INSIGHT INTO CRATER FORMATION, SHOCK METAMORPHISM AND EJECTA DISTRIBUTION FROM LABORATORY EXPERIMENTS AND MODELING. K. Wünnemann[1], M.-H. Zhu[1,2], D. Stöffler[1], [1]Museum für Naturkunde Berlin, Leibniz Institute for Research on Evolution and Biodiversity, Germany, Kai.Wuennemann@mfn-berlin.de, [2]Space Science Institute, Macau University of Science and Technology, Macau..

Introduction: Impact gardening of planetary landscapes is a poorly quantified surface process that is the result of the formation of numerous craters of different size and age. The excavation, ejection, and deposition of material originating from different stratigraphic, lithological, and rheological units depending on the pre-impact structure of the target and the size of the impact event forms a complex stratigraphy of impactites from numerous events. In particular, for the petrological and geochemical evaluation and radiometric dating of critical lunar samples it is important to unravel the complex ejection and emplacement history of Apollo specimens with respect to large basin-forming and younger regional impact events. The ejection and distribution of material as a consequence of hypervelocity impact can be considered as a ballistic process. Angles and velocities of ejected particles have been recorded in small-scale laboratory experiments by Particle Image Velocimetry (PIV) [e.g. 1], but information on the original location of the ejected particles in the target and their shock exposure are lacking. We present the analysis of laboratory impact experiments at NASA Ames Research facility in 1972 that have been published only partially so far [2]. In these experiments the pre-impact location of ejecta in the target and its final deposition was determined by using color-coded sand and a catcher system. In combination with numerical modeling we provide insight of the ejection kinematics and thermodynamics. Rigorously tested and calibrated numerical models enable to predict the genesis and emplacement of ejecta as a function of complex target settings (layers of different lithologies and properties, and thermal gradients) for impact crater formation ranging from simple craters to large impact basins (see also companion abstract Zhu et al., "Numerical modeling of ejecta distribution and crater formation of large impact basins on the moon").

Experiments: In two campaigns (19 experiments) plastic (Lexan) cylinders (series I) [2] and aluminum spheres (series II) with a mass of 0.30 to 0.38 g were fired vertically into targets of quartz sand with velocities ranging from 5.86 to 6.90 km/s producing craters 29.5-33.6 cm in diameter. In each experiment layers (9 mm thick) and rings (2-3 cm wide) of colored sand were placed at different positions (depths, radii) in the target. The ejecta were collected in bins at various radial distances r from the point of impact (r = 16-105 cm; ~1.1 to ~7 crater radii). Besides mass also the degree of shock metamorphism of individual particles in each bin at a given radial distance was determined.

Modeling: We used the iSALE [3,4,5] shock physics code to simulate the experiments. The behavior of the quartz sand target was modeled by a Drucker-Prager rheology and ANEOS [6] combined with the $\varepsilon-\alpha$ compaction model [4]. We used tracer particles to record the shock conditions and to determine angle and velocity of ejection. Subsequently, we calculated the ballistic trajectories for each tracer to work out the deposition distance.

Results: Fig. 1 shows the relationship between pre-impact location and ejection distance of particles obtained from the analysis of experiments and numerical modeling. Generally, we find a good agreement between models and experiments comparing crater size (not shown here) and the mass of the deposited ejecta per unit area versus radial distance. The mass of the ejecta decreases with distance according to a power-law (solid black line in Fig. 1a/b fitted to model results), which is in good agreement to previous studies [e.g. 8]. Note, the slight increase in mass at distances >90cm is due to material that bounced of the wall of the target chamber. It should be also noted that the data quality decreases with distance as there is only a relatively small number of tracers and sand grains ejected to such distances. Generally, the number of sand grains is much higher than the number of tracers.

Comparing the distribution of color-coded sand we also find a good correlation between experiments and models up to a deposition distance of approximately 50-60 cm. Up to this distance ejecta mainly originate from the outer most rings (orange and blue). At larger distances the model predict that most tracers were ejected from the green ring whereas in the experiments most ejected grains are violet, red or black (color of the innermost rings). In particular, black grains occur at all distances in the experiments. In terms of simple ballistic ejection mechanics this distribution is difficult to explain and we attribute the observation to some specifics in the experiments: (1) from the somewhat asymmetric distribution of ejecta in different radial directions we conclude that there was some offset (~1.5 cm) between the point of impact and the geometric center of the colored rings; (2) black lacquer that was sprayed on the target to identify the pre-impact surface may have dyed the top layer of grains black and, as a consequence, those grains, misinterpreted as black, were basically found at all distances in the experiments; (3) due to the irregular shape of the quartz grains their surface was not entirely covered with dye and they may have lost there marking during the ejection and were interpreted as uncolored (quartz grains below the color-coded ring layer); (4) The ejection process may have been affected by a jet of the propellent gas streaming out of the launch tube behind the ejecta.

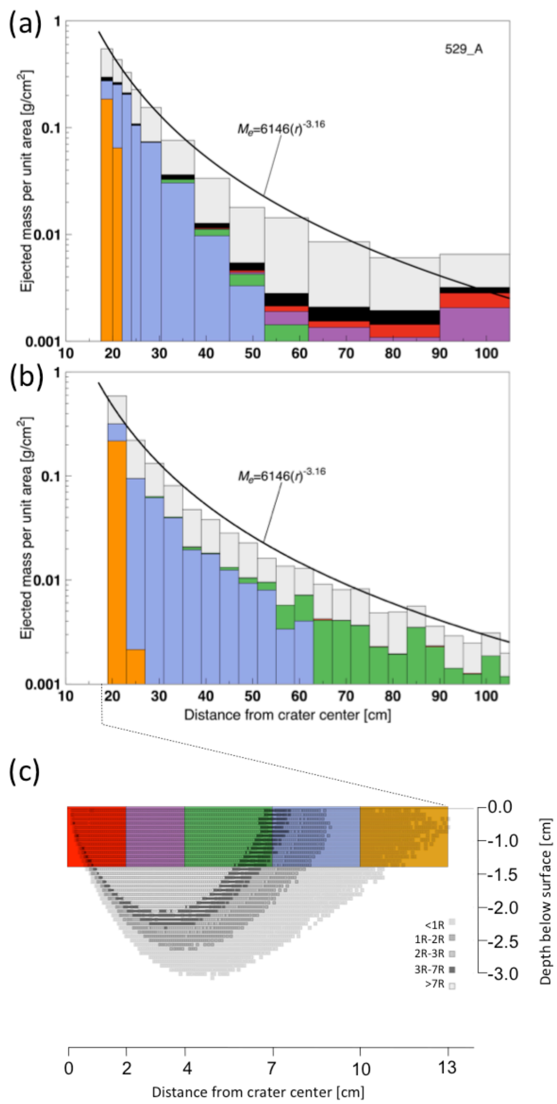

Figure 1: Comparison of color-coded ejecta distribution in experiment (a) and model (b). The original location of colored rings (shifted by 1.5 cm, see text for explanation) in the model and different zones of the excavation depths of ejecta and their final deposition distance are shown in (c).

In the models we tried to account for (1) by shifting the impact point by 1.5 cm into the red zone of tracers (Fig 1c); however, it is not possible to adjust the models for (2), (3) and (4). Fig 1c shows the excavation depth of material deposited at different distances (grey contours) based on numerical models.

The analysis of quartz grains from the experiments enables to distinguish different types of shock metamorphic particles resulting from melting, and from agglutinary and comminutive processes: (1) melt particles ($P_{max} >\sim 13$ GPa); (2) shock lithified sand with strong shock effects in quartz (diaplectic glass and planar deformation features) and lack of porosity ($P_{max} = \sim 13$ to ~ 5.5 GPa), (3) shock lithified sand without distinct shock effects but still zero porosity ($P_{max} =\sim 5.5$ to ~ 0.9 GPa), and (4) fractured quartz grains ($P_{max} <\sim 0.9$ GPa) [e.g. 9, for the projectile target interaction see also companion abstract by Hamann et al., "Experimental impacts of aluminum projectiles into quartz sand: Formation of khatyrkite (CuAl2) and reduction of quartz to silicon"]. Our results confirm that material closest to the point of impact experience the highest shock pressures and are ejected the furthest. However, a direct quantitative comparison between the distribution of shocked ejecta between models and experiments is difficult, because of the small shock volumes that cannot be resolved adequately in the numerical models. High-resolution models enable to quantify the total amount of shocked material according to the different shock levels (1-4), but those models do not allow predicting the final distribution.

Conclusion: The agreement between observations from impact experiments and results from numerical modeling is generally satisfactory. Deviations can be explained by limitations of the experimental method. On the other hand, the experiments provide insight into the shock modification of sand grains way beyond the resolution that is possible in numerical models. The models allow for a more systematic study of the ejection parameters (velocity, angle, shock pressure, temperature) as a function of material properties (see [10] and companion abstract Luther et al., "Numerical simulation of ballistic and non-ballistic ejection processes as a function of material properties"). The validation of our model in this study now enables in a next step meaningful upscaling of our results on laboratory scale to dimensions of natural craters.

References: [1] Anderson J.L.B. et al. 2003, J. Geophys. Res. 108(E8); [2] Stöffler D. et al., 1975, J. Geophys. Res. 80; [3] Amsden, A. et al. 1980, Los Alamos National Laboratories Report, LA-8095; [4] Wünnemann K. et al. 2006, Icarus, 180; [5] Collins G.S. et al. 2004, M&PS 39; [6] Thompson S.L. and Lauson H.S. 1972, SC-RR-71 0714; [7] Melosh H.J. 2007, M&PS, 42; [8] Hörz et al., 1983, Review of Geophysics and Space Physic, 21, 1667-1725; [9] Kowitz A. et al., 2013, EPSL 384, 17-26; [10] Collins G. S. & Wünnemann K., 2007, 38th LPSC, p. 1789.