INSIGHT INTO THE DISTRIBUTION OF HIGH PRESSURE SHOCK METAMORPHISM IN RUBBLE-PILE ASTEROIDS. N. Güldemeister[1,2], J. Moreau[1,3], T. Kohout[1,4], K. Wünnemann[2,5]. [1]Department of Geosciences and Geography, University of Helsinki, Finland (nicole.gueldemeister@mfn.berlin), [2]Museum für Naturkunde, Leibniz Institute for Evolution and Biodiversity Science, Berlin, Germany, [3]Department of Geology, University of Tartu, Estonia Institute of Geology, [4]Institute of Geology of the Czech Academy of Sciences, Prague, Czech Republic. [5]Freie Universität Berlin, Institute for Geological Science, Germany.

Introduction: Shock metamorphism in ordinary chondrites is driven by impact events between asteroids. The degree of shock metamorphism [1] depends on the amount of energy (i.e., pressure) deposited upon impact. Extensive numerical modeling [2−5] and shock experiment research [6] focused on the darkening of ordinary chondrites. Shock-darkening of asteroids happens at two different stages of the shock scale, at shock stage C-S7 (>70 GPa, whole rock melting, [1]) or between shock-stage 5 and 6 (40–60 GPa, metals and iron sulfides melt veins [2−7]). All darkening processes affect the reflectance spectra of ordinary chondrites. If an asteroid fragment of the S-complex asteroids is shock-darkened, its spectra will be similar to C/X-complex asteroids. Such observation would affect the generally accepted distribution of asteroids in the Main Asteroid Belt [7,8].

We investigate the impact conditions on asteroids in order to study the volume of possibly shock-darkened asteroidal fragments and to provide a general overview of shock metamorphism within impacted rubble-pile asteroids. Therefore, we employed the iSALE shock physics code [9] and based our research on the following knowledge. The distribution of porosity in rubble-pile asteroids strongly depends on the internal structure [10]. If an asteroid has high average porosity, the internal structure may be composed of dense and low-porosity boulders surrounded by more loose and porous materials.

The aim of the research is to highlight what type of asteroid collisions can explain the abundance of high shock stage materials of the L-chondrite type [12] and the abundance of shock-darkened asteroidal fragments.

Methods: The iSALE code simulates hypervelocity impact processes in solid materials. We used the ε-α compaction model [9] for porosity with fixed strength properties from [13] and an ANEOS for dunite to represent the material of the projectile and asteroid. We applied a cylindrical-symmetry 2-D Eulerian frame of

reference with Lagrangian tracers to study the distribution of peak shock pressures [14,15].

For this, we use numerical models of simplified rubble-pile structures of asteroids where porosity is heterogeneously distributed between boulders and finer materials and study:

a) The distribution of peak shock pressures (shock metamorphism) in the initial elements of the impacted asteroids (loose material, boulders) and quantification of shock fractions.

b) Quantification of shock-darkening material (shock stages in the rubble-pile asteroid as well as in ejected and escaping material).

The model of a rubble-pile asteroid of 5km in diameter is represented by several porous boulders of varying sizes surrounded by loose material (Fig. 1). For the different impact scenarios, we varied the impact velocities (4−10km/s), the projectile diameters (800-1600m) and the porosities of the boulders (10−30%) as well as the porosity of the surrounding loose material (75−100%).

Results and discussion: The distribution of peak shock pressures strongly depends on both impact velocity and projectile size (Fig.1). With decreasing impact velocity (10 km/s on the left to 4 km/s on the right), a significant decrease of shock pressures can be observed. Smaller impactor sizes (Fig.1 c and d), while keeping all other parameters constant, (boulder and loose material porosity) also lead to a decrease in shock pressures. However, the effect of the impact velocity is stronger than the effect of impactor size.

Comparing peak pressures of the shown scenarios with cases considering larger boulder porosities (not

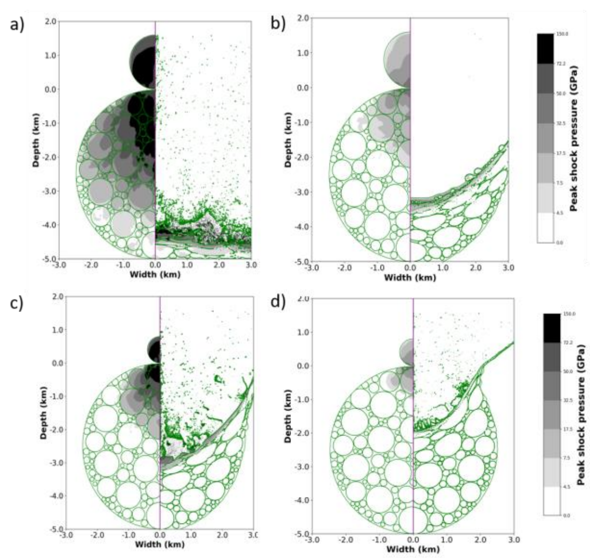

Fig.1. Peak pressure distribution in the rubble-pile asteroid after the collision event. Left panels show tracers that are set back to their original positions, right panels show the final positions of tracers recording peak pressures. a) and b) show impacts of a 1600 m projectile onto a rubble-pile with boulders of 10% porosity surrounded by loose material (75% porosity) with impact velocities of 10km/s (a) and 4 km/s (b); c) and d) show impacts of a 800 m projectile, respectively.

shown here) only results in small differences. We can also show that the rubble-pile asteroid is almost completely destroyed (right panels in Fig. 1) and the porosity of the loose material is crushed out by the shock wave.

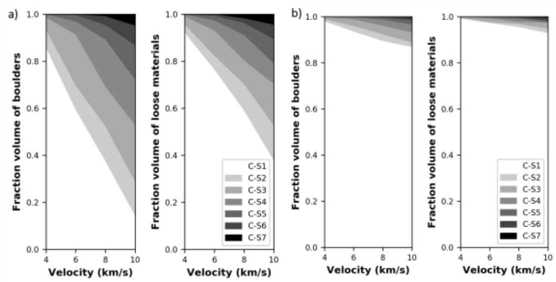

Fig 2. Fractions of boulders and loose material affected by shock after the shock stage classification from [1] considering different impact velocities plotted on the x-axis for a 1600 m projectile in diameter (a) and a 800m projectile in diameter (b). Boulders have porosity of 10%, loose material of 75%.

Regarding the observed shock stages for the boulders and loose material, fractions affected by shock after the shock stage classification of [1] are shown in Fig. 2 for different impact velocities (x-axis) considering a collision of a large impactor (Fig. 2a, 1600m) and a small impactor (Fig. 2b, 800m). For smaller impact velocities, we do not reach shock effects that would lead to shock-darkening which is also not the case for the smaller impactor where only a very small fraction of the material is affected by shocks corresponding to higher shock stages (C-S2 to C-S7). Thus, the fraction of material recording high shock metamorphism is only significant for higher impact velocities with larger projectiles.

In Fig. 3 we show the results from the investigation of the ejecta for different collision scenarios dependent on impact velocity. The efficiency of shock-darkening (mass of shock-darkened material in the rubble-pile normalized to the impactor size), as seen in Fig. 3a, increases significantly with increasing impact velocity and is strongly dependent on the porosity of the boulders. Considering more porous boulders (triangles in plot), less material is shock-darkened. Fig. 3b and c show the shock-darkened mass which is escaping with respect to the total shock-darkened mass in the rubble-pile (b) and with respect to total escaping mass. It can be shown that for the most energetic impact between 15 and 45% of the shock-darkened mass in the rubble-pile asteroid are escaping from the asteroid. Here we also see a strong dependency on impact velocity. Furthermore, we have observed that a large amount of material is escaping; depending on the impact energy up to 90% of the asteroid mass (not shown here). However, only a small portion of the total escaping mass is actually shock-darkened, for almost all collision scenarios less than 6%, as shown in Fig. 3c.

To conclude, high levels of shock metamorphism in ordinary chondrites requires impacts with high velocities (8−10km/s) and large projectiles in order to exceed at least 20% of target mass within the C-S5, C-S6 and C-S7 shock stage distribution within rubble-pile asteroids as well as a sufficient amount of shock-darkened escaping material. Therefore, the abundance of high shock stage meteorites of the L-chondrite type may be linked to a more intense impact event able to reproduce large amount of high shock stage meteorites.

Acknowledgments: Our thanks go to the iSALE developers. This work is supported by the Academy of Finland and the European Regional Development Fund and the programme Mobilitas Pluss (Grant No. MOBJD639).

References: [1] Stöffler et al. (2018) *Meteorit. Planet. Sci.*, 53, 5-49. [2] Moreau J. et al. (2017) *Meteorit. Planet. Sci.*, 52(11), 2375-2390. [3] Moreau J. et al. (2018). *Phys. Earth Planet. In.*, 282, 25-38. [4] Moreau J. et al. (2019). *Icarus*, 332, 50-65. [5] Moreau J. and Schwinger S. (2020), 310, 106630. [6] Kohout T. et al. (2020) *Astron. Astrophys.*, 639, A146. [7] Kohout T. et al. (2014) *Icarus*, 228, 78-85. [8] DeMeo F. E. and Carry R. P. (2014) *Nature*, 505, 629-634. [9] Wünnemann K. et al. (2006) *Icarus*, 180, 514-527. [10] Housen and Holsapple (2003) *Icarus*, 163, 102-119. [11] Asphaug et al. (1998) *Nature*, 393, 437-440. [12] Bischoff et al. (2018) *Meteorit. Planet. Sci*., 1-14. [13] Cremonese et al. (2012) *Planet. Space Sci.*, 66, 147-154. [14] Elbeshausen et al. (2009) *Icarus*, 204, 716-731. [15] Elbeshausen and Wünnemann (2011) *Proc. 11th Hypervelocity Impact Symposium 2010.*

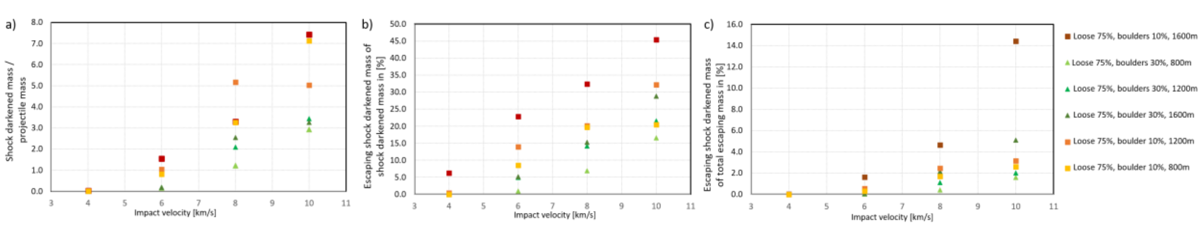

Fig. 3. Ejecta analysis for a collision of a projectile with varying size onto a rubble-pile asteroid with boulders of 10 or 30% porosity surrounded by loose material of 75% porosity. a) Material mass that is shock-darkened normalized to the projectile size as a function of impact velocity. b) Percentage of escaping shock-darkened material. c) Percentage of escaping material that is shock-darkened with respect to total mass of escaping material.