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Craters without ejecta

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ABSTRACT

A significant portion of the Solar System's population of minor bodies may be quite porous. A unique aspect of crater formation in porous bodies is that large craters may form without the ejecta deposits that are associated with craters on less porous bodies. In this paper, laboratory experiments and scaling theories are used to identify the conditions under which ejecta deposits are suppressed. The results are consistent with the interpretation that large craters on asteroid Mathilde (porosity ∼50%) and Saturn's moon Hyperion (porosity >40%) apparently formed without producing significant ejecta deposits, while smaller bodies do have notable regoliths.

1. Introduction

The ejecta blanket, or deposit, is the layer of loose excavated surface material that was launched from inside a crater to land outside the periphery of the crater. It is an intuitively obvious feature to anyone who has thrown a rock into a pile of sand or a puddle of water. Ejecta deposits were recognized and discussed from the time of Galileo to the mid 1900s during the debate over the volcanic versus impact origin of craters. Since the onset of the modern era of cratering research in the 1960s, numerous field, observational, theoretical and computer studies have provided great detail on the structure and formation of ejecta deposits, and their importance in the evolution of the terrestrial planets, satellites, and minor bodies of the Solar System. The excavation and deposition of material during a cratering event play a fundamental role in the degradation and erasure of existing surface features, the formation of secondary craters, the exposure history of regolith material to solar and galactic cosmic rays, the formation of meteorites, and the process of understanding the formation of terrestrial impact craters from field observations. In short, ejecta deposits are hallmark features of impact craters.

Therefore, the observations of Asteroid 253 Mathilde returned by the NEAR mission in 1997 were very surprising. Several large craters in close proximity and in a pristine state dominate Mathilde's surface landscape. Evidently, mutual degradation by ejecta deposits or seismic shaking did not occur (Veverka et al., 1999; Chapman and Merline, 1999). The NEAR observations might not have been as surprising if Mathilde were the first minor body to be viewed up close because one might conclude that all of the ejecta from the large craters escaped Mathilde's weak gravity field. However, Mathilde, with a mean diameter of 53 km, is larger than asteroids Gaspra (14 km) and Ida (36 km), both of which showed evidence of significant ejecta several years earlier during the Galileo mission. More recently, Cassini observations of Saturn's 270-km moon Hyperion indicate a lack of ejecta deposits (Thomas et al., 2007) based on its well-preserved crater population.

The unusual appearance of Mathilde and Hyperion has been attributed to their relatively high porosity: ∼50% for Mathilde (Veverka et al., 1999) and >40% for Hyperion (Thomas et al., 2007). Housen et al. (1999) and Housen and Holsapple (2003) have shown that large craters can form in porous materials without significant ejecta deposits. In porous materials, much of the crater volume forms by permanent compaction of the voids. The energy losses incurred during this process result in ejection velocities so low that much of the ejected material fails to clear the crater rim, and lands short of the crater radius. As described in the next section, this process only occurs for large craters formed in highly porous materials. The purpose of this paper is to determine the conditions for which ejecta deposits do not form and to point out the areas that need further work in order to improve our understanding of cratering on porous bodies.

2. Formation of ejecta deposits

We begin with a description of the ejecta formation from a hypervelocity impact into a typical soil of low or at most moderate

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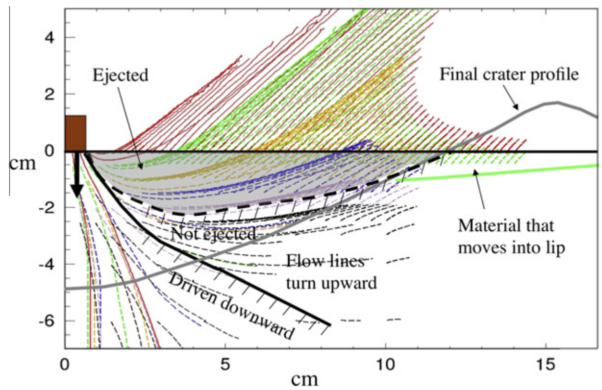

Fig. 1. Streamlines of material flow from a numerical (CTH) simulation of impact cratering in fully dense sand (density = 1.8 g/cm^3, porosity = 35%) at 1 G gravity. The projectile was a 1.35 g polyethylene cylinder with a speed of 1.8 km/s. Material below the thick black curve is driven downward. Material above that curve, but below the thick black dashed curve is displaced outward and upward but is not part of the ejecta deposit. Only the material above the dashed curve is ejected. The gray curve shows the final crater profile. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

porosity. As shown below, this includes materials with porosities lower than about 35%. An impact in such a material generates a shock wave that sets the surface and sub-surface material in motion. For example, Fig. 1 shows the results from a code calculation of a projectile impact at 1.8 km/s into dry sand with 35% porosity. All material that originates beneath the thick black line in the figure is driven downward into or below the crater floor. Material above that line and beneath the thick black dashed line is initially driven downward, later turns upward, but is never ejected from the crater. All material originating above the black dashed line moves up toward the surface and is ejected. The thick solid gray line indicates the final crater profile. Since this dry sand is initially "fully dense", i.e. is at its maximum packing density, its porosity plays little role in the cratering process.[1] In this case the difference between the volume that is ejected and the final crater volume represents the material that is driven downward, outward and up into the crater lip, instead of being compacted to a higher density. The ejected material forms a thin curtain moving outward at the crater edge, until the growth of the crater is arrested by either the soil strength or by gravity. Any material that does not escape the impacted body then returns to the surface and forms the ejecta deposit that surrounds the crater.

Housen et al. (1983) considered the formation of ejecta deposits in dry soil and rock that typically have less than about 30–35% porosity. They showed that the topography of ejecta deposits depends on whether the final crater size is determined by the strength of the surface material (strength regime) or by gravitational forces (gravity regime). The division between these two regimes is determined by the ratio of a stress measure, Y, i.e. some strength of the surface material,[2] to a characteristic lithostatic stress, ρgR, where ρ is the density of the material, g is the gravitational acceleration and R is the crater radius.[3] In the strength regime, where $Y/\rho gR \gg 1$ (e.g. small craters in materials with non-zero strength), the ejecta may be dispersed to distances large compared to the crater, thus producing a discontinuous ejecta deposit. In the gravity regime, where $Y/\rho gR \ll 1$ (e.g. large craters in weak materials), craters exhibit continuous ejecta deposits that are geometrically similar at all size scales.[4] This general behavior has been observed in lab and field cratering studies of low or moderately porous target materials. It can be explained by the following scaling arguments, which serve as a point of departure for highly porous targets.

2.1. Scaling of ejecta deposits

Consider a particle launched at distance x from the impact point at velocity[5] v and angle θ measured from the surface. Our interest here is material that returns to the surface, with an initial velocity well below the escape velocity (although escape of ejecta is considered below). Assuming a flat surface, the particle lands at distance r from the impact where:

$$r = x + \frac{v^2 \sin(2\theta)}{g} \tag{1}$$

The ejection velocity is a function of the launch position x and is given by the ejecta velocity distribution $v(x)$. In the strength regime the velocity distribution is a function of the launch position normalized by the crater radius (Housen et al., 1983; Housen and Holsapple, 2011)

$$v\sqrt{\frac{\rho}{Y}} = f\left(\frac{x}{R}\right) \tag{2}$$

Now consider material ejected from a fixed point relative to the crater radius, i.e. at a fixed value of x/R. Eq. (2) shows that the ejection velocity, and therefore the ballistic range of this material, is *independent* of crater size. For example, if material launched at $x/R = 0.5$ from a 1-m crater travels a distance of 100 m, then material launched at a similar position from a 100-m crater would travel the same distance. However, in the latter case, the material lands relatively closer to the crater rim. This can be seen by substituting Eq. (2) into Eq. (1) and dividing by the crater radius R:

$$\frac{r}{R} = \frac{x}{R} + \frac{Y}{\rho g R} f^2\left(\frac{x}{R}\right) \sin(2\theta) \tag{3}$$

Eq. (3) shows that, at fixed x/R, the normalized ballistic range r/R decreases as crater size increases. In a series of increasingly larger events, material launched from homologous positions relative to the crater radius lands relatively closer to the crater. As a result, the ejecta deposit of a small strength-dominated crater forms much further from the crater in terms of crater radii than does the deposit of a large (but still strength-dominated) crater in the same material.

But the crater size is determined by gravitational forces at sufficiently large size scales where the strength of the material is unimportant. In this gravity-dominated regime, the ejecta velocity distribution is (Housen et al., 1983; Housen and Holsapple, 2011)

$$\frac{v}{\sqrt{gR}} = f\left(\frac{x}{R}\right) \tag{4}$$

Substitution of Eq. (4) into Eq. (1) gives

$$\frac{r}{R} = \frac{x}{R} + f^2\left(\frac{x}{R}\right) \sin(2\theta) \tag{5}$$

[1] In experiments in dry fully dense sand, there is a small amount of fine powder produced by crushing of the material in the high-pressure region near the impact. However, most of the cratering flow in dense sand is incompressible. That is not true for materials with higher porosity that crush at much lower pressure.

[2] As in previous publications, e.g. Housen and Holsapple (2011), we emphasize here that there must be a material stress measure Y for the strength, such as a cohesion, tensile strength, crush strength or any other measure with stress units. This is not the case for dry sand where its resistance to deformation is proportional to the lithostatic pressure according to an angle of friction concept. That lithostatic pressure is not a fixed material measure, but instead depends on the problem scale.

[3] R refers to the *apparent* radius of the crater, i.e. the distance from the point of impact to the point where the crater intersects the original surface of the target. The radius to the crater rim is typically about 20% larger.

[4] Geometric similarity of ejecta deposits means that the thickness of the deposit at some range is independent of crater size if both the thickness and range are normalized by the crater size.

[5] Note, the terms velocity and speed are used interchangeably in this paper.