SHATTERED DIRT: SURFACE FRACTURE OF GRANULAR ASTEROIDS. Erik Asphaug, Dept. of Earth and Planetary Sciences, University of California, Santa Cruz (easphaug@ucsc.edu)

Introduction: The hypothesis explored here is that asteroid 433 Eros, a relatively large (~33 km x 13 km x 13 km) rocky near-Earth asteroid, is structurally similar to the upper meters of the Moon – that it is globally a dry rocky dust-rich regolith, beaten apart by eons of cosmic impacts, but under 1/300th the gravity.

According to this view, the fractures expressed on the surface of Eros – as well as Phobos, Ida and other asteroidal bodies – are not cracks in hard rock, but are fissures in the mildly cohesive soil which comprises their bulk. Fissures form in the outer tens of meters in response to impacts (or possibly tides in the case of Phobos) and fade away by reverberation and gardening from later small impacts. At depth, where overburden exceeds cohesion, deformation is continual.

We are driven to this conclusion by the physics of rock fracture. The conclusion is supported by the expected behavior of powdery soils in microgravity. But the puzzle of why the fissures have pits, and why they occur in parallel, may not be explained until we have a better look at these very interesting small worlds.

The problem with strength: Eros has been regarded as a fractured monolith or "shatter pile", which is a rocky body with structural integrity across global scales, and whose components are jointed but not jumbled [e.g. 1, 2]. But contemporary models of fragmentation and disruption [3] predict that any large rocky asteroid will be transformed into a jumble of dust, gravel, talus and boulders on a timescale much shorter than its catastrophic disruption lifetime. So there is a discrepancy between physical predictions – that asteroids should be rubble piles – and observational interpretations – that cracks imply crackable solid bedrock.

Figure 1. Buzz Aldrin's boot print on the Moon (Apollo 11 photograph). Fissures up to several cm deep were observed in the powdery soils of the Moon. Scaled to asteroid gravity, lunar soil could support faults 10's of meters deep.

The basic problem with the shatter-pile model for Eros is that the fracture energy of intact rock is much greater than its gravitational potential. The particle velocity of rock broken by an elastic acceleration scales with the square root of strength, $Y \sim \rho v^2$. Typical intact rock with Y~10 MPa will fracture at characteristic particle velocities v~20 m s^{-1}, in excess of the asteroid's escape velocity (v_{esc}~10 m/s). Even allowing for numerous mitigating factors it is difficult to conceive of hundreds of fractures forming in intact rock [as mapped by 5] without the rock mass being jumbled into an unrecognizable form. There is no such thing as a rock on a 10^{-3}G asteroid that is fractured in place.

Fractures in dirt: Irregular shape of itself does not imply structural integrity. It has been argued [4] that global slopes (at 100 m baseline) are gentle (~10°) on Eros except within impact craters (~30°-40°), what one expects for lunar-like regolith blasted around by impacts. As for the presence of fissures, this also does not require structural integrity. The comparison is to fracturable granular materials such as powders. For instance, if contact energy scales with the inverse of grain size (e.g. with surface energy per unit mass), then boulder piles on Eros should behave somewhat like xerographic toner under 1G, and support fissures. Soils on asteroids will be very cohesive compared to the small gravitational stress, and support fractures.

Lunar soil is observed to sustain fissures several cm deep (e.g. Figure 1). Scaling linearly to Eros gravity, lunar-like soil can sustain fissures 10's of m deep on an asteroid, consistent with the scale of the fracture grooves that are seen on this and other asteroids including Ida, Gaspra and Phobos. Below that depth failure is by continuum deformation.

If the fracture occurs in a medium orders of magnitude weaker than rock – cracks forming in dirt, that is – then it would resolve two problems: (1) Fractures and fissures would form easily, and become muted easily, as observed. (2) Their formation would entail low particle velocities and therefore no jumbling.

The motivating observation is that the majority of faults on Eros occur in the upper tens of meters. Assuming lunar-like regolith with cohesion ~1 kPa, faulting in an Eros-sized dry dirt ball is *expected* to a depth of tens of meters.

As regards the idea of shattering in place: for a cohesion of ~1 kPa the characteristic elastic particle velocity required to create a fissure is only ~10 cm/s, locity required to create a fissure is only ~10 cm/s, significantly lower than Eros' escape velocity. Ironically, then, it is the very observation that has been claimed to falsify the hypothesis of rubble pile structure – the prevalence of fractures – that best supports it. Eros may be a shatter pile – but only if made of shattered dirt. The argument applies equally to other fissured asteroids such as Ida, Gaspra and Phobos.

Density of dirt: Sometimes the relatively low porosity of Eros is taken as evidence for a fractured monolithic or shatter-pile structure, as opposed to a rubble pile structure full of voids. The inferred bulk porosity is 20-30% based on comparison of its measured density (2.7 g cm^{-3}; [6]) with the density of analogous meteorite rocks (ordinary chondrites, typically ~3.4 g cm^{-3}). But this porosity is what one expects for a rubble pile. 30% is about the porosity of sand and talus, even before one allows for infilling by smaller grains. Better yet, return to the example of lunar regolith. The rock-strewn dust-rich upper meter of the Moon has bulk density ~1.5 g cm^{-3}; compared to the material density of basalt (2.7 g cm^{-3}) upper lunar regolith has about the same porosity as the bulk of Eros.

The pits: Pitted chains in the fracture grooves of Phobos have been proposed [7] to be expressions of the drainage of loose material into fissures below. Pitted chains are observed, though more subdued, on Eros. This too has been used to argue for the requirement of a competent faulted substrate. However, pitted chains do form in cohesive powders when they are pulled apart under 1G, and [8] use cohesive powder in scale models of Mars pitted groove formation.

Why not Itokawa? The absence of fissures on Itokawa may seem a puzzle. By this reasoning Itokawa should be even more cohesion-dominated, and express prevalent faults. But this very small asteroid (1/70 D_{Eros}) has a different response to impacts than a larger one [9], having a much smaller critical crater diameter for global resurfacing. Small impacts might shake down any fissures. But also, Itokawa appears lacking in surficial dust, the source of soil cohesion, as its small grains are easily picked away by the solar wind.

Brittle-ductile transition: Continuum deformation occurs at depth, where overburden exceeds cohesion. A global-spanning fault system like Rahe Dorsum, for instance, does not indicate brittle deformation throughout the interion. Large scale deformation is ductile below ~100 m (for the assumed cohesion) and only is expressed as faults above the brittle-ductile transition, just as on any other planet.

Conclusions: Robinson et al. [10] concluded that "continuous grooves, steep continuous ridges, and fault planes suggest, despite the heavy fracturing, that [Eros] possesses mechanical strength to some degree and is not strictly a gravitationally bound granular object." This is true; however, when the degree to which Eros must have strength is scaled to the gravitational stresses that are applicable, regolith-like cohesion exceeds the overburden in the upper ~10-100 m where structure is observed.

There remain enigmas, but it would appear most concordant with the data for Eros to made largely of rock-strewn dirt. The same goes for Ida, Phobos, Gaspra, and other asteroids whose networks of fracture grooves could not possibly form in place under dynamical elastic loads in intact bedrock. Fractures in dirt form easily and go away easily, and require a cohesion similar to that measured in dry lunar regolith.

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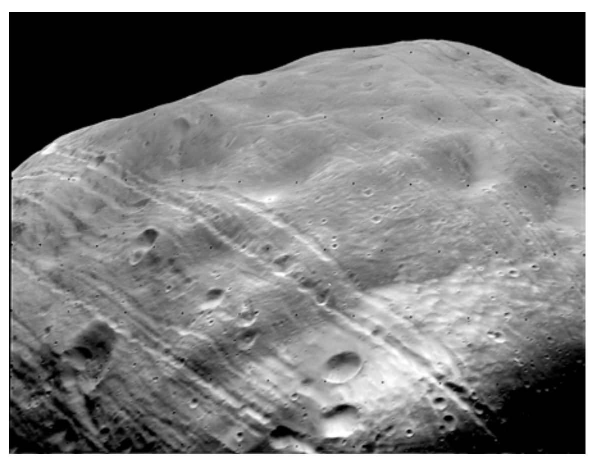

The fissures on Eros, Phobos (above, Viking image) and other asteroids are proposed to be pulled or sheared apart in granular regolith, not cracks in solid rock. They come and go easily. The mechanism of granular collapse has, on an asteroid, a subtle interplay with the solar wind which ionizes the surface and picks off the finest particles.