EXCAVATION OF APOLLO SAMPLE 76535 DURING THE FORMATION OF THE SERENITATIS BASIN.
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Introduction: Lunar sample 76535 was collected within the Serentatis impact basin during the Apollo 17 mission. This rock was quickly identified as one of the most unique samples collected from the Moon. Characterized as a troctolite, sample 76535 is an unbrecciated monomict that formed in the lunar crust at depths between 45 – 65 km [1], is comprised of olivine, plagioclase, and orthopyroxene [2], and has an ^{40}Ar/^{39}Ar excavation age of 4.25±0.01 Ga [3]. Given that it formed deep in the lunar crust or upper mantle, it must have been ejected during a large, basin-forming impact event. However, sample analysis shows that sample 76535 has experienced maximum shock pressures of no more than 6 GPa [1,2,4], remarkably low given its expected ejection history.

Because of its location within Serenitatis Basin, the most straightforward geologic history for sample 76535 is that it was ejected during the Serenitatis impact event. However, impact scaling relationships indicate that this impact event was not large enough to eject rocks from 45 – 65 km deep; the only impact definitively large enough to excavate rocks from such depths is that which formed South-Pole Aitken Basin [1]. However, a sample with a petrographic history like 76535 would not be able to travel the full distance to its discovered location from the SPA impact alone. This necessitates that the sample underwent a second, similarly low-pressure impact to deliver it to Serenitatis Basin [1]. Furthermore, geochemical analysis suggests that the troctolite samples collected in the Apollo missions would have formed on the lunar nearside, in the presence of KREEP [5], supporting the hypothesis that sample 76535 originated within or near Serenitatis Basin.

An alternate hypothesized mechanism for bringing lightly shocked, deep material to the surface such as sample 76535 is through excavation of deep crustal and upper mantle material during the crater collapse stage of impact basin formation. Crater collapse is characterized by the closing of the transient crater, when material accelerates back to the point of impact, and in turn generates a central uplift. In this work we consider the possibility that this "excavatation" during crater collapse can draw upper mantle rocks to what eventually forms the basin floor without subjecting them to significant shock pressure. If this proves to be a viable mechanism for displacing deep crustal material to the surface during relatively large impact events, then 76535 could have been emplaced during the Serenitatis impact event while meeting the age and shock constraints recorded in the rock.

Methods: We use the shock-physics hydrocode iSALE-2D [6–10] to test the hypothesis that lunar sample 76535 was ejected as part of the crater collapse stage, rather than the excavation stage, during the Serenitatis impact event. We employ a curved target geometry because of the large basin diameter relative to the curvature of the Moon. The lunar-like target is structured with a 40 km thick granite crust overlying dunite mantle with a core with a 350 km radius at the center; the crustal thickness is based on average crustal thickness surrounding Serenitatits [11]. The 100 km in diameter dunite impactor strikes the target at 17 km/s. Cells are 1 km, resulting in model resolution of 50 cells per projectile radius for all runs. We use a range of thermal profiles with lithospheric thermal gradients in the crust and upper mantle from 10 – 30 K/km transitioning to an adiabat at 1300 K. These thermal gradients overlap with the range (8-17 K/km) inferred at the time of 76535's excavation [1].

With iSALE-2D, we can track global and crust-mantle topography during a simulated impact as well as individual thermal and pressure histories of model cells using Lagrangian tracer particles. We evaluate our models based on (1) matching modeled crustal thickness profiles with that of modern-day Serenitatis Basin, and (2) detecting the presence of lightly-shocked material at the surface at the end of basin formation.

Preliminary Results: Our primary goal is match the modeled crustal thickness profiles to those of Serenitatis Basin. We find that models with a 20 K/km thermal gradient best-fit the observations of crustal thickness in and around the Serenitatis Basin (Figure 1). We are still refining our parameter search and expect to produce even better fits to the observed basin crustal thickness.

With respect to the distribution of lightly shocked material at the surface, we find that lightly shocked material is displaced from initial depths 45 – 65 km and redeposited on the surface under all preimpact conditions, consistent with the hypothesized impact history of sample 76535. Figure 2 shows the post-impact distribution of tracer particles with initial depths (A) and peak shock pressures (B) for our best-fit morphologic model with 40 km crust and 20 K/km thermal gradient. Within the full range of thermal conditions tested, we note that more lightly-shocked tracer particles are found at the surface for models with lower thermal gradients.

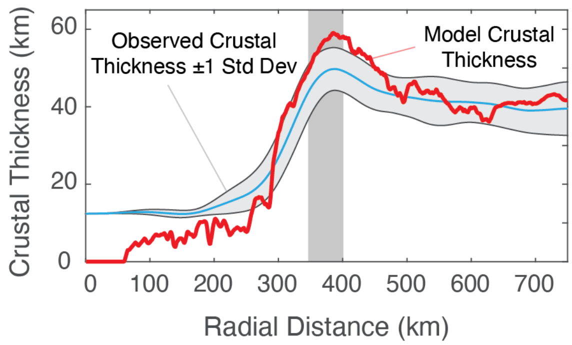

Figure 1: Comparison of GRAIL-derived average crustal thickness of Serenitatis Basin with best-fit post-impact crustal thickness (40 km think crust, 20 K/km thermal gradient). A 2.5-km wide moving average filter is applied to the model crustal thickness profile. Gray bar shows the location of the Apollo 17 landing site from the basin center, where the width broadly correlates to the uncertainty in crater rim.

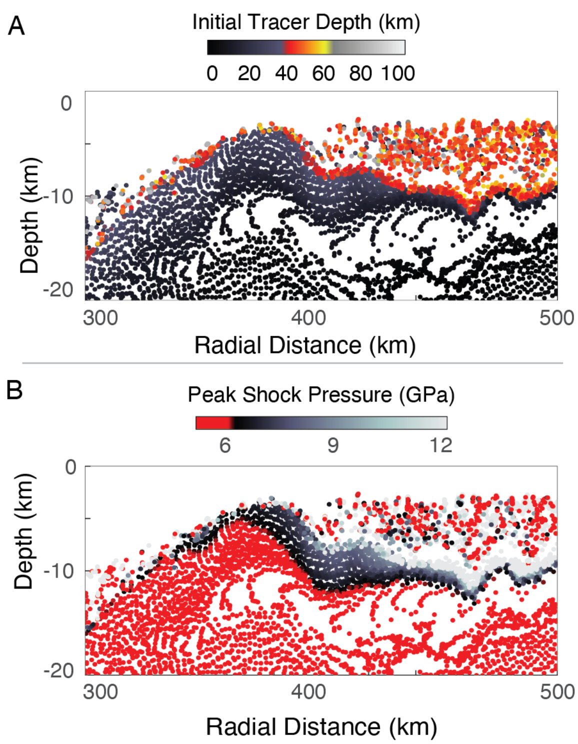

Figure 2: Distribution of tracer particles 3 hours post-impact with 40 km thick crust and a 20 K/km thermal gradient. Tracer particles are colored according to their preimpact depth (A) and peak shock pressures (B). Warm-colored tracers in each panel meet the corresponding observational constraints.

These preliminary results show that material can be extracted during latter stages of crater formation without subjecting it to extreme shock pressures associated with the earlier excavation stage. In the case of sample 76535, these results show that it could have been "ejected" during the Serenitatis impact event to the basin floor where it was collected. The implications of this result stretch beyond simply the geologic history of sample 76535; by essentially dating the Serenitatis impact event, the discovery of sample 76535 pushes back the timing of the Late Heavy Bombardment and implies that the SPA impact is older than its current age estimate of 4.25 based on [1]. Crater count estimates from LOLA data are consistent with this interpretation that Serenitatis is one of the oldest lunar basins [12], as well as radiometric dating in many of the other Apollo 17 samples found in the Serenitatis Basin and returned to Earth [13].

Conclusions: Ejection during an impact event is traditionally considered as a process occurring early in the impact event. However, especially in the case of large, energetic basin-foraming impacts, the extensive crater collapse stage may facilitate displacing material up from depths and depositing it to the surface as a previously unconsidered pathway. In this work, we consider "excavation" during crater collapse as a viable history for lunar troctolite 76535, a paradoxically lightly-shocked sample formed at depths comparable to the upper mantle. Noting its proximity to the similarly-aged Serenitatis Basin, we show that this sample could have been displaced to the basin floor during crater collapse of the Serenitatis impact event while avoiding the high peak shock pressures associated with near-surface ejecta.

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