NUMERICAL MODELLING OF THE DEEP IMPACT MISSION EXPERIMENT K. Wünnemann[1], G. S. Collins[2], and H. J. Melosh[1], Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA, wunnema@lpl.arizona.edu, [2]Department of Earth Science and Engineering, Imperial College London, London SW7 2AZ, UK, g.collins@imperial.ac.uk .

Introduction: NASA's Deep Impact Mission (launched January 2005) will provide, for the first time ever, insights into the interior of a comet (Tempel 1) by shooting a ~370 kg projectile onto the surface of a comets nucleus. Although it is usually assumed that comets consist of a very porous mixture of water ice and rock, little is known about the internal structure and in particular the constitutive material properties of a comet. It is therefore difficult to predict the dimensions of the excavated crater. Estimates of the crater size are based on laboratory experiments of impacts into various target compositions of different densities and porosities using appropriate scaling laws; they range between 10's of meters up to ~250 m in diameter [1]. The size of the crater depends mainly on the physical process(es) that govern formation: Smaller sizes are expected if (1) strength, rather than gravity, limits crater growth; and, perhaps even more crucially, if (2) internal energy losses by pore-space collapse reduce the coupling efficiency (compaction craters).

To investigate the effect of pore space collapse and strength of the target we conducted a suite of numerical experiments and implemented a novel approach for modeling porosity and the compaction of pores in hydrocode calculations.

Numerical Model: We utilized a newly developed porosity model which is based on the well known P-α model [2, 3]. The major difference consists in using a volumetric strain dependency for the compaction of pore space instead of the usually applied pressure relationship (P-α model). A detailed description of the new porosity model is given by Wünnemann et al. (this volume). The new compaction model was incorporated in the SALE-3MAT hydrocode [4], which is based on the SALE hydrocode [5] and is basically very similar to SALEB by Ivanonv et al. [6]. We used the Tillotson equation of state to compute pressure and temperature as a function of internal energy and density. To account for the resistance of rocks against shear failure we applied a simple Mohr-Coulomb law, wherein strength Y is a function of pressure: $Y=\mu p+C$. μ is the friction coefficient and the C the cohesion of the material at zero pressure.

Specific model settings: We carried out Eulerian-mode impact simulations on porous Basalt to estimate the expected dimension of the crater on Tempel 1. Due to resolution limitations (we used a computational grid size of 550×500 cells with a cell size of 2.5 cm) we computed the impact of a larger but less dense projectile with the same mass as the projectile in the real experiment. Thus, instead of Copper we use an Aluminum cylinder, 1 m in diameter and 0.175 m high (total mass is ~371 kg; resolution of the projectile is 20×7 cells). The impact velocity is the same as in the experiment, 10.2 km/s.

The porosity of a comet's nucleus has never been measured directly and models predict a wide variation, ranging up to 80%. Therefore we used different initial porosity conditions (0, 50, and 80%) in the impacted target. Moreover, little is known about the strength properties of a comet. Previous studies estimate the yield strength ≤100 Pa [7]. Accordingly we used in our models a cohesion C=100 Pa and 0 Pa and an internal friction coefficient of μ=0.1 and 0.5, respectively.

The size of the comet's nucleus is very roughly estimated at about ~6 km diameter, thus curvature of the surface can be neglected in the simulations. Gravity was derived assuming a spherical shape with a mass according to the assumed porosity and density. Hence gravity ranges from 0.0005 m/s^2 (80% porosity) to 0.002 (0% porosity) with ρ=2800 kg/m³ (density of Basalt matrix).

Due to the small gravity the total formation time of the crater may last up to 300 s [1]. With a maximum time step of 1×10^{-6} (limited by the cell size and the sound speed of Basalt), 3×10^{8} iterations would be necessary to compute the entire process, which is not accomplishable. We present here models of the first 0.1 s. To simulate the entire cratering process in a reasonable time frame, regriding of the computational mesh part way through that calculation is required, to enlarge cell size and thus, decrease the number of cells.

The Effect of porosity: Fig 1 shows the shape and extent of the crater for different target porosities (0%, 50% and 80%) and densities after t=0.1 s. Basically, the more porous the target, the less dense and thus the deeper and wider the crater cavity at the given time steps. There is still a large amount of kinetic energy left in an area surrounding the cavity, so the crater growth continues (see Fig 2) and it is possible that the final crater dimension might become as large as 60 m or more in diameter as predicted from scaling laws [1]. A rather interesting result was obtained for the case of non-porous rock (porosity=0%). If the density is low

(similar to density with 80% porosity) the size of the crater is even larger than that formed in a porous target (80%). This is a simple consequence of the less rapidly declining shock wave in non-porous material. Energy is not lost by the compaction of pore-space, the coupling efficiency is increased, and thus the crater dimensions become bigger. This is also true for the non-porous target with a density similar to the one of the matrix where the crater cavity has almost the same size as the one with target porosity of 50%.
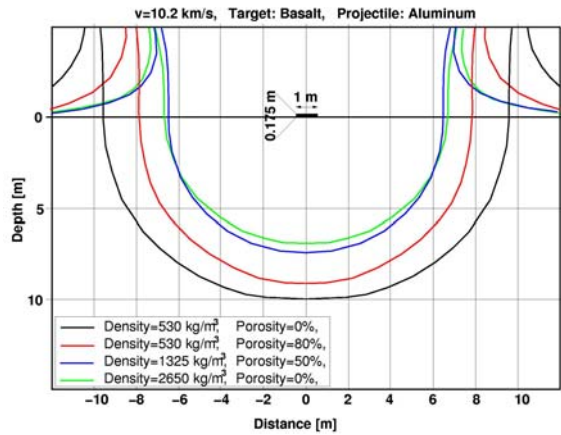

Fig 1: *Crater dimensions for different target porosities 0, 50 and 80% after t=0.1 s. There is no cohesion in the target (C=0) and the friction coefficient μ=0.1.*

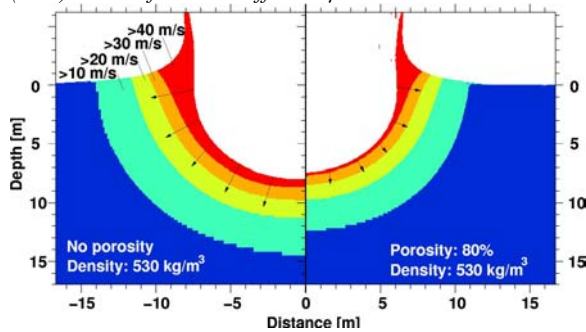**Fig 2:** *Velocity distribution of the excavation flow after 0.05 s. Left hand side correspond to non-porous rock model (ϕ=0, ρ=530 kg/m³), right hand side shows porous case (ϕ=80%, ρ=530 kg/m³). There is no cohesion in the target (C=0) and the friction coefficient μ=0.1.*

Figure 2 shows a comparison of the absolute velocity of the excavation flow after 0.05 seconds, in the simulations with a non-porous (left) and 80% porous (right) target of the same initial bulk density. At the stage of crater growth illustrated in Fig. 2 it can be assumed that the flow is directed outwards, away from the point of impact. The velocity distribution of the excavation flow suggests that the more rapid growth of the crater in the non-porous target is not just an early-stage effect; absolute velocities are larger in the non-porous rock model, and the zone where the absolute velocity is positive extends further from the impact

site. We anticipate, therefore, that the final crater will be larger for the non-porous target than for the porous one. This observation is in agreement of experimental results on rock samples and loose sand [1].

The Effect of strength: Whether the final crater is determined by strength or gravity cannot be derived from the models yet, since they last no longer than 0.1 s. But the models show that, even at this early stage. the crater is smaller for a stronger target (see fig.3). In the two models illustrated in Fig. 3 we used the same porosity (80%) and gravity conditions for the target rock but varied strength *Y*. A striking observation from these models is that, apart from the differences in depth and diameter, the angle of the ejecta curtain is significantly smaller for the more resistant target. This is a typical phenomena observed in many experiments and can be used to determine the strength of the target.
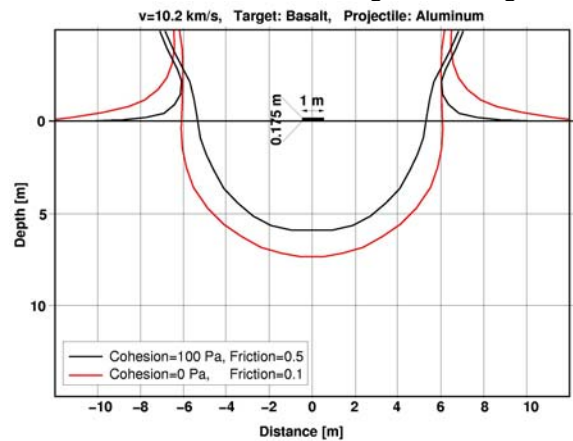

Fig. 3: *Crater dimensions for different target strengths after t=0.05 s. The porosity is 80% and the density is 530 kg/m³.*

Conclusion: Hydrocode modeling will play an important role in the data analysis of the deep impact mission. As these examples show, differences in crater size and shape can be used to constrain the parameters of the comets nucleus. As a future perspective we will compute the entire process until the main dynamic motions have ceased. This is a challenging task with respect to the long formation time of the crater in low gravity conditions.

References: [1] Richardson et al. (2005) *Space Science Reviews* (accepted). [2] Hermann (1969) J. *Appl. Phys.* 40, 2490-2499. [3] Carroll et al. (1972) J. *Appl. Phys.* 43, 1626-1636. [4] Wünnemann K. and Ivanov B. A. (2003) *Plan. Space Science, 51,* 831-845. [5] Amsden A. A. Et al. (1980) *LA-8095 Report,* Los Alamos National Lab., 101 p. [6] Ivanov et al. (1999) *GSA Special Paper* 339, 389-397. [7] Scotti et al. (1993) *Nature* 365, 733.