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

Kevin R. Housen*, Keith A. Holsapple† & Michael E. Voss*

* Shock Physics Group, MS 8H-05, The Boeing Company, PO Box 3999, Seattle, Washington 98124, USA
† Department of Aeronautics and Astronautics, 352400, University of Washington, Seattle, Washington 98195, USA

**The asteroid Mathilde has suffered at least five giant impacts. Previous studies suggest that Mathilde's giant craters should be surrounded by blankets of ejecta that are kilometres deep[1,2], yet the craters show no evidence of filling by material excavated during later nearby impacts[1,3]. Computer simulations of impacts have been used to suggest that the absence of ejecta arises because the impact energy is deposited in a small volume, due to Mathilde's unusually high porosity[4], which produces ejecta velocities so high that nearly all of the material escapes Mathilde's gravitational field[5]. Here we report laboratory measurements of high-velocity impacts into porous material, which support an alternative explanation[3]: the crater is formed mainly by compaction, not excavation. The small amount of ejecta lofted in our experiments have velocities sufficiently low that nearly all of the material is redeposited within the crater bowl. The crater itself results from material being compressed, rather than ejected. This type of cratering implies that highly porous asteroids are minor contributors of meteorites, because essentially no material escapes the asteroids.**

Numerical simulations of cratering face significant difficulties in realistically modelling the complex response of porous geological materials to high-speed impact. Therefore, it is useful also to study cratering experimentally. Laboratory experiments have a significant 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 centrifuge can be used to simulate large-scale cratering events directly[6]. To show the basis for centrifuge modelling, consider the impact of a projectile of radius $a$, velocity $U$, and mass density $\delta$, into an asteroid composed of a granular soil of strength $s$, mass density $\rho$, and friction angle $\phi$, 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]:

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

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 $g'a$. The utility of increased gravity in centrifuge modelling stems from this condition: a big impact on an asteroid (large $a$, small $g'$), has the same value of $g'a$ as a small impact taking place in 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 omitted 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 $g'D$ is constant, because both $g'a$ 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 (1 $g$ is 981 cm s$^{-2}$, so $g'_C = 4.9 \times 10^5$ cm s$^{-2}$). Karoo and two other giant craters, Damodar and Kuznetsk, are shown in Fig. 1.

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 that 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 500$g$ into a low-density, porous, crushable silicate material (Fig. 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 1$g$ 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$^{-1}$, a greater portion were in the range 3–5 m s$^{-1}$, but most were below ~1 m s$^{-1}$. At 500$g$, an ejection speed of 5 m s$^{-1}$ gives a ballistic range of only 0.5 cm, or ~20% of the crater radius. Thus, nearly all ejecta in the 500$g$ 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 (Fig. 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 1$g$ 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 spacecraft 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 both the shear strength (cohesion) of the material, and gravitational lithostatic stresses. This has led to two main 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—that is, when lithostatic stresses are dominant ($\rho g'D \gg s$)—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 500$g$ impacts ($\rho g'D = 3 \times 10^6$ 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 500$g$ craters would have been substantially smaller than the 1$g$ crater. In contrast, the 500$g$ craters were in fact larger.
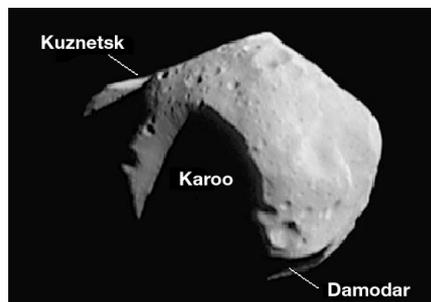
**Figure 1** Mathilde, a 53-km-diameter asteroid imaged by the NEAR spacecraft. The largest crater, Karoo, has a diameter of 33.4 km. The two additional craters indicated each have diameter of 29 km. A puzzling aspect of Mathilde is how these large craters could form in such close proximity and still retain a pristine appearance.

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 intergranular 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 $3 \times 10^7$ dyn cm$^{-2}$ permanently compacted our porous material to twice its initial density, a density then comparable to that of dry fully dense sand.

The compaction stress was not the only factor that determined crater size; otherwise the volumes of the 1$g$ and 500$g$ craters would have been about equal. The movie at 1$g$ 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 volume of the 1$g$ crater. This bulking would not occur in large craters (or at 500$g$) 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 from that of denser, rocky objects. On a rocky asteroid, impacts of all sizes eject debris, some of which escapes and may eventually strike the Earth as meteorites. The rest is re-deposited on the asteroid surface, degrading extant craters and contributing to
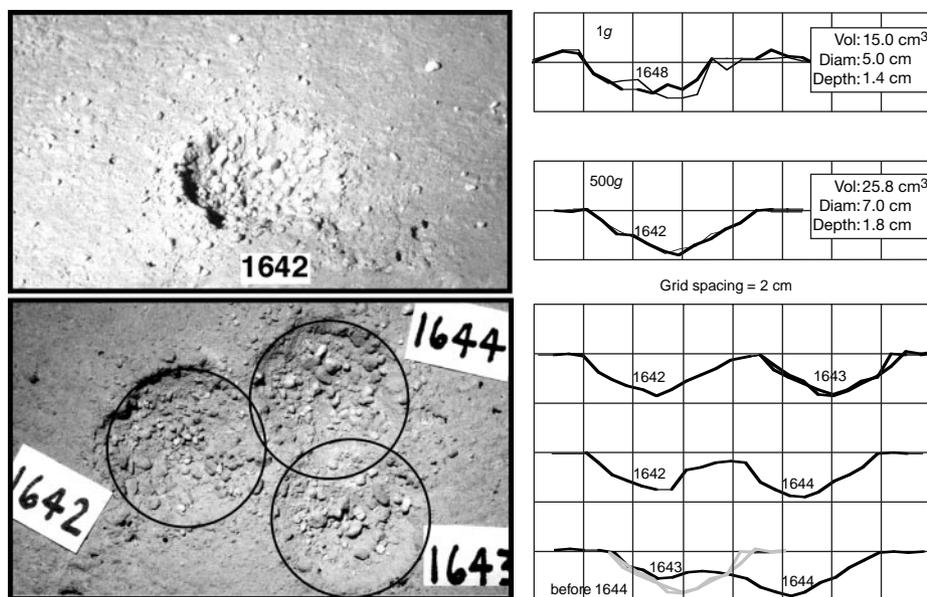


**Figure 2** Experimental impact craters formed in a crushable material designed to illustrate the mechanisms that may occur on low-density asteroids. The target material has a bulk density of 0.9 g cm$^{-3}$, a porosity of 60%, and consists of a mixture of quartz sand, perlite (a porous, easily crushable, silicate), fly ash (a binding agent) and water. The perlite ranges from dust-sized particles up to the ~5-mm 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 g; density, 1.04 g cm$^{-3}$) at 1.9 km s$^{-1}$. Shots 1642–1644 were performed at 500$g$ on a centrifuge in order to simulate the lithostatic stress and ejecta ballistics of large cratering events on an asteroid. In crater 1642 (top left panel) 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 500$g$ were formed close to the 1642 crater (bottom left panel). As shown in the crater profiles (right panels), formation of crater 1643 had no visible effect on crater 1642, even though their rims were nearly touching. Crater 1644 formed even closer, breaching the rim of craters 1642 and 1643. Intersection of the rims resulted in some slumping of material into craters 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 probably due to both suppression of ejecta and damping of the shock; both of which are a consequence of a highly porous material.

regolith build-up. In contrast, on a highly porous asteroid, only small impacts (perhaps $D < 1$ km for Mathilde) produce ejecta deposits outside 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 (the most efficient packing of particles). In this case, compaction cratering could only occur by crushing of 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 $2-3$ g cm$^{-3}$. Thus, compaction cratering in silicates can only occur if the bulk density is well below $\sim 2$ g cm$^{-3}$. We note that large craters on the martian moons Phobos cm and Deimos (densities $\sim 1.9$ g 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 $\sim 20$%. 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. Ejection velocities would then increase, allowing escape of some debris and formation of ejecta blankets around large craters, much as we expect for compact, rocky bodies. □

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# Spatial sampling of crystal electrons by in-flight annihilation of fast positrons

A. W. Hunt*†, D. B. Cassidy*†, F. A. Selim‡, R. Haakenaasen§, T. E. Cowan†, R. H. Howell†, K. G. Lynn‖ & J. A. Golovchenko*¶#

* Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA
† Lawrence Livermore National Laboratory, Livermore, California 94550, USA
‡ Engineering Physics Department, Alexandria University, Alexandria 21544, Egypt
§ Norwegian Defense Research Establishment, 2027 Kjeller, Norway
‖ Department of Physics, Washington State University, Pullman, Washington 99164, USA
¶ Division of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts 02138, USA
# The Rowland Institute for Science, Cambridge, Massachusetts 02142, USA

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**Energetic, positively charged particles travelling along a low-index crystal direction undergo many highly correlated, small-angle scattering events; the effect of these interactions is to guide or 'channel' (refs 1–8) the particles through the lattice. Channelling effectively focuses positive particles into the interstitial regions of the crystal: nuclear collisional processes such as Rutherford backscattering are suppressed, while the number of interactions with valence electrons increases. The interaction of channelled positrons with electrons produces annihilation radiation that can in principle[9–12] serve as a quantitative, spatially selective probe of electronic charge and spin densities within the crystal: in the interstitial regions, two-photon annihilation is enhanced relative to single-photon annihilation, because the latter process requires a nuclear recoil to conserve momentum. Here we report observations of single- and two-photon annihilation from channelled positrons, using a monoenergetic beam flux of $10^5$ particles per second. Comparison of these two annihilation modes demonstrates the ability of channelled positrons to selectively sample valence electrons in a crystal. Useful practical implementation of the technique will require the development of more intense positron beams with fluxes approaching $10^7$ particles per second.**

These experiments were performed at the recently constructed 3-MeV monoenergetic positron beamline at Lawrence Livermore National Laboratory. An electrostatic accelerator was modified to accommodate a 109 mCi $^{22}$Na positron source, a tungsten moderator, as well as appropriate focusing optics in the terminal. The positrons were accelerated to 2.65 MeV and then passed through two bending magnets, two solenoid focusing lenses and two quadrupole astigmatism correctors, all designed, constructed or modified for
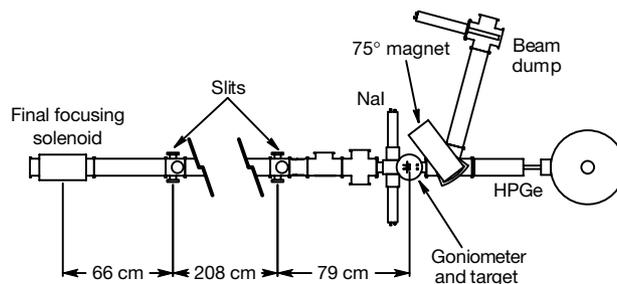


**Figure 1** Experimental set-up. Shown is a diagram of the final leg of the 3-MeV monoenergetic positron beamline at Lawrence Livermore National Laboratory.