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ORIGIN OF HETEROGENEITIES UNDERNEATH SMALL CRATERS – MODELLING OF IMPACT-INDUCED COMPACTION OF REGOLITH. Y. Wang^{1,2}, K. Wünnemann^{2,3}, Z. Xiao^{1,4}, R. Luther², T. Liu², R. Röhlen², ¹Planetary Environmental and Astrobiological Research Laboratory, School of Atmospheric Sciences, Sun Yat-sen University, Zhuhai, China (Yichen.Wang@mf.berlin), ²Museum für Naturkunde, Leibniz Institute for Evolution and Biodiversity Science, Berlin, Germany, ³Freie Universität Berlin, Berlin, Germany. ⁴CAS Center for Excellence in Comparative Planetology, Hefei, China.

Introduction:

Most of the Moon's surface is covered by a layer of fine-grained debris (i.e., regolith) formed by repeated impacts from centimeter- to kilometer-sized cosmic bodies and space weathering [1]. The estimated average thickness of the regolith (~10 m at the lunar highland and ~5 m at lunar mare [2]) is much greater than the penetration depths of remote sensing and landed exploration, both of which contribute to our understanding of lunar geology.

The interior structure of the regolith provides insight into how it evolved and, thus, contains information about the dynamic history of the Moon's surface. Liu et al. (2022) [3] proposed a model of the size-frequency distribution of fragments of the lunar megaregolith. A recent consensus is that the interior structure of the regolith comprises a gradually coarsening sequence of particles towards greater depths [4]. It is generally believed that the topmost mature regolith is porous, rather homogenous, and dominated of fine-grained particles with few boulders larger than 1 cm [1].

The ground penetrating radar onboard the Yutu-2 rover of the Chang'E-4 mission enabled to map the subsurface structure of the upper regolith [5, 6] and confirmed the absence of large subsurface boulders within the top-2-meter regolith [6]. Interestingly, an abundance of small heterogeneities of denser most likely less porous and probably cohesive materials seems to exist within the upper ~4 cm regolith [7]. More than 25% of these heterogeneities are located beneath meter-scale impact craters, suggesting a relationship between crater formation and the origin of the heterogeneities, which would imply that their occurrence in other locations in the upper regolith is also impact related, but the craters have been degraded [7]. However, the origin of these heterogeneities is still debated. One simple interpretation is that they are distal ejecta from a rather recent larger impact event that were delivered to the landing region [7], possibly within the past ~80,000 years [8]. An alternative hypothesis is that they are impactor remnants from a primary [9] or a low-velocity secondary impact (for example, from the nearby Zhinyu crater). Their subsurface location may result from the collapse of the crater wall during late stage modification of simple crater formation.

Another possibility is that these dense materials are impact breccias welded by melt [7]. Some small fresh craters along the rover path feature high-

reflectance materials on the crater floor, that might be glass-rich impact breccias [10, 11]. Such breccias may have been buried by diffusive downslope movements on crater walls as part of the degradation of small craters. This process may indicate that small impacts forming melt-welded impact breccia in mature regolith would substantially reduce the porosity of local regolith [7].

Understanding the formation mechanism and genesis of these heterogeneities at small impact craters can shed light on the evolution of regolith. On the one hand impact processes create porosity and, thus, contribute to the fine grained nature of regolith, on the other hand impact crushes pore space resulting in the compaction of matter and the formation of denser clumps [12]. Given the high formation rate of small primary [8] and secondary craters [13] on the Moon, widespread patches of such dense materials likely exist in the shallow subsurface, albeit covering only limited areas beneath the crater floor. It may explain the highly heterogeneous interior structures observed in lunar regolith, which is critical for understanding lunar regolith formation.

Methods: We use iSALE-2D shock physics code [14–16] to simulate the effect of small-scale impacts on the porosity of mature lunar regolith. In our simulation, we employ the Tillotson equations of state for basalt for the impactors and the target. We assume a porosity of 25% in the basalt target to represent the mature lunar regolith.

In order to test the different proposed origins of these heterogeneities, we vary the size and velocity of the impactor in our models. We use impactor sizes ranging from 10 cm to 1 m in diameter. As there is no consensus whether these small craters are primary [9, 10] or secondary craters [11, 17], we vary the impact velocities. We used a velocity of 12.7 km/s representing primary impact events, which corresponds the vertical component of the average lunar impact velocity (18 km/s) at a 45° angle [18]. For secondary impacts, we assume velocities of 1 km/s, which is typical for secondary impact events, and 100 m/s, which is based on the assumption that these small craters were formed as secondaries of the Zhinyu crater [17].

We use Lagrangian tracers in iSALE to track the motion of impactor materials and the compaction of target materials as a consequence of the impact-induced shock waves and plastic waves.

Preliminary Results: Fig. 1 shows snapshots of the impact of a one-meter-diameter impactor at different impact velocities. In the cases of velocities of 12.7 km/s and 1 km/s, we find that the top-most target beneath the transient crater experiences a reduction in porosity at an early stage of crater formation during the so-called contact and compression stage, with less or no reduction at lower impact velocities. No obvious fully compacted region (i.e., the porosity decreased to zero, which corresponds to a distention $\alpha=1$) is found (Figure 1a), but a gradual decrease of porosity with distance at an impact velocity of 1 km/s. At an impact velocity of 100 m/s no compaction occurs (Figure 1b). Upon excavation of the crater the zone of compacted material forms a thin layer along the crater wall underneath a thin veneer of impactor material (red matter in Fig. 1 a,b,c,d) that is initially nonporous. In general, the efficiency of compaction at impact velocities that correspond to the formation of secondary craters is rather low. More efficient compaction occurs in case the small craters are primaries.

In addition, our models indicate that a significant amount of impactor material is not ejected and remains inside the crater. From a modelling point of view it is challenging to track the thin veneer of impactor material until late stages of crater formation due to several reasons. First, resolution in the models becomes an issue, and second, the fragmentation process is difficult to simulate. However, it is likely that chunks of the impactor remain inside the crater and are buried during late stage collapse and slumping of the crater walls. In contrast, if the small craters are primaries formed at much higher impact velocities, significantly less impactor material remains inside the crater making it less likely that this material is the origin of the observed heterogeneities.

Future work: Currently, all simulations have only been performed up to the very early impact stages. Therefore, the next step is to simulate the entire impact process and track the fate of impactor remnants and highly compacted target materials. Our models allow for a quantitative test of the different proposed formation mechanism of the observed heterogeneities inside the top fine-grained mature regolith.

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References: [1] McKay, D. S. et al., (1991) *Lunar sourcebook: A user's guide to the Moon*, pp. 285–356. [2] Shukratov, Y. G. and Bondarenko, N. Y., (2001) *Icaurs*, 149(2), 329–338. [3] Liu, T., et al., (2022) *EPSL*, 597, 117817. [4] Wilcox, B. B. et al., (2005) *Meteoritics & Planet. Sci.*, 40(5), 695–710. [5] Li, C. et al., (2020) *Sci. Adv.*, 6(9), eaay6898. [6] Xiao, Z. et al., (2021) *GRL*, 47, e2020GL090935. [7] Ding, C. et al., (2021) *JGR:Planets*, 126,

e2021JE006917. [8] Speyerer, E. et al., (2016) *Nature*, 538(7624), 215–218. [9] Yang, Y., et al., (2021) *Nat. Astron.*, 6, 207–213. [10] Lin, H. et al., (2020) *GRL*, 47, e2020GL087949. [11] Gou, S. et al., (2020) *EPSL*, 544, 116378. [12] Xiao, Z., (2022) *Nat. Geosci.*, 15, 512–513. [13] Costello, E. S., et al., (2018) *Icarus*, 314, 327–344. [14] Amsden, A. A., et al., (1990) *Los Alamos Natl. Lab. Rep.*, LA-8095. [15] Collins, G. S., (2004) *Meteoritics & Planet. Sci.*, 39(2), 217–231. [16] Wünnemann, K. et al., (2006) *Icarus*, 180(2), 514–527. [17] Ding, C., et al., (2020) *GRL*, 47, e2020GL87361. [18] Elbeshhausen, D. K., et al., (2009) *Icarus*, 204(2), 716–731.

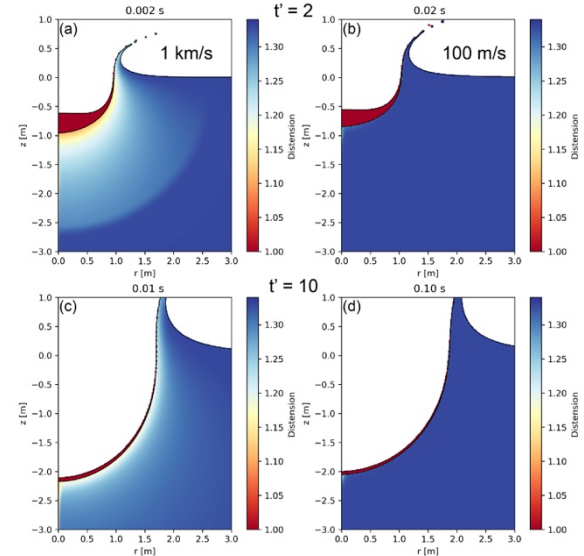


Figure 1. Snapshots of distention α , with $\alpha=1/(1-p)$, p is porosity for a one-meter-diameter impactor with an impact velocity of 1 km/s (a, c) and 100 m/s (b, d). The initial initial porosity of the target 25% and of the impactor 0%. Each row shows the same impact stage, represented by dimensionless times (t'), defined as $t'=(t*v)/L$, where L =projectile diameter, v =impact velocity, and t =time. Black contours represent material boundaries. The space resolution is of 40 CPPR (cells per projectile radius).