majority of projectiles impacting the lunar surface were planetesimals leftover from the main phase of terrestrial planet formation [10]. From this left-over population, the Moon received ~ ½ of the impacts of Mars. Thus, according to the estimated size of the impactor (D ~ 1500 km) forming the Borealis basin on Mars [11], the impact of a several hundred kilometer-sized body on the Moon is not unlikely. For this work we conducted a series of numerical models of giant impacts on the Moon to test quantitatively the large collision hypothesis for the formation of the nearside-farside dichotomy on the Moon.

Methods: We use the iSALE shock-physics code [12] to simulate giant impacts. We model the Moon as a 3,500-km-diameter sphere with 700-km-diameter iron core. The crustal thickness is assumed to be 50 km. We use gabbroic anorthosite and dunite to represent the lunar crust and mantle. The differentiated projectile has a dunite mantle and iron core. We assume the Moon was warm [13] at the time of this giant impact event. Here, we simulate head-on collisions only and assume the impact site is to be at 15^o N, 23^o W, the center of the Procellarum basin [14].

Results: Fig. 1 illustrates the basin-forming process for an impactor of 780 km in diameter (100 km radius of iron core) with an impact velocity of ~ 7.5 km s^{-1}. During the basin-forming process, the impactor penetrates into the target, displacing and excavating target material; the floor of the excavation cavity is covered with a thick veneer of impactor and crustal material (Fig. 1b).

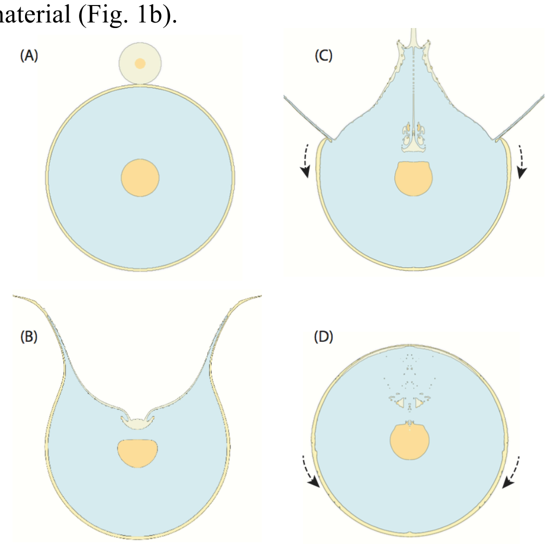

Fig. 1 Snapshots of crater formation for a giant-impact (D ~ 780 km and v ~ 7.5 km s^{-1}) on the Moon. The arrows in (c) and (d) indicate the movement and bulking of crustal material during the impact cratering process.

The collapse of the hot central uplift pushes crustal material in a radial direction resulting in a thickened crustal region comparable in extent to the farside highlands (Fig. 1c). The migration of crustal and mantle material around the basin fills the excavated cavity with the melt pool covering the inner part of the basin (~ 2500 km in radius). The proximal ejecta slump back into the basin and eliminate the specific morphologic features of basin structures (Fig. 1d). Impactor mantle mixed with crustal material remains near the surface inside the basin, forming a new crust ~ 30 km thick. Most of the iron core of the impactor mixes with the Moon's mantle beneath the impact site and only a small part merges immediately with the Moon's core.

The modeled crustal thickness varies along the arc distance from the impact site (Fig. 2). It increases from ~ 30 km at the basin boundary to ~ 60 km at an arc distance of 90 degree from the basin center, reaching a maximum value of ~ 70 km at an arc distance of 130 degrees. The crustal thickness then decreases slowly to ~ 65 km at an arc distance of 170 degrees. At the antipode (170-180 degrees), the post-flow ejecta has a high variation in thickness from 0 to 30-40 km because of the small areas within the arc intervals, and was not included in the calculation of the new crustal thickness.

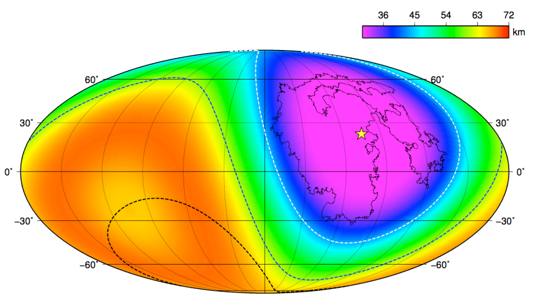

Fig. 2 The modeled crustal thickness distribution. The white and blue lines represent the boundaries of transient and final crater; the black dashed line represents the boundary of SPA basin; the yellow start represents the impact location.

Discussion: The proposed giant impact produces a crater structure, but does not preserve the morphological features like small basins that were formed later. The boundary of the modeled transient crater (~ 1800 km in radius) corresponds to the size of the PKT [15] and the rim of the final crater is located at the nearside-farside boundary (see Fig. 2). The impact forms the new crust with a thickness of ~ 30 km on the nearside and ~ 60-70 km on the farside, which is roughly consistent with the crustal thickness model derived from the gravity observations [7].

Assuming an initial global layer (20 km) beneath the crust, the KREEP material at the impact site is ejected along with crust and mantle material during basin formation. Ejected KREEP material that is deposited close to the basin rim slumps back into the basin, accumulating at the bottom of the new crust. Due to the asymmetric crustal thickness resulting from the giant impact, the depth of the KREEP layer varies between the nearside (~ 30 km) and farside (~ 60-70 km). Consequently, the relatively shallow KREEP layer at the nearside could have been excavated and transported more easily to the surface by subsequent basin-forming impact events (e.g., Imbrium), forming the observed KREEP on the lunar surface with high concentrations on the nearside [15]. On the farside, significant impacts would be required to excavate KREEP or bring it closer to the surface from its 60-70 km depth.

As the impactor added substantial mass to the Moon, the question arises of whether this event left an imprint on the isotopic composition of the Moon as compared to Earth. However, if the dichotomy-forming impactor derived from the same homogeneous inner disk reservoir as that of the Moon-forming impactor and proto-Earth [16], *no* isotopic effect for elements, like O [17] and Ti [18], is expected. By contrast, for W isotopes the situation is different because the ^{182}W compositions of the bulk impactor is different from that of the lunar mantle. The proposed impact may have led to an increase or decrease of the ^{182}W abundance in the Moon, depending on the degree to which the projectile core equilibrated isotopically with the lunar mantle (Fig. 3). As our simulations suggest that a significant fraction of the projectile core equilibrated with the mantle, the dichotomy-forming impact probably significantly lowered the ^{182}W composition of the Moon (Fig. 3). Thus, one important implication of this scenario is that prior to the impact, the Moon had a larger ^{182}W anomaly than presently observed. This is important, because the giant impact model of lunar origin predicts a significant ^{182}W anomaly in the Moon [19], but such an anomaly has so far not been detected. Instead, analyses of lunar samples show that the ^{182}W composition of the Moon is very similar to that of Earth's mantle [19, 20]. This conundrum can be explained by our model, which predicts that prior to the formation of the Moon's dichotomy, the lunar mantle had a significant ^{182}W anomaly.

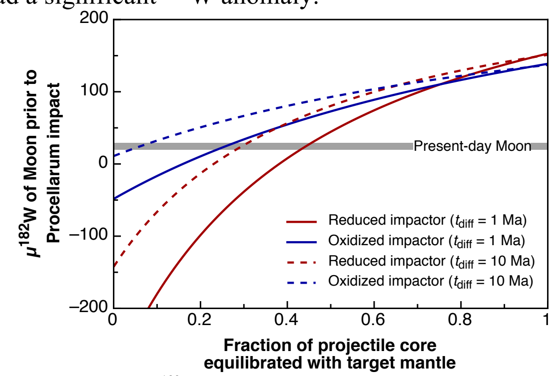

Fig. 3 Effects on μ^{182}W for different impactor compositions and different differentiation timescales after solar system formation. The grey horizontal bar represents the $\mu^{182}W = 24\pm5$ ppm for the Moon. Calculations assume a mass of the impactor 7.6×10^{20} kg and that the impactor mixed with a mass of 3×10^{21} kg of lunar mantle material. Assumed mantle W concentration were 19 ppb (Moon) and 5 (reduced) and 55 (oxidized) ppb in the impactor mantle.

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