THE EFFECT OF TARGET STRENGTH VARIATIONS ON COMPLEX CRATER FORMATION: INSIGHT FROM NUMERICAL MODELLING

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Introduction: A phenomenological model for the formation of impact craters in uniform crystalline targets now exists, based on decades of geological, geophysical, experimental and theoretical study [e.g. 1, 2, 3]. An impact excavates a deep, bowl-shaped cavity that subsequently collapses under gravity to form the final crater morphology. Numerical simulations have verified this model, to a large extent, by reproducing the final crater morphology of many large terrestrial craters [e.g. 4, 5], and the size morphology progression of lunar impact craters [6]. Despite the importance of this standard model in a planetary context, many craters in our Solar System do not form in a uniform crystalline target. The majority of the Earth's surface, for example, is covered by sedimentary rocks and or a water layer. Depsite the importance of layering throughout the solar system, very little is known about the effect this has on the cratering process. In this presentation I review recent progress in understanding the effect of target layering on impact crater formation using numerical models.

The effect of target layering on crater formation: The termination of crater growth and the degree and nature of subsequent crater collapse is controlled by gravity and the "strength" of the target material. In this context, strength means the shear strength of the target after it has been processed by the shock wave (fractured, heated, and set in motion) and until the major cratering motions have ceased. It is variations in this dynamic strength within a target that have a profound effect on crater formation. Substantial variations in target strength exist in many contexts in the solar system, due to variations in material and temperature: water and sediment layers on Earth and Mars; brittle and ductile ice or water layers on the icy satellites; regolith layers on asteroids, comets and other airless bodies; and, at the largest scale, crust over mantle on differentiated planets and satellites. Amongst these are some general cases that have been investigated by recent numerical modelling studies:

***Surface water*:** A number of numerical modelling studies demonstrate that the presence of a water layer has two principal effects on impact crater formation [7-13]: (1) to reduce the size of the crater formed on the seafloor, and; (2) to enhance, or modify the late-stage collapse of the crater. For a given size impact, the effect of the water layer can be characterized by the ratio of impactor diameter to water depth [7]. If the water depth is an order of magnitude, or so, bigger than the impactor diameter all the impactor's energy goes towards forming a crater in the water layer, and no crater is formed on the ocean floor. If the water depth is less than about twice the impactor diameter, on the other hand, the final crater is only slightly smaller in size than the corresponding dry-target crater and only minor changes to large-scale crater morphology occur. For intermediate water depths the cratering process is drastically altered. The seafloor is affected by the passage of the shockwave that forms when the impactor strikes the water; by high velocity water resurge flows; and by the temporary removal of the substantial overburden of the water column. The final manifestation of such a seafloor disturbance is yet to be fully quantified by numerical modelling, but is likely to be broader than the equivalent crater had the impact occurred on land, possibly with a larger central uplift.

***Weak over strong*:** Many known terrestrial craters formed in a mixed sedimentary and crystalline target. In several notable cases, impact induced deformation was much enhanced in the sedimentary layer, giving the crater a characteristic "inverted-sombrero" morphology: a broad, shallow outer basin, surrounding a deeper inner basin. Numerical modelling has demonstrated that this type of crater morphology can be reproduced if the sedimentary layer is substantially weaker than the underlying basement (because it is poorly-lithified or water-saturated, for instance; see Figure 1). Simulations of the Mjolnir [8] and Chesapeake Bay [14] impacts, for example, show just this behavior and are in excellent agreement with interpretations of geophysical data from the craters.

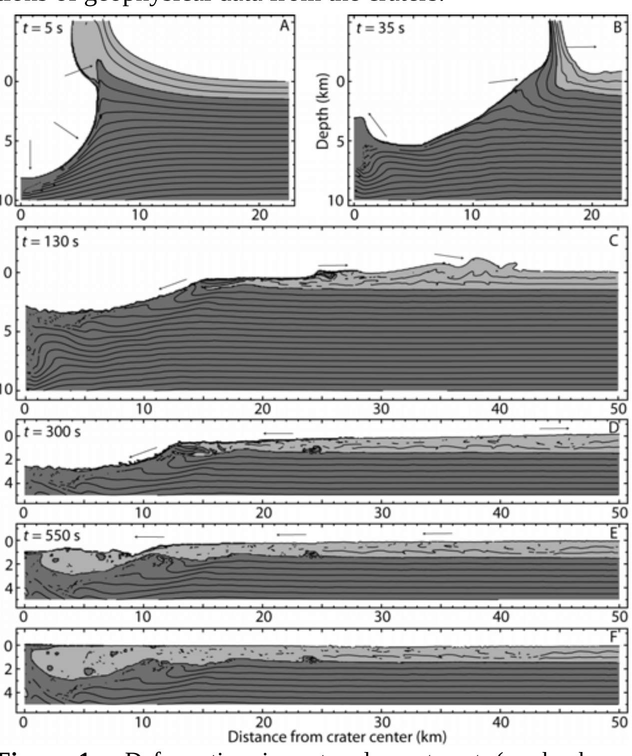

Figure 1. Deformation in a two-layer target (weak above strong) from a numerical simulation of the Chesapeake Bay impact [15]. Dark grey is crystalline basement; light grey is weak sediments). Arrows denote average direction of major motions.

***Strong over stronger*:** In more typical subaerial targets differences in layer strength are less significant than at Cheaspeake Bay, for example. Nevertheless, the presence of sediments can affect the structure of similar size craters if the sediment thickness is different. The Ries and Haughton impact structures, for example, are two craters of similar size (~15-25-km), but with different thicknesses of sediments above the crystalline basement (~0.8 vs ~1.8 km), and quite different interpreted morphology. Preliminary numerical modeling work suggests that the structural differences between Ries and Haughton impact craters are primarily due to the difference in thickness of the sedimentary cover and that the impact energy involved in both was about the same [15,16].

Chicxulub, Vredefort and Sudbury are three larger terrestrial impact craters that, again, differ in structure primarily because of differences in pre-impact target structure. A comprehensive modeling study of all three impacts [17] showed that inclusion of all the important layers—sediment, crust and mantle—each with a common strength model, produces results that are in good agreement with a broad range of available geological data and interpretation based on geophysical data.

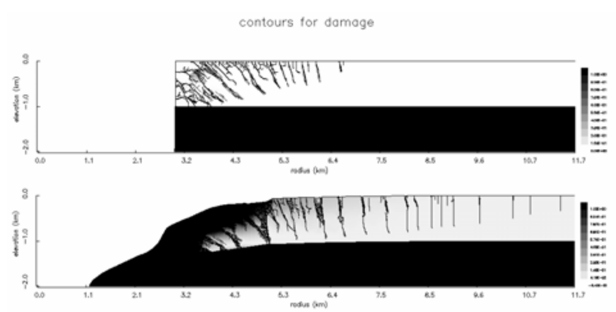

Figure 2: Fracturing in an axisymmetric two-layer cylindrical cavity collapse simulation with a strong, brittle layer over a weak, ductile layer. The shading denotes the amount of damage (black = completely damaged, white = undamaged). From [24].

***Strong over weak*:** Theoretical and numerical modeling of multi-ring craters [18,19] suggests that external ring formation is a consequence of the basal drag exerted on a brittle, elastic surface layer by a weaker, more mobile substrate as it flows inwards to compensate for the absence of mass in the excavated crater. This model has been further constrained for Valhalla-type multi-ring basins, where the rings are closely-spaced, concentric fault-bound graben. The formation of these faults appears to require that the elastic upper layer be thin and that the mobile substrate be confined to a relatively thin layer [20-22]. This rheologic situation occurs on the icy satellites and in rare cases on the Earth. For example, the curious Silverpit "crater", which may be an impact crater, exhibits similar characteristics to Valhalla-type impact basins. It has been suggested that in this case the mobile subsurface layer was caused by the presence of overpressured chalk layers at depth that acted as detachments and expedited inward flow of a thin subsurface layer [23]. Numerical modeling has provided insight into multi-ring cratering. Figure 2 shows results from a simple cylindrical cavity collapse model [24]: the mobile lower layer flows inward causing the elasto-plastic layer above to sag downward. Flexure in the brittle layer causes extensional fractures to form in the upper layer.

Bridging the gap: The presence of strength variations within a target can have a dramatic effect on crater formation. Layering can affect crater size and morphology, and produce craters with multiple concentric rings, the diameter of which may be misleading as a measure of impact size. To best study these craters it is imperative for collaboration between modelers and observers. It is also essential that the dimensions of complex crater features are described explicitly to avoid misinterpretation [25].

The most useful observational data for impact modelling is large-scale: characterization of the pre-impact target (density, porosity, strength, water content); amount of erosion since impact; magnetic, gravity and seismic velocity anomalies; characterization of post-impact target (e.g. shock barometry, temperature estimates, fracture density and spacing, strain measurements) as a function of radial distance from center. There is a need, therefore, for an appropriate method for averaging small (microscopic, or outcrop-scale) measurements over larger regions.

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