IMPACT-INDUCED SHOCK MELTING AND EJECTION OF MATERIAL IN AN ASTEROIDAL ENVIRONMENT – IMPLICATIONS FOR THE DEFICIT IN MELT AGGLUTINATES IN ITOKAWA SAMPLES. K. Wünnemann[1], J. Engelmann[1,2], R. Luther[1], C. Hamann[1,2], M.-H. Zhu[3], [1]Museum für Naturkunde, Leibniz Institute for Evolution and Biodiversity Science, Berlin, Germany (kai.wuennemann@mfn-berlin.de); [2]Freie Universität Berlin, Institute for Geological Sciences; [3]Space Science Institute, Macau University of Science and Technology, Macau.

Introduction: The surfaces of atmosphereless bodies are subject to a continuous flux of impactors ranging from micro-meteoroids to large, crater-forming objects. Independent from the size-scale hypervelocity impacts generate shock waves that lead to distinct shock metamorphic effects in silicates including melting and the formation of amorphous glasses. On the Moon, impact gardening and space weathering have formed a regolith layer dominated by impact melt particles (agglutinates) [1]. The regolith layer on the asteroid Itokawa (25143), directly sampled by the Hayabusa mission [2], shows a distinctly different picture: dust particles exhibit different (solid-state) shock features, but agglutinates appear to be rare. The deficit in impact melt in the Itokawa regolith may be explained in two ways: (1) the relatively low impact velocities on asteroids in comparison to the Moon generate shock pressures insufficient to cause melting; (2) the vast majority of impact generated melt is ejected and escapes the low gravity environment on asteroids. (1) can be ruled out as several studies have shown that shock melting and agglutinate-like particles occur in granular target material even at impact velocities as low as ~ 5 km s^{-1} [1,3,4]. This is because the high porosity in regolith reduces the critical pressure for shock melting significantly [5]. Here we investigate the second option, that most impact melt is ejected and escapes the gravity field. By a suite of numerical models we quantify the generation of impact melt particles and determine how many of these particles are ejected at velocities faster than the escape velocity on an Itokawa-like asteroid as a function of impact velocity and porosity

Methods: We use the iSALE shock-physics code [6] to simulate hypervelocity impact processes. In a first step we validated our model against laboratory experiments, where 6.36-mm-diameter-aluminum spheres were shot into ~ 42% porous quartz sand, producing craters of ~ 33 cm diameter and ~ 6 cm depth [7]. Tracing of particle movement was facilitated by 9-mm-thick, horizontal strata of differently colored quartz sand that were placed at different positions in the target, and ejecta were collected up to 6 crater radii [8]. In a second step we conducted a suite of impacts in a low gravity environment at velocities ranging from 5–20 km s^{-1} and target porosities of 0–60%, mimicking the conditions on asteroids comparable to Itokawa. The thermodynamic behavior of the projectile and target was approximated by ANEOS for aluminum and quartz in the simulation of the experiments and basalt [9,10] for Itokawa-like impacts. To account for target porosity and its effect on the reduction of the critical shock pressure required for melting we used the ε–α compaction model [6]. The amount of material that experienced a certain shock pressure was measured by recording the peak shock pressure with tracers. Tracers were also used to record the ejection velocities and angles to determine (1) the amount of particles that were collected by the ejecta catchers in the experiments and to trace back their origins, and (2) the amount of material that escapes the gravity field in the suite of impact models on Itokawa-like asteroids. The resolution in our models was 60 CPPR (cells per projectile radius) to quantify the shocked volume and 20 /10 CPPR to determine the ejection parameters. To calculate the ejected melt volume, we superimpose the contour for material that is ejected at a certain ejection velocity (e.g. white dots in Fig. 1A for minimum ejection velocity) on the contours for peak shock pressure in tracers that were plotted at their original location (Fig. 1A, see also [8]). The geometric overlap then corresponds to the amount of shocked ejecta.

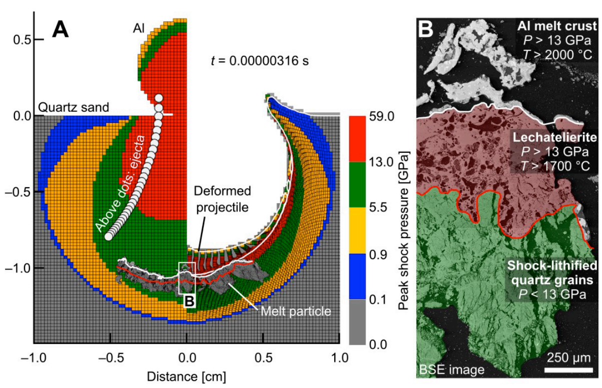

Fig. 1 Peak shock pressure as a function of distance from numerical modeling (A; color contours) compared to the shock zoning documented in a representative melt particle (B; BSE image). Pressure estimates in B are based on calibrated shock barometry in sandstone [e.g. 11].

Results - *Model validation* Fig. 1 illustrates the progressive decay of the shock wave in our numerical model (A) in comparison to melt particles recovered from the craters in the experiments. Optical and electron microscopy reveal a layered structure of decreasing shock metamorphism (B) that is in excellent agreement with distinct zones of peak shock pressure (see inlay in Fig. 1 A).

All ejected particles were collected in catchers and analyzed to estimate the shock pressure they were exposed to [7,8]. Fig. 2 shows the percentage of the total mass of melt particles and shock lithified aggregates of sand normalized to the total amount of ejecta from a representative experiment in comparison to the numerical model [8]. Again we found an excellent agreement that confirms our model and the tracer approach to be well-suitable for quantifying the amount of shocked material and to track the trajectories of ejecta.

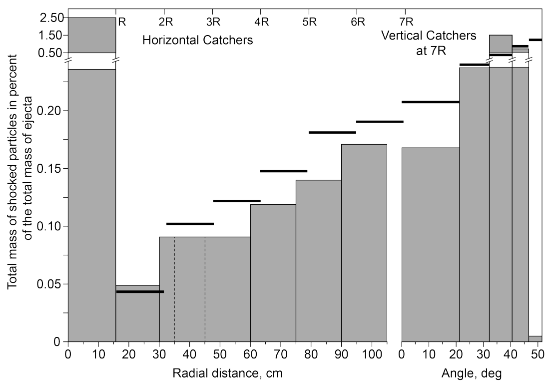

Fig. 2 Distribution of the percentage of the total mass of melt particles and shock lithified aggregates of sand normalized to the total amount of ejecta from experiment (grey columns) and numerical model (black horizontal bars). For further details, see [8].

Parameter study: Fig. 3 shows the results of impact models on an Itokawa-like asteroid. We assumed a higher gravity of g = 0.0162 m s^{-2} in comparison to the real gravity on Itokowa of g = 0.0001 m s^{-2}. Note that gravity does not affect melt production and has little effect on the ejection mechanics. Both was tested (in models with g = 0.0162–1.62 m s^{-2}) and found to be negligible for the present study. To calculate the escape volume, we used the real escape velocity on Itokowa of ~ 0.2 m s^{-1}. We also verified that the amount of melt relative to the size of the impactor is constant. Fig. 3 shows the percentage of melt that is ejected and escapes the gravity field (ejection velocity > escape velocity of 0.2 m s^{-1}) as a function of impact velocity and target porosity. At zero porosity (brown line) no melt is generated at 5 km s^{-1} . At 7.5 km s^{-1} almost 70% of the generated melt escapes the gravity field. At higher velocities more melt is generated, but the relative amount of escaped melt decreases. In fact the vast majority of melt that does not escape the asteroid remains inside the crater and is not ejected. This is most likely due to the fact that we consider vertical impacts only, which is a limitation of the 2D cylindrical geometry in our models. Material that is highly shocked and located in a cone-shaped volume underneath the point of impact is displaced into the target, lining the crater wall as a thin veneer, but is not ejected. This may change significantly in case of more realistic oblique impacts. For porosities ⩾20%, melt is already generated at an impact velocity of 5 km s^{-1}, but the escape melt volume also decreases with increasing impact velocity.

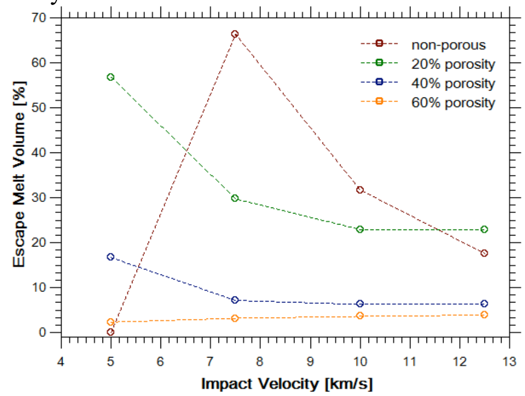

Fig. 3 Percentage of melt that is ejected and escapes the gravity field of an Itokawa-like asteroid relative to the total amount of generated impact melt as a function of impact velocity. According to [8,] we assume for the critical peak pressure for melting ~ 60, 30, 15, and 5 GPa for 0%, 20%, 40%, and 60% porosity, respectively. The projectile diameter is 50 m. We assumed an basalt ANEOS for both target and projectile.

Conclusion: Our models are in excellent agreement with observations from laboratory experiments, building high confidence in our results. Although our estimated critical shock pressures for melting of porous basalt may be questionable, different critical shock pressures would only cause a small shift of the lines shown in Fig. 3. Given the fact that ejection dynamics change significantly in case of oblique impacts, the biggest limitation clearly is the vertical impact simplification. Overall, our study demonstrates, that a significant amount of melting occurs at relatively low impact velocities if the target is porous. However, our models also predict that in case of vertical impacts a significant amount of the generated melt remains inside the crater and is not ejected and, thus, does not escape from the asteroid. In future studies we want to investigate the effect of impact angle.

References: [1] Hörz F. et al. (2005) Meteorit. Planet. Sci., 40, 1329–1346. [2] Nakamura T. et al. (2011) Science 333, 1113–1116. [3] Daly R. T. & Schultz P. (2016) Icarus, 264, 9–19. [4] Hamann C. et al. (2016) Geochim. Comsochim. Acta, 192, 295–317. [5] Wünnemann K. et al. (2008), EPSL 269, 529-538. [6] Wünnemann K. et al. (2006), *Icarus*, *180*, 514-527. [7] Stöffler D. et al. 1975 JGR 80, 4062–4077. [8] Wünnemann K. et al. (2016), *M&PS*, *51*, 1762-1794. [9] Melosh H. J. 2007. M&PS 42, 2079–2098. [10] Pierazzo B. et al. (2005) GSA Special paper 384, 443–457. [11] Kowitz A. et al. (2016) M&PS 51, 1741–1761. [12] Reimold and Stöffler (1978) LPSC 2805-2824.