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Attachment 2: Preprint of

Compaction as the origin of the unusual craters on the asteroid Mathilde

Kevin R. Housen, Keith A. Holsapple and M.E. Voss

Nature **402**, 155-157 (1999)

Asteroid Mathilde has been pummeled by at least five giant impacts (Figure 1). Previous experience with cratering suggests Mathilde's giant craters should each be surrounded by kilometer-deep blankets of ejecta, i.e. material excavated during the impact events[1,2]. Curiously, there appears to be very little ejecta around Mathilde's craters; they show no evidence of filling by ejecta from adjacent large craters[1,3]. A previous explanation for the missing ejecta, based on computer simulations, is that Mathilde's unusually high porosity (50±20%[4]) confines the deposited impact kinetic energy to a localized volume, and produces excavation velocities so high (greater than ~ 20m/s) that nearly all ejecta escape Mathilde's gravitational field[5]. Here we report on laboratory experiments in a highly porous material that give a different explanation[3]. The crater is formed primarily by compaction, not excavation. The small amount of material that is lofted has velocities and ranges so small that nearly all of it is re-deposited within the crater bowl, thereby sparing neighboring craters from ejecta in-filling. This peculiar style of cratering implies that highly porous asteroids are minor contributors of meteorites, because essentially no ejecta escape these asteroids.

Numerical simulations of cratering face significant difficulties in realistically modeling the complex response of porous geological materials to high-speed impact. Therefore, it is useful to also study cratering experimentally. Laboratory experiments have a major advantage in that they use actual geological materials, and provide benchmark data as tests for numerical simulations.

Experiments, however, necessarily involve craters much smaller than those of interest on Mathilde. To bridge this gap in size scale, a geotechnic centrifuge can be used to directly simulate large-scale cratering events[6]. To show the basis for centrifuge modeling, consider the impact of a projectile of radius, a, velocity U, and mass density δ, into an asteroid composed of a granular soil of strength s, mass density ρ, and friction angle ϕ, and whose surface gravitational acceleration is g. Standard methods of dimensional analysis show that the dependence of crater diameter, D, on these seven parameters can be written in terms of five dimensionless groups[6-8]:

$$\frac{D}{a} = f\left[\frac{ga}{U^2}, \frac{s}{\rho U^2}, \frac{\rho}{\delta}, \phi\right]$$

Two impacts are physically the same (equivalent) if the four groups on the right side are the same for the two events. Then they must also have the same ratio of crater size to impactor size, D/a. If the two events involve the same materials and impact velocity, the sole remaining requirement for equivalence is that they have the same product ga. The utility of elevated gravity in centrifuge modeling stems from this condition: a big impact on an asteroid (large a, small g), has the same value of ga as a small impact on a centrifuge (small a, large g). The centrifuge reproduces the physical conditions of the large event, but at greatly reduced size scale[6-8]. In particular it gives the same lithostatic stress as the large-scale event. Assuming that no significant variable has been overlooked in the dimensional analysis, the small-scale test is physically the same as the large impact at the same velocity in the same material.

Equivalence also implies that gD=constant, because both ga and D/a are constant. Therefore, the diameter, D_C, of a centrifuge crater that simulates a crater of diameter, D_M, on a Mathilde-size body is given by $D_C = D_M \, g_M \, / \, g_C$, where g_M, and g_C are the gravitational and centrifugal accelerations on Mathilde and the centrifuge respectively. Mathilde's largest crater, Karoo, (D_M=33 km, g_M=1 cm/s^2) corresponds to a 6.7-cm diameter crater in a g_C=500G experiment (1G is 981 cm/sec^2, so g_C=4.9x10^5 cm/s^2).

Centrifuge experiments are essential for complete simulations of impact events, even in cases where gravity has little effect on crater size, such as small impacts into a strong material like rock. This is because gravity controls the ballistics and final state of lofted material and, therefore, always affects the ejecta blanket. Fortunately, equivalence of crater size also guarantees the ejecta blanket of a centrifuge crater is a geometric replica of the asteroid event[2].

We used a centrifuge to perform impact experiments at 500G into a low density, porous, crushable silicate material (Figure 2). Shot 1642 produced a remarkable crater that displayed essentially no ejecta outside the crater bowl. The small quantity that was ejected was less than 2% of the crater mass. This contrasts sharply with all previous experiments in soils, which always display well-developed ejecta blankets[2].

The lack of ejecta was investigated further in shot 1648, an impact into the same material, but at 1G so that ejecta velocities could be measured from high-speed movies (initial ejection velocities are independent of gravity[2]). Although ejecta were produced in 1648, the speeds were quite low. The fastest observed ejecta had a speed of only 19 m/s, a greater portion were in the range of 3 to 5 m/s, but most were below ~1 m/s. At 500G, an ejection speed of 5 m/s gives a ballistic range of only 0.5 cm, or ~20% of the crater radius. Thus, nearly all ejecta in the 500G event must have landed inside the crater. The fact that the crater retained some 98% of its mass, yet was not filled by its own ejecta, can only be explained if most of the crater volume formed by compaction of pore spaces (Figure 2), in contrast to the shearing and lofting observed in familiar geological materials. This same conclusion applies to the equivalent large craters on a Mathilde-size body, assuming its material behaves like our low-density, porous material.

Ejecta velocities were large enough to allow the 1G crater (1648) to develop a substantial ejecta blanket. Its 5-cm diameter is equivalent to a 50-m diameter crater on a Mathilde-size body. This suggests that small craters on Mathilde could have ejecta blankets, although they probably would not be detected in the NEAR images because of limited resolution.

Unlike the events reported here, cratering in common geological materials is largely an incompressible process. A crater is excavated as material is sheared and lofted to locations outside the crater. Thus, the stresses of the impact process must exceed the shear strength (cohesion) of the material, and gravitational lithostatic stresses. This has led to two major categories of impact events, depending on whether crater size is determined mainly by material strength or by gravity. For impacts in which the cohesive strength exceeds the lithostatic stresses, the scaled crater diameter, D/a, is independent of event size. In the other case, i.e. when lithostatic stresses are dominant ($\rho g D >> s$), the scaled crater diameter diminishes with increasing event size[7,8].

The craters formed in our experiments fall into neither of these categories. The porous material was too fragile for strength measurements, but qualitative comparison with other weak materials[9] indicate its strength is much smaller than the lithostatic stresses experienced in the 500G impacts ($\rho g D$=3x10^6 dyn/cm^2). That is, gravity played a more dominant role than strength. However, crater size was not controlled by gravity either; if it were, the 500G craters would have been substantially smaller than the 1G crater. In contrast, the 500G craters were actually larger.

Rather than being controlled by shear strength or gravity, crater size in the porous material was determined mainly by the stress required to compact pore spaces. In loosely packed porous materials, compaction occurs at low pressures by breaking weak inter-granular bonds and rearrangement of grains to reduce the volume of void spaces. This mechanism is distinct from the shock compaction of fully-dense materials[10], or the collapse of pores and cracks observed in silicate rocks[11], both of which require very high pressures, at least 10^9 dyn/cm^2. In contrast, tests in a hydraulic press showed that a pressure of 3x10^7 dyn/cm^2 permanently compacted our porous material to twice its initial density, a density then comparable to dry fully dense sand.

The compaction stress was not the only factor that determined crater size; otherwise the volumes of the 1G and 500G craters would have been about equal. The movie at 1G showed a mass of slow material lofted vertically to a height of ~10 cm, which fell back into the crater. This material probably expanded, reducing the 1G crater volume. Bulking would not occur in large craters (or at 500G) because the ballistic height of the vertically launched material would be negligible compared to the crater size.

If our material is representative of bodies like Mathilde, these experiments show that the traditional strength- and gravity-dominated regimes of impact cratering do not pertain to porous asteroids. Instead, crater size is governed by pore compaction from the outgoing pressure shock. Consequently, the impact-driven evolution of porous asteroids may be entirely different than that of denser, rocky objects. On a rocky asteroid, impacts of all sizes eject debris, some of which escape and may eventually impact the earth as meteorites. The rest is re-deposited on the asteroid surface, degrading extant craters and contributing to regolith buildup. In contrast, on a highly porous asteroid, only small impacts (perhaps $D < 1$km for Mathilde) produce ejecta deposits exterior to the crater rim (like shot 1648), whereas blankets would be absent around large craters. Only a small amount of ejecta would escape Mathilde. Such asteroids would liberate significant meteoritic material only from catastrophic impacts that shatter and disperse the whole body.

High porosity does not guarantee formation of compaction craters. For example, dry sand has a porosity of 35%, but sand craters form primarily by excavation, with significant ejecta blankets at all sizes. Compaction in sand is minimal because it is already near a "fully dense" state, i.e. the most efficient packing of particles. In this case, compaction cratering could only occur by crushing the constituent sand grains, which requires stresses much higher than those experienced by most of the cratered material. Most granular silicate materials are at their fully dense state when their bulk density is in the range of 2-3 gm/cm^3. Thus, compaction cratering in silicates can only occur if the bulk density is well below ~2 gm/cm^3. Interestingly, large craters on the Martian moons Phobos and Deimos (~1.9 gm/cm^3) do not show strong evidence of compaction effects[12], probably because they are close to the fully dense state. Furthermore, even initially highly porous asteroids about ten times larger than Mathilde's diameter would have lithostatic stresses comparable to the crush pressure of the material used here, and would naturally compact to near a fully dense state due to self gravity. Therefore, compaction cratering is not expected to be common on large asteroids.

High porosity may even be a fleeting characteristic of Mathilde-sized asteroids. As shown by laboratory experiments[13,14], and by Mathilde, highly porous bodies can withstand multiple large impacts without disruption. Each impact locally compresses the asteroid, because its volume decreases by the crater volume, while all mass is retained. Formation of the five largest craters on Mathilde (D_M>20 km) increased its bulk density by ~20%. Hence, Mathilde's initial density may have been even lower than the present value, especially considering that additional large craters may exist on the unobserved half of its surface. Over time, porous bodies may be compacted by impacts to the point of being fully dense. Ejecta velocities would then increase, allowing escape of some debris and formation of ejecta blankets around large craters, much as we envision for compact, rocky bodies.

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Acknowledgements. This work was supported by NASA's Planetary Geology and Geophysics Program.

FIGURE CAPTIONS

FIGURE 1 Mathilde, a 53-km diameter asteroid imaged by the NEAR spacecraft. The largest crater, Karoo, has a diameter of 33.4 km. The two additional craters indicated each have diameter of 29 km. A puzzling aspect of Mathilde is how these large craters could form in such close proximity and still retain a pristine appearance.

FIGURE 2 Experimental impact craters formed in a crushable material designed to illustrate the mechanisms that may occur on low-density asteroids. The target material has a bulk density of 0.9 gm/cm^3, a porosity of 60%, and consists of a mixture of quartz sand, perlite (a porous, easily crushable, silicate), fly ash (a binding agent) and water. The perlite ranges from dust-sized particles up to the ~ 5mm chunks visible in the bottoms of the craters. Craters were formed by impacts of polyethylene cylinders (diameter=0.65 cm, length=0.63 cm, mass=0.21 gm, density=1.04 gm/cm^3) at 1.9 km/s. Shots 1642-1644 were performed at 500G on a centrifuge in order to simulate the lithostatic stress and ejecta ballistics of large cratering events on an asteroid. In 1642 only ~ 2% of the crater mass was ejected beyond the crater edge. This crater formed primarily by compaction, as opposed to excavation, of the target material. This was verified by imaging the regions under the crater with computed tomography, which showed an increase of density beneath the crater, with a maximum value nearly twice the initial density. Compaction of pore spaces results in efficient damping of the shock as it propagates into the target, which may explain why the large craters on Mathilde formed in such close proximity with little evidence of seismic disturbance of nearby craters. To investigate this further, two additional craters at 500G were formed close to the 1642 crater. The 1643 crater had no visible effect on 1642, even though their rims were nearly touching. Crater 1644 formed even closer, breaching the rim of 1642 and 1643. Intersection of the rims resulted in some slumping of material into 1642 and 1643. These experiments show that large craters in porous crushable targets can form with little degradation of existing proximal craters. The appearance of Mathilde's pristine large craters is likely due to both suppression of ejecta and damping of the shock; both of which are a consequence of a highly porous material.

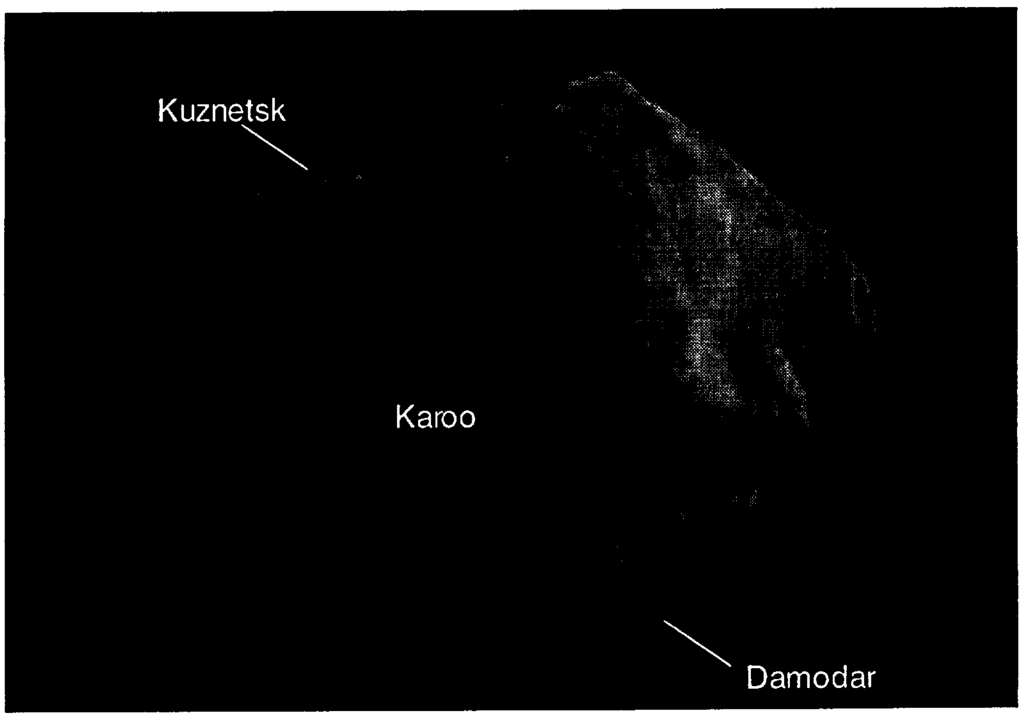

Fig 1. Housen, Holsapple & Voss. Designed for 67% reduction.

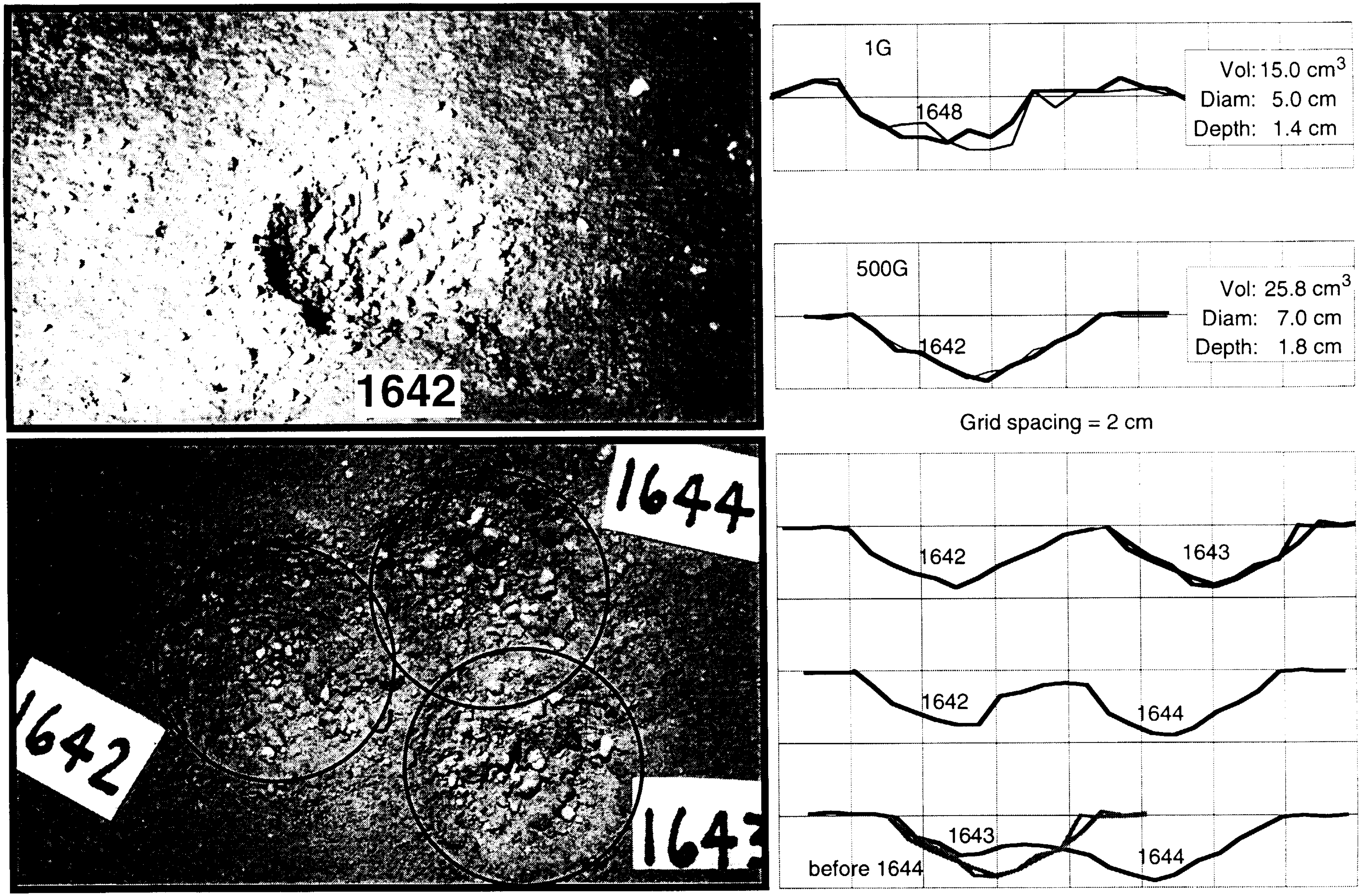

Fig 2. Housen, Holsapple & Voss. Designed for 65% reduction.