IMPACT CRATERING IN SOFT SEDIMENT LAYERS.

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Introduction: Soft sediments cover much of the Earth and Mars, ranging from a few meters to 1km in thickness. While soft sediment impacts are widely studied in laboratory-scale experiments, there are few preserved examples on the Earth that allow direct comparison at large scales. One exception is the vast depositional loess deposits in Argentina that date back to the Miocene [1, 2]. Detailed petrologic studies reveal enhanced melting yet shocked minerals similar to crystalline basement rocks but at a scale of tens of microns [3,4].

The present contribution addresses the effect of unconsolidated sedimentary layers on the morphology of eroded impact structures, buffering of shock effects, and comparisons with relict structures to estimate the amount of missing sequences. Hypervelocity impact experiments were used to asess the effect of low-impedance surface layers on crater diameter, substrate damage, and soft-sediment compression. The resulting craters are compared with much larger structures on Mars with possible implications for larger terrestrial craters formed in easily eroded target materials.

Experimental Studies: Hypervelocity impact experiments at the NASA Ames Vertical Gun Range used porous sand and plasticene layers of different thicknesses over an aluminum plate for impacts at different angles. In addition, craters into pumice targets with layers at different depths were differentially eroded in order to assess the sensitivity to and expression of relict features.

Vertical impacts (90°) into the sand-over-aluminum target easily penetrated the low-impedance surface layer. Even though the crater bottomed-out at the substrate surface to form a diameter:depth ratio of 15:1, crater diameter in the surface layer remained unaffected until the layer depth (h) was reduced to less than three times the projectile diameter (a) as shown in Fig. 1. In this case, crater diameter and depth for gravity-controlled growth are not simply related but are decoupled, except for extremely thin layers. This appears to be the result of isolated shear (within a plane due to decreased coefficient of friction).

Decoupling crater diameter and depth reflects different processes controlling each dimension. While shock rarefaction off the free surface of the target controls crater diameter in loose particulates, projectile penetration affects crater depth. Penetration is limited by shock rarefactions in the projectile (both from the top and laterally) that decelerate and disrupt it until dynamic resistance (yield strength) limit further travel [e.g., 5]. Consequently, lateral crater growth in a low-impedance (low strength) surface layer can be limited by gravity while penetration is limited by both the shock transferred from the low-impedance veneer to the substrate and the residual momentum of this impactor (and compressed target material).

High-speed imaging and 3D-PIV techniques demonstrate that ejection angles and velocities of particulates from the veneer are not significantly different from values for impacts into a target composed of just the veneer. For example, ejection angles for sand over aluminum remained close to 48° (from the horizontal), comparable to the nominal 45° for a half-space experiment using just sand. Most collisions on planetary surfaces, however, are not vertical. Oblique impact experiments reveal that crater diameters for impacts at an angle of 45° are unaffected as h/a approaches 1. Impact angles less than 15° push h/a to less than 0.5 when the projectile fails and couples most of its energy to the target by ricocheting debris before significant penetration [6].

A low-impedance surface layer also can significantly reduce damage to the underlying competent substrate. Vertical hypervelocity impacts (90°) penetrate low-impedance layers and excavate the substrate until the depth of the final crater in the layer approaches the excavation depth, which is about 50% of the final crater depth.

Surface layers more effectively shield the subsurface during oblique impacts. Shielding is a corollary to the increased coupling to the surface layer, as indicated by reduced effects on crater diameter with smaller values of h/a (Fig. 1). Three processes contribute to reduced damage in the substrate. First, peak pressures directed downward in the target below the impact point are reduced by the vertical velocity component, as expressed by crater scaling [7], target damage [8], and peak shock pressures [9-11]. Second, the substrate is shielded from damage due to the reduced transmission of the shock from a low-impedance to a high-impedance material. Third, reflection of oblique shocks from interfaces reduce the peak pressures transmitted below. These three processes can decouple diameter and depth, provided that the surface layer does not have such a low impedance that the projectile penetrates through it unabated. The first two processes combined predict that a 5 km/sec at 30° into a layer of sand over an aluminum plate would cause damage to the plate as if it were an impacted directly at a velocity of less than 1 km/s.

Experiments with impacts into compressible particulates (such as pumice dust or loess) produce highly compacted materials beneath the floor. These compressed floor "plugs" can be removed intact following the impact experiments. When nearly completely eroded away, only small mounds of compressed dust (and melt) remain.

Implications and Tests: On Earth, impacts into thick deposits of loess or ice would be effectively destroyed. Impact craters on Mars, however, provide large-scale tests for the resulting expressions in eroded sedimentary sequences. Fluvial and eolian processes have produced thick, layered, unconformable sequences with significant accumulations around both poles, Arabia, and Medusa Fossae Formations [12]. Extremes in orbital forcing currently result in the cyclic redistribution of volatile-rich deposits. As a result, unusual crater relicts remain, including “pedestal craters” and inverted crater (circular mesas and knobs). “Pedestal craters” here refer to impact structures situated on a plateau with outward facing scarps.

Mechanisms proposed to account for pedestal craters at high latitudes include ejecta covering volatile-rich substrate [12], impact-generated winds [13], and an impact-heated atmosphere that results in melting and cementation of the ejccta [14]. These are not mutually exclusive models; rather, they apply in different environments and at different scales.

An outward-facing scarp develops as the underlying soft (volaitel-rich) sediment back-wastes the ejecta toward the crater rim. In extreme cases, only the crater floor (or exposed subfloor) remains, thereby leaving an inverted crater, i.e., the floor (rather than the rim) stands in relief above the deflated surroundings. In some regions, cycles of deposition filled the central crater and form resistant layers.

Secondary craters also can form inverted topography. For example, secondary chains from the crater Lyot extend into the northern plains but remain as inverted topography (elongated, rimless mounds or chains of hummocky material) [15]; similar inverted secondaries are well documented around the crater Mie near the Viking 2 landing site [16]. Regions that exhibit such crater relicts also exhibit anomalous crater size-frequency distributions: extremely young ages (Amazonian) based on small craters but very old (Noachian) based on large craters. They also typically have numerous small mounds superimposed across nearly all but the youngest large craters. The number density of these small mounds is consistent with the number of missing craters inferred from crater statistics. Consequently, very young surface ages for some regions on Mars may reflect exhumation ages (rather than unit ages) similar to the terrestrial record.

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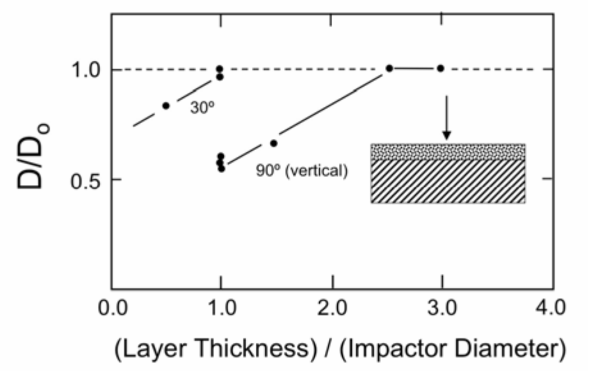

Figure 1: Effect of surface layer of loose sand (No. 24 represented by granular pattern) over 2024 aluminum (diagonals) on crater diameter (D) scaled to the diameter formed totally in sand. All impact speeds are 5 to 5.5 km/s (0.318 cm to 0.635 cm Pyrex). Surface layer has little effect on crater diameter for oblique impacts (30°) until the layer approaches the diameter of the projectile, even though the crater depth is reduced to a projectile diameter with minimal damage to the substrate. Such experiments suggest that oblique impacts into soft sediments may be efficiently eroded, leaving little trace except perhaps a shock-lithified floor.