

# MELT PRODUCTION AND EJECTION AT LUNAR INTERMEDIATE SIZED IMPACT CRATERS: WHERE IS THE MOLTEN MATERIAL DEPOSITED? T. Liu<sup>1</sup>, R. Luther<sup>1</sup>, L. Manske<sup>1</sup> and K. Wünnemann<sup>1,2</sup>,

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**Introduction:** Impact melt rocks are the only lunar sample material that allows for absolute dating of impact events. Therefore, these samples are key to unveiling the early bombardment history of the Moon. However, due to the mixing of melt products ejected from distant craters, the interpretations of lunar samples are difficult [1]. Here, we use the iSALE 2D shock physics code to quantify the production of impact-induced melt and especially its distribution in ejecta blankets for lunar craters of intermediate size (1.5 – 50 km in diameter).

**Methods:** We carried out a suite of iSALE simulations with varying projectile diameter ( $L$ ) from 100 m to 3 km. We use an analytic equation of state (ANEOS) for basalt to describe the thermo-dynamical behavior of lunar crust (cf. [2]). Material strength, damage, and porosity were accounted for using the models of [3], [4], and [5, 6], respectively. Due to the long-term impact fragmentations, the lunar near-surface lithologies are assumed to be porous. The presence of porosity enhances melt production [7]. We set the porosity profile following the exponential function of Besserer et al. (2014) [8] that best matches gravity data. Another consequence of the long-term impact fragmentations is the damage of crustal rocks. Damage reduces the strength which was found to have a strong effect on the distribution of ejecta [9]. Here we assume the same gradient for the material damage.

To investigate melt production sufficiently high resolution in the models is required. At the same time simulations of the entire ejection process are only possible at coarser resolution. To reach a good compromise for the computational costs in terms spatial resolution, computation time and accuracy to quantify melt production and deposition upon ejection, we apply a **3-step approach** for simulations:

*Models to determine impact-induced melts.* To quantify melt production, we first have to determine the critical shock pressure  $P_c$  where the post-shock final temperature exceeds the melt temperature [7, 10] as a function of porosity. Impact-induced melts are generated if the material experiences peak shock pressures ( $P_{peak}$ ) in excess of  $P_c$ . Due to the presence of porosity in the basaltic crust, the thermodynamic state is calculated assuming that the crushing of pores can be separated from the compression of the solid component [7]. We use Lagrangian tracers to record  $P_{peak}$  during the passage of the shock wave. The total melt production is

the sum of the tracer masses whose  $P_{peak}$  is higher than  $P_c$ .

The impact velocity is the principal factor governing the production of impact melt. In our models, the average impact velocity of 18 km/s on the Moon is kept constant. We use a high resolution of 40 cells per projectile radius (CPPR) to model the early stage of impact processes until the shock wave has attenuated below  $P_{peak}$ .

*Models to analyze ejecta deposit.* Lagrangian tracer particles are also used to track ejected materials. Tracers are considered to be ejected when they reach the altitude of one projectile radius above the surface, and we determine their speed, angle, time, position and mass. We extrapolate the trajectory back to the surface and record the launch position. The cumulative number of tracers deposited at a given distance allows for determining the thickness of the ejecta blanket assuming a reference density of the ejected material equals to the density of the solid component in the un-compacted material (basalt, 2860 kg/m<sup>3</sup>).

Although distal ejecta have a definite dependence on the impact angle, the ejecta deposited within several crater radii could scale as a normal impact using the normal component of impact velocity [11]. In the models that are designed to track ejecta trajectory, the normal component of impact speed for the most likely impact on the Moon (45°) is considered (i.e., 13 km/s). Given that 10 CPPR is often sufficient to simulate crater growth [7], 10 CPPR is taken for these models, and they run until the crater reaches the maximum volume, which is assumed to be a good approximation for the transient craters [12] when the ejection process has ceased.

*Combining data of impact-induced melt and ejection.* Typically, each cell in iSALE models is assigned a single tracer. For better analysis, we make the positions of tracers in 10 CPPR-models exactly the same as those in the 40 CPPR-models by putting 16 uniformly distributed tracers in each cell. To estimate melt distribution in ejecta,  $P_{peak}$  of the ejected tracers derived from 10-CPPR models is revised by replacing it with that from 40-CPPR models.

**Production of impact-induced melt:** As in previous studies [13], the volume of impact melt ( $V_m$ ) increases exponentially with increasing diameter of transient craters ( $D_t$ ):  $V_m = cD_t^d$ , but our results (Figure 1) present a more gentle slope ( $d = 3.09$ ;  $c = 2.37 \times 10^{-3}$ ) than the analytical value ( $d = 3.8$ , [13]) when  $D_t$  is

directly taken from iSALE models. This is partially caused by the decreasing influence of the porosity gradient with increasing projectile size, and is also related to the determination of  $D_t$ . After the model-derived  $D_t$  is replaced with the scaled  $D_t$ . The results present an exponent  $d = 3.55$  ( $c = 4.41 \times 10^{-3}$ ).

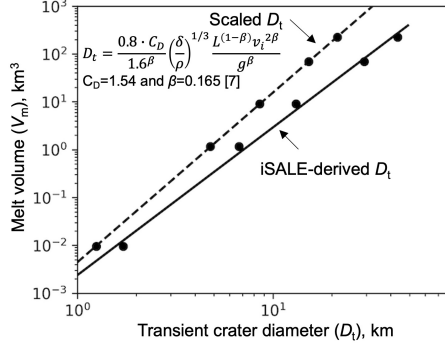


Figure 1 Melt production as a function of crater size.

**Ejection of impact-induced melt:** A power law expression for the ejecta thickness ( $T$ ) as a function of landing distance ( $r$ ) based on observations was formulated [14]:  $T(r) = T_0(r/R_t)^{-B}$ , where  $R_t$  is the transient crater radius as derived with iSALE. In Figure 2, we plot the thickness of the deposited ejecta against the radial distance normalized by  $R_t$ . The thickness of the deposited ejecta decreases with distance according to a power-law with an exponent of  $\sim -3.0$ , which is consistent with the laboratory experiments [15] and the observation of lunar ejecta blankets [14].

To study the melt distribution in ejected materials, we calculate the thickness of a hypothetical “melt blanket” ( $T_m$ ), which only consists of impact-induced melt material. We use the same way as we calculate the total thickness of the ejecta blanket, but consider only the materials that are molten. Our simulation results (Figure 2) show that the melt thickness  $T_m$  of the ejecta blanket is also a function of landing distance following a power law:  $T_m(r) = T_{m0}(r/R_t)^{-B_m}$ . Similarly to the total ejecta blanket, the thickness of the melt blanket is decreasing with the distance from crater center, but the slope of the “melt blanket” is more gentle than that of the total blanket and has an exponent around -2.3. In addition, even though the thickness of both the ejecta and the melt blanket decreases with distance from crater center, the total thickness decreases faster than the melt blanket, and hence, the concentration of impact melt in the ejecta blanket increases.

**Conclusions:** As in previous studies, we found the production of impact-induced melt is a function of transient crater size following a power law. But due to the decreasing porosity gradient with depth, the melt production for small craters is more significantly enhanced compared with that of larger craters leading to

a gentler slope. In addition, while the thickness of both ejecta and melt blanket decrease with the distance from the crater center, the melt concentration within the blanket is almost linearly increasing. It indicates that impact melt is highly concentrated not only inside the crater but also in the most distal ejecta.

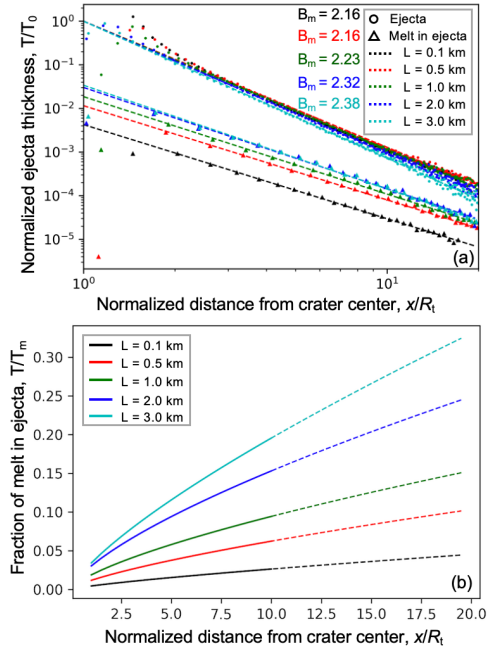


Figure 2 (a) Ejecta thickness and melt contribution. (b) Concentration of melt in the ejecta blanket.

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