THE THIRD REGIME OF CRATERING: SPALL CRATERS.

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Introduction: Small cm-sized craters in brittle materials (rocks and ices) formed from impacts in laboratories on Earth have an outer broad shallow region of surface spall (tensile fracture), surrounding a central (pit) crater of greater depth. That has been known for some time, and is usually just treated as an annoyance in our attempts to make lab simulations of "real" craters. Mostly we just ignore the difference and use the conventional strength regime cratering rules for all strength craters.

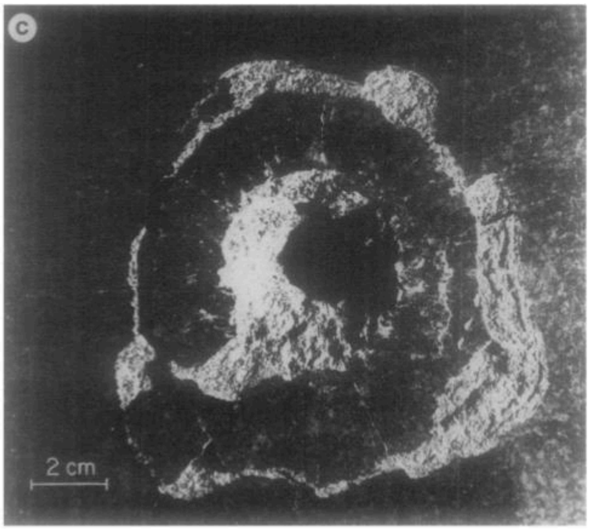
But is that valid? We know that on Earth, the spall feature for explosive craters in rocks only occurs for crater smaller than a meter or so [1] What about impacts on a small asteroid? We present the view here that spall craters are very important in the overall study of cratering, and even dominate the cratering on small brittle bodies. We show the existence of, in addition to the standard strength and gravity regimes, a third important regime of crater formation dominated by spall: it is a subset of the strength regime.

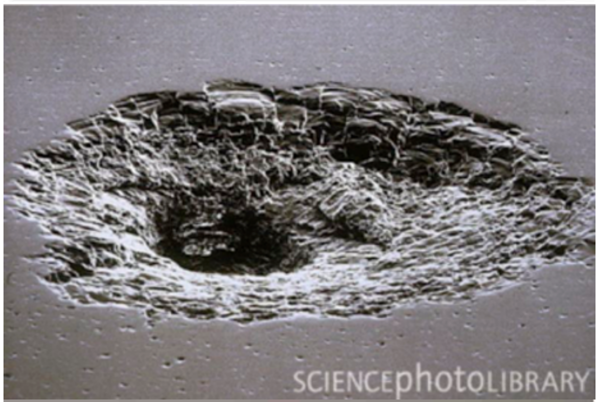
We develop the scaling theory for those craters. The theory is based on two ideas about the formation proceses. The first is based on the role of gravity in removing a spall region, and the second is based on size-dependent strength. We revisit scaling laws for the strength regime of cratering and use those to estimate the size crater at which the spall features will be present or absent.

The results have important implications regarding cratering on the smaller bodies of the Solar System and in the interpretation of surface morphology and crater counts for a rocky, 10-100 km object. The application to an Eros-sized rocky body would suggest a relative dearth of small craters but an abundance of blocks.

Spall Craters: The following three figures illustrate spall crater features. The first is for a cm-sized crater in San Marco Gabbro [2]. The second is a Scanning Electron Micrograph of a mm-sized crater in the surface of a window of Space Shuttle Challenger [3] . The third is a crater formed by the authors in California River rock at a speed of 5.6 km/s.

These figures all show the same crater morphology: a broad, flat outer spall crater formed from the tensile failure or spall of the material, with a much smaller central pit crater. The diameter of the spall crater is 3-4 times that of the central crater [4].





That creates a problem in trying to simulate large cratering events in small-scale in the laboratory in these brittle materials. Should one, for example, include the volume of that spalled material in scaling formulas? Or instead, should one ignore that volume and only consider the volume of the central pit crater region, which is much smaller. What is the fate of the material in that spalled region? How do we relate the small-scale results to the larger events of interest? What about for cratering on small bodies? We address the scaling issues for such spall craters.

Scaling theory: Conventional crater scaling theory is based on the "point-source" assumption: that the initial deposition of energy and momentum is at a single point and instantaneous compare to the length and time scales of the cratering process [5]. In that case, there are no separate dependences on impactor radius *a,* velocity *U,* and mass density δ, but instead the cratering depends on a single combined "coupling parameter" measure of the power law form $C=a\,U^{\mu}\,\delta^{\nu}$. That this point-source assumption applies quite broadly to hypervelocity impacts is been well proven by theory and experiments over the last several decades[5].

In this case any linear dimension such as the crater radius *R* must be related to the impact conditions by the non-dimensionl form [5]:

$$\frac{R}{a}\left[\frac{Y}{\rho U^2}\right]^{\frac{\mu}{2}}\left[\frac{\rho}{\delta}\right]^{\nu} = \text{const}$$

where ρ is the target density and *Y* its strength. This tells us that when the impact velocity *U* and the target strength *Y* (target material) are fixed, the radius *R* of craters will scale proportionally to the impactor radius *a*. (The scaling defined by this equation is traditionally called "cube root" scaling, since a linear dependence on the impactor radius implies a cube-root dependence on its mass and energy.)

But therein lies a dilemma. If the above arguments are valid, this form must hold for *every* length scale of the resulting crater. It will hold for the outer diameter, central pit depth, central pit radius, depth of a spall region and, the outer radius of spall region. As the size of the impactor *a* increases, the size of every crater dimension will increase linearly and equally for impacts into a given material at a given impact velocity. Therefore, the entire crater shape would be invariant and its morphology would be determined by one overall size scale. If there is a spall region at small size, there will be a similarly shaped, but proportionally larger spall region at large size.

But that is not what happens, as was discussed in the introduction. The spall features vanish for large craters. Something in the above argument is not correct. There are two proposed reasons for this. They are discussed in turn.

Scaling of Spall: The fundamental assumption of strength (cube-root) scaling for cratering is that the strength dominates gravity for all aspects of the process, so that gravity can be entirely ignored. That may be only partially true. It is true that the initial energy deposition and properties of the outgoing shockwaves satisfy cube-root scaling, and gravity has no affect. In a brittle material, the reflection of those shock waves at the free surface creates spall surfaces just beneath the target surface [6]. The depth to those surfaces also scales in a cube-root manner. So a crater of any size will have spall surfaces out to a cube-root scaled range. However, for the spall plate above those surfaces to be lifted from the surface to become part of the crater requires enough initial vertical velocity to overcome gravity. At small gravity, the entire plates can be launched form the crater. Therefore, although strength creates all of the initial conditions, gravity determines whether spall contributes to the crater or not.

Further, there is an additional factor about crater scaling: the fact that the effective strength of a rock decreases to some power of size for increasing event size. That also plays a role in determining those conditions for which spall cratering is important.

Results: Both of these concepts will be discussed in the presentation. It is found that on a given size body, Various estimates of the numeric determines the equation for that limit:

$$D_{crater}(km) < 8.6\left[D_{asteroid}(km)\right]^{-.67} \quad \textbf{(1)}$$

Thus, all craters on a km-sized rocky body are predicted to be spall dominated. For 5-20 km objects, such as Gaspra (6.1 km), Ida (15.7 km) and Eros (16.8 km), (assuming negligible regolith and bare rock surfaces) craters smaller than a km or so will be spall craters. Since typically a spall crater will have an outer radius that is 3-4 time that of a excavation crater, that would introduce an offset in crater size distribution curve compared to the impactor size distribution. And, finally, on such a body, the spall plate launchings would create many blocks and rocks with diameters on the order of 10-20 m.

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