Subsurface damage from oblique impacts into low-impedance layers

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Layered planetary surfaces occur ubiquitously in the solar system, where sedimentary sequences or icy layers overlay crystalline bedrock. Previous experimental studies investigated how the presence of weak layers overlying a strong basement affects crater morphology, subsurface damage and soft-sediment compression. Numerical studies generally focus on the final morphology as a function of thicknesses and burial depths of weak layers. In field studies of impact craters, the shock state of minerals is a key metric.

Here, we evaluate the effect of a surficial low-impedance layer on peak pressure magnitudes and consequent damage extent in the competent substrate. Laboratory experiments coupled with 3D CTH models of oblique (30° from horizontal) hypervelocity impacts at laboratory and planetary scales show that surface layers with a thickness on the order of the projectile diameter shield the underlying surface and absorb/scatter ~70% of the impact energy. Numerical simulations reveal that surficial layers reduce peak pressure magnitudes within the subsurface by ~60–70%, while damage in the substrate is due to shear failure. Sedimentary layers are more efficient shields than icy layers, but both reduce the extent of subsurface damage and the resulting shock levels recorded by minerals. These results indicate that a thin surficial low impedance layer mitigates the expression of shocked minerals in the substrate even when a structural response is still observed.


1. Introduction

Layered terrains are ubiquitous in the solar system. Planetary surfaces such as Mars and the Earth are covered in sedimentary sequences, including unconformable icy layers. On Mars, thick unconformable layered deposits cover broad regions, undergoining exhuamation [e.g., Schultz and Lutz, 1988; Greeley et al., 1992; Kolb and Tanaka, 2001; Niles and Michalski, 2009] while thick, layered mixtures of ice and dust drape the two poles [e.g., Byrne, 2009, and references therein; Cutts, 1973; Herkenhoff and Plaut, 2000; Murray et al., 1972; Phillips et al., 2008; Plaut et al., 2007]. On Earth, deposits (both lithified and unlithified) cover continental regions while thick ice sheets cover the polar regions. The impedance of sedimentary layers is generally lower than the underlying bedrock (where impedance is defined as the product of the uncompressed density and the sound speed). For low-angle impacts (e.g., <30°), significant contrasts in impedance, such as surface deposits, could affect the diameter of the crater and the damage recorded in the substrate [Schultz, 2006, 2007].

Early experimental studies at the NASA Ames Vertical Gun Range investigated effects of weak particulate layers overlying strong layers on crater diameter, substrate damage and soft-sediment compression. Oberbeck and Quaide [1967] used crater morphologies to infer past layering on planetary surfaces. Small-scale experiments revealed that changing the thickness of the surface layer relative to the crater diameter could reproduce different crater morphologies found on the lunar surface. This work allowed estimating the layer thickness from size-frequency distributions of various crater types.

Numerical studies examining the effects of layered targets on the cratering process generally focus on how the final crater morphology is altered by different types, and thicknesses, of low-impedance layers for specific crater structures (e.g., Artemieva et al. [2004] (Bosumtwi); Collins and Wünnemann [2005] (Chesapeake); Collins et al. [2008] (Ries, Haughton, El-gygytgyn); Crawford et al. [2004] (Chesapeake); Kenkmann et al. [2005] (Upheaval Dome); Pierazzo and Melosh [1999] (Chixculub); Shuvalov et al. [2005] (Lockne); and Wünnemann et al. [2005] (Ries)). A study by Collins et al. [2008] reveals that major structural differences in mid-sized terrestrial craters, such as Haughton and Ries, can be explained by differences in the thickness, or absence, of pre-impact sedimentary cover. The authors
find that both the transient and final crater diameters increase with sediment thickness for vertical impacts of equivalent energy.

[5] Other studies assess morphology changes in a broader sense. In a study using CTH to examine icy-layered terrains on Mars, Senft and Stewart [2008] modified properties of a subsurface ice layer (thickness, ice fraction and depth) in order to investigate changes in crater morphology between glacial and interglacial periods. Their simulations of vertical impacts suggest that many of the odd or unusual crater morphologies that are seen on Mars might be explained by the presence of a near-surface ice layer. In the case of a surface-ice layer, crater formation proceeds similarly to an impact into basalt. For a very thick ice sheet, the ice separates from the basalt ejecta, thereby creating an inner crater in the basalt and an outer crater in the overlying ice analogous to the smaller nested craters on the moon. Their results also indicate the lower impedance surface layers may lead to slightly deeper craters overall (from the pre-impact surface, including the surface layer) compared to vertical impacts directly into basalt, whereas buried ice layers can lead to craters that are shallower than expected.

[6] In a separate study, Senft and Stewart [2007] used CTH simulations to illustrate how a weak regolith layer over basalt also can affect final crater morphology. In this case, the layer was significantly thicker than the projectile diameter: a thickness of 10 m compared to projectile diameters of 0.5–1.75 m. This study replicated the morphologic variations observed in small lunar craters (for vertical impacts), as interpreted from experimental results by Oberbeck and Quaide [1967] and Quaide and Oberbeck [1968].

[7] While these studies concentrated mainly on specific crater structures or final morphologies, here we discuss the measurable quantities left in the rock record when the surface layer thickness is on the order of the projectile diameter. The goals of this study are twofold: first, to compare model results to experiments at laboratory scale in order to determine what parameters are well matched. We focus on the effects of impact angle (15°–30°) and the material composing the surficial layer on subsurface deformation. Second, models at large-scale determine what features and processes match the small-scale experiments. This comparison then allows an explanation of large-scale models based on intuition from the laboratory. Specifically, we concentrate on the damage in, and peak pressures experienced by, the competent substrate, which may be the only evidence after erosion on Earth or Mars. Shock levels in minerals and the extent of subsurface damage provide clues for the surface materials, now removed.

2. Methods

[8] We use a combination of laboratory experiments and three-dimensional CTH models to study the effects of thin, surficial low-impedance layers. The CTH models are not meant to match the exact structures seen in laboratory experiments, but rather to inform about the processes behind them: numerical models allow peak pressures to be tracked for a variety of impact conditions at both small and large scales. The experiments, which provide the initial insight into the effects of low-impedance surface layers, also provide an important reality check for the models and reveal details of failure structure and morphology.

2.1. Laboratory Experiments

[9] The Ames Vertical Gun Range (AVGR), located at the NASA Ames Research Center in Mountain View, CA, uses a two-stage hydrogen light gas gun capable of firing projectiles with velocities ranging from 0.5 to ~7 km/s (depending on projectile size). The target chamber has a 2.5-m diameter and is able to accommodate a wide variety of target types and setups. The chamber can be maintained at a vacuum level below 0.3 torr or can be filled with a variety of gasses to simulate different environments. High-speed cameras (up to 1 million frames per second) are used to record impact events. One of the unique characteristics of the AVGR is the ability to change the impact angle from 0 to 90°, in 15° intervals, while keeping the target oriented correctly with respect to gravity (other angles can be achieved by tilting the target slightly). This is especially important when experiments involve particulate targets or fluids, and allows assessing oblique impacts into a variety of target types.

[10] Transparent polymethylmethacrylate (PMMA) targets provide a unique opportunity to track the failure evolution and map the final damage structures within the target, something that is not easily done with rock or metal targets. At room temperatures and high strain rates, PMMA is brittle and has mechanical properties similar to rocks at the surface of the earth; consequently, it is an ideal rock analog for laboratory studies [Li and Lambros, 2001; de Joussineau et al., 2003; Rittel and Brill, 2008; Dorogoy et al., 2010]. PMMA and other similar polymeric materials, in addition to their mechanical properties, also exhibit birefringence, which makes them useful for studies of dynamic failure processes in rock [e.g., Li and Lambros, 2001; de Joussineau et al., 2003; Misra et al., 2009; Rosakis, 2002, Rosakis et al., 1999, 2004, 2008].

[11] For the present study, planar targets were 15 × 15-cm cast Acrylite blocks with thicknesses ranging from 5 cm to 6.35 cm. Targets with non-uniform geometry were constructed separately, including layered targets, and the acrylic blocks were placed on a Styrofoam block to minimize free-surface effects below. In order to determine the effects that low-impedance layers have on the cratering process (and damage growth in particular), several different layer geometries were considered. Layer thickness ranged from about one to two times the projectile diameter (i.e., 1a to 2a). The experiments presented in this study were conducted at impact angles of 15° and 30° above horizontal with impact velocities ranging from 5.2 to 5.7 km/s, with 0.635-cm Pyrex spherical projectiles. Plasticine (Sculpture House premium Plastilina clay), pumice powder and ice layers with thicknesses ranging from 0.635 cm to 1.25 cm on top of the acrylic blocks mimic layered surfaces on planetary bodies. To create the layered targets, pumice powder was poured onto the top of the block, and Plasticine layers were rolled onto specific thicknesses and pressed onto the PMMA blocks. In order to create ice layers, a layer of water was frozen onto the block overnight. Table 1 summarizes the experimental conditions for the eight experiments detailed in the results section. The damage growth was imaged at frame rates from 250,000 to 500,000 frames per second.
2.2. CTH Models

[12] CTH is a multidimensional, multimaterial, two-step Eulerian hydrocode developed by Sandia National Laboratories [McGlaun et al., 1990] where the Eulerian mesh is fixed in space, allowing the material to flow through it. The first step utilizes a Lagrangian mesh that deforms as the material moves, and the Lagrangian forms of the governing equations are solved. In the second step, the deformed mesh is then remapped into the original Eulerian mesh. The code is designed to model strong shock, large deformation events so that the user can choose from a range of equations of state (EOS) and material models.

[13] Tracking failure during oblique hypervelocity impacts requires an accurate failure model to understand failure processes and damage accumulation. Unfortunately, it is complicated to track both shear failure and extensional failure simultaneously. Therefore, failure due to shear deformation is tracked separately from failure due to tension [e.g., Stickle and Schultz, 2011; Stickle et al., 2009].

[14] Three-dimensional models are used for 1:1, direct, comparisons between laboratory and numerical experiments using identical impact conditions to the experiments. The calculations use a Mie-Grüneisen EOS for the Pyrex impactor [Marsh, 1980], PMMA block and Styrofoam base (both are available within the CTH package). Plasticine was modeled using a Mie-Grüneisen EOS after Thomsen et al. [1979], while the ANEOS package [Thompson, 1990; Thompson and Lauson, 1984] was used to model ice layers. A summary of equation of state and material model parameters used in these models is shown in Table 2. Parameters that were not used in the model, or undefined (such that default values were used), are left blank.

[15] For laboratory-scale models, Pyrex projectiles were modeled using a pressure-dependent yield surface that incorporates thermal softening and density degradation. The model assumes that Pyrex fails like a geologic material, which is sufficient for this study for modeling the projectile breakup following impact. Because extensional and shear failure are tracked separately, a slightly more complicated strength model was necessary to model failure in the PMMA substrate; consequently, two separate failure criteria were used. Extensional failure occurs when the stresses exceed the tensile strength of the material, i.e., spallation. The Johnson-Cook fracture (JCF) model is used to illustrate regions undergoing shear deformation. JCF is a scalar damage model that predicts failure of materials due to equivalent plastic strain as a function of pressure, temperature, strain rate and loading path. Plastic strain and damage begin accumulating in the material

Table 1. Experimental Conditions From the AVGR Experiments

<table>
<thead>
<tr>
<th>Experiment Number</th>
<th>Target Thickness (cm)</th>
<th>Layer</th>
<th>Impact Angle (deg)</th>
<th>Impact Velocity (km/s)</th>
<th>Projectile</th>
</tr>
</thead>
<tbody>
<tr>
<td>081111</td>
<td>6.35</td>
<td>No layer</td>
<td>30</td>
<td>5.5</td>
<td>0.635-cm Pyrex</td>
</tr>
<tr>
<td>090618</td>
<td>5</td>
<td>No layer</td>
<td>30</td>
<td>5.2</td>
<td>0.635-cm Pyrex</td>
</tr>
<tr>
<td>090621</td>
<td>5</td>
<td>0.635-cm Plasticine</td>
<td>30</td>
<td>5.68</td>
<td>0.635-cm Pyrex</td>
</tr>
<tr>
<td>110107</td>
<td>5</td>
<td>1.25-cm Plasticine</td>
<td>30</td>
<td>5.45</td>
<td>0.635-cm Pyrex</td>
</tr>
<tr>
<td>110108</td>
<td>5</td>
<td>1.25-cm ice</td>
<td>30</td>
<td>5.39</td>
<td>0.635-cm Pyrex</td>
</tr>
<tr>
<td>110110</td>
<td>5</td>
<td>0.635-cm ice</td>
<td>30</td>
<td>5.71</td>
<td>0.635-cm Pyrex</td>
</tr>
<tr>
<td>110111</td>
<td>5</td>
<td>0.635-cm pumice powder</td>
<td>30</td>
<td>5.69</td>
<td>0.635-cm Pyrex</td>
</tr>
<tr>
<td>100621</td>
<td>5</td>
<td>No layer</td>
<td>15</td>
<td>5.2</td>
<td>0.635-cm Pyrex</td>
</tr>
<tr>
<td>110114</td>
<td>5</td>
<td>0.635-cm Plasticine</td>
<td>15</td>
<td>5.7</td>
<td>0.635-cm Pyrex</td>
</tr>
</tbody>
</table>

Table 2. EOS and Material Strength Parameters Used in CTH Models

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Pyrexa</th>
<th>PMMAb</th>
<th>Plasticinec</th>
<th>Ice d</th>
<th>Styrofoam</th>
<th>Basalt</th>
<th>Dunite</th>
<th>Granite</th>
<th>Sandstone e</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cc)</td>
<td>2.23</td>
<td>1.186</td>
<td>1.69</td>
<td>0.919</td>
<td>0.035</td>
<td>2.86</td>
<td>3.32</td>
<td>2.68</td>
<td>2.1</td>
</tr>
<tr>
<td>Sound speed (km/s)</td>
<td>2</td>
<td>2.3</td>
<td>1.4</td>
<td>3.18</td>
<td>2.74</td>
<td>5.17</td>
<td>6.65</td>
<td>3.78</td>
<td>3.78</td>
</tr>
<tr>
<td>Linear coefficient of the Us-up</td>
<td>1.5</td>
<td>1.75</td>
<td>2.978</td>
<td>–</td>
<td>1.319</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Hugoniot curve: S1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quadratic coefficient of the Us-up</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Hugoniot curve: S2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Grüneisen parameter: Γ</td>
<td>1</td>
<td>0.91</td>
<td>1</td>
<td>–</td>
<td>1.18</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Cv (erg/g/°C)</td>
<td>1 \times 10^{11}</td>
<td>3.5 \times 10^{11}</td>
<td>–</td>
<td>1.34 \times 10^{11}</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>Yield strength (MPa)</td>
<td>1000</td>
<td>120</td>
<td>0.05</td>
<td>15</td>
<td>0.5</td>
<td>250</td>
<td>250</td>
<td>250</td>
<td>50</td>
</tr>
<tr>
<td>Yield Strength at P = 0 (MPa)</td>
<td>2</td>
<td>–</td>
<td>–</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.26</td>
<td>0.37</td>
<td>0.44</td>
<td>0.3</td>
<td>0.25</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
<td>0.26</td>
</tr>
<tr>
<td>Strain to failure</td>
<td>–</td>
<td>10%</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Mohr-Coulomb parameter</td>
<td>0.5</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(internal friction angle) at P = 0: dy/dp</td>
<td>0.25</td>
<td>0.25</td>
<td>–</td>
<td>0</td>
<td>–</td>
<td>0.16</td>
<td>0.16</td>
<td>0.16</td>
<td>0.16</td>
</tr>
<tr>
<td>Melting temperature, Tm (eV)</td>
<td>0.25</td>
<td>0.25</td>
<td>–</td>
<td>0</td>
<td>–</td>
<td>0.16</td>
<td>0.16</td>
<td>0.16</td>
<td>0.16</td>
</tr>
</tbody>
</table>

aMarsh (1980).

bStickle and Schultz [2011] and library coefficients.
cChristensen et al. [1968] and Austin et al. [1980].
dGold [1977].
eAi and Ahrens [2004].
3. Results

3.1. Laboratory Experiments

A suite of laboratory experiments at the NASA Ames Vertical Gun Range revealed the effects of layer thickness and layer type on damage resulting from hypervelocity impacts. As described below, the presence of a low-impedance surface layer significantly affects the damage seen in the underlying, competent substrate. Similar effects are observed in the hydrocode simulations, but with some significant differences.

Because PMMA turns opaque when it is damaged, it is relatively easy to visualize subsurface damage. Figures 2a–2f show top views of the damage resulting from 30° impacts into PMMA blocks with varied materials and thicknesses as low-impedance surface layers. The images show the competent substrate (here, the PMMA block) after the low-impedance
layer was removed. The solid black lines outline the approximate crater shape and size in the competent substrate, the dashed line outlines the boundaries of the “spall region” and the dotted line outlines the extent of the damage on the surface. Without a surface layer, the damage is relatively circular and the crater is oblong along the impact trajectory (Figure 2a). A one projectile-diameter-thick (i.e., $a$, where $a$ is the projectile diameter) Plasticine layer reduces the crater size, symmetry, and the overall extent and depth of the main damage region (Figures 2c and 5). If the layer thickness is increased to two projectile diameters (thickness = $2a$; here, 1.27 cm; Figure 2e), no damage occurs in the competent substrate. Similar responses occur for pumice and ice layers. For a thickness equal to one projectile diameter, both the subsurface damage and crater size in the competent substrate are drastically reduced (Figures 2b and 2d); for the case of a pumice layer (Figure 2b) there is minimal damage in the substrate and no crater at all. When a 1.27-cm ice layer (thickness = $2a$; see Figure 2f) is present, most of the damage in the subsurface is concentrated downrange. The area directly beneath the impact point (the “main damage zone” shown in Figure 5) has no damage and there is not a crater present, similar to the case of the $2a$-thick Plasticine layer.

These results indicate that more energy is coupled into the Plasticine layer than a comparable ice layer for an oblique impact (Figure 3). The distance was measured from

Figure 2. Top view of 6 AVGR experiments showing the extent of subsurface damage. The solid black lines show the approximate outline and size of the crater, the dashed lines show the spall zone, and the dotted lines outline the extent of the damage on the layer interface (the top surface of the PMMA block). The arrows show the impact trajectory. Note that Figure 2a has two crater outlines, showing a central, elongate, deeper region within the main crater structure. There is no spall zone or crater form in Figures 2b, or 2c, and only a small region in Figure 2f. The orange lines in Figure 2f show where the subsurface damage intersects the surface in discrete cracks.
the projected impact point on the interface between the subsurface and the layer (a schematic is shown in Figure 3b) in order to compare damage extent in the competent substrate between layered and unlayered targets. In all cases, the plots reveal that impacts into layered targets result in smaller final damage zones than impact directly into PMMA (e.g., Figure 2b). Further, Plasticine and pumice layers more effectively shield the subsurface than ice (Figure 3a). As expected, thicker surface layers result in less damage (Figures 3c and 3d).

Experiments at an angle of 15° above the horizontal show the damage resulting from an impact directly into a planar PMMA target (Figure 4, top) compared with an impact into a 1a-thick Plasticine layer over a planar PMMA target (Figure 4, bottom). As expected, the overall damage extent for a 15° impact is less than the damage from a 30° impact because more of the energy and momentum is decoupled with the impactor [Schultz and Gault, 1990a, 1990b, 1991; Schultz and Crawford, 2008]. A 1a-thick Plasticine layer atop the PMMA target, however, results in zero subsurface damage beneath the impact point, and no crater is formed. Like the 30° ice impact, there is minimal damage in the form of shallow, concentric cracks downrange.

A low-impedance layer causes changes in the evolution of the damage zone relative to impacts into PMMA only. Figures 5 and 6 reveal the evolution of damage growth for the case of an impact into PMMA, without and with a surface layer (one-projectile-diameter) of Plasticine, respectively. Directly following impact into PMMA, a small region of bubbles forms near the surface behind the shock wave (Figure 5, 4 μsec). A hazy region of damage containing many semi-parallel, subarcuate failure planes quickly follows at 8–12 μsec [see also Stickle and Schultz, 2010]. This damage zone initially grows into the target from uprange to downrange. Approximately 16 μsec after impact, a “tongue” of damage extends into the target roughly following the initial trajectory, but wraps around to either side, reducing in depth uprange. The shock wave reflects from the bottom of the target 20–30 μsec after impact (dependent on target thickness), resulting in a region of tensile failure paralleling the target surface on
results in significant damage at the base of the block and, in
grows downrange. The reflection of the shock wave again
line of trajectory intersects the surface of the PMMA and
30\,\text{m}
to a small region near the surface, emerging approximately
damage due to the passage of the shock wave is confined
begins later. It is also significantly reduced and shallow. The
travel through the surface layer, damage in the substrate
considerably (Figure 6). Because the shock wave must first
layer.
the star shows the approximate impact point on the surface
regions: the main damage zone beneath the impact point and
shape on the
surface, the dashed line shows the beginning of the spalled
region and the dotted line shows the approximate outline
of the extent of the surface damage. The star indicates the
approximate impact point, while the arrow shows impact
direction. (bottom) Damage following a 15-degree impact
at 5.7\,\text{km/s} into a planar PMMA target with a 1 projectile-
diameter thick layer of Plasticine on top. Note the lack of
damage underneath the impact point when a low-impedance
layer is present. The arrow indicates impact trajectory, and
the star shows the approximate impact point on the surface
layer.

Figure 4. (top) Damage following a 15-degree impact at
5.2\,\text{km/s} into planar PMMA target without a surface layer. The solid line gives the approximate “crater” shape on the
surface, the dashed line shows the beginning of the spalled
region and the dotted line shows the approximate outline
of the extent of the surface damage. The star indicates the
approximate impact point, while the arrow shows impact
direction. (bottom) Damage following a 15-degree impact
at 5.7\,\text{km/s} into a planar PMMA target with a 1 projectile-
diameter thick layer of Plasticine on top. Note the lack of
damage underneath the impact point when a low-impedance
layer is present. The arrow indicates impact trajectory, and
the star shows the approximate impact point on the surface
layer.
the bottom. The damage finished growing between 40 and
50\,\mu\text{sec} after impact, leaving behind three main damage
regions: the main damage zone beneath the impact point and
 crater; the downrange, diving “tongue”; and the tensile failure
at the base of the target.

[34] The low-impedance layer alters damage evolution considerably (Figure 6). Because the shock wave must first
cross through the surface layer, damage in the substrate
begins later. It is also significantly reduced and shallow. The
damage due to the passage of the shock wave is confined
to a small region near the surface, emerging approximately
30\,\mu\text{sec} after impact. Damage begins where the projected
line of trajectory intersects the surface of the PMMA and
grows downrange. The reflection of the shock wave again
results in significant damage at the base of the block and, in
this case, near the surface. Most of the subsurface damage
results from the reflected shock wave (revealed in the top
view; Figure 2c). Although not strong enough to induce
damage initially, the rarefaction off the bottom surface results
in significant damage due to the prestressed state behind the
shock. This is not the case for all layered targets. For example,
a one-projectile-diameter pumice layer on the PMMA target
(Figures 2b and 3b) absorbed and scattered the initial shock.
Even though the PMMA below is weakened, no rarefaction
damage occurs.

3.2. CTH Simulations and Comparisons with
Experiments

[25] Numerical models paralleling the experimental series
reveal the underlying physical processes and conditions.
Understanding these processes provides a better understanding
of large-scale computational experiments and the planetary
impact record. It is important to note that we are not
attempting to predict (nor perfectly match) the morphology
and complicated structures seen in our experiments. Rather,
the models are used to provide insight into the physical
processes responsible for these structures, specifically the
pressure and strain experienced by the target material.

[26] As a first step, 1:1 comparison models were calcu-
lated with initial conditions identical to the experiments
while tracking properties such as failure, damage, stress
and strain history. As before, the Johnson-Cook Fracture
model [Johnson and Cook, 1985] was used to assess
regions of shear failure in the target with the failure criterion
set in terms of equivalent plastic strain to failure (again,
assumed to be 10\% strain). The evolution of strain provides
a proxy for the failure occurring following an impact. This
is separate from, but similar to, the scalar damage parameter,
D, which indicates failed material at D = 1. In conjunction,
models are useful to understand the pressure and temperature
history through time.

[27] The strain evolution from the model can be combined
with a corresponding time sequence from laboratory
experiments (e.g., Figure 7). For a one-projectile-diameter
thick ice layer on top of the PMMA substrate, the CTH
simulations reveal large amounts of plastic strain in the
central damage zone. This correlation indicates that the sub-
surface damage is due to shear failure (Figure 7). The models
show a reduced damage zone compared to an equivalent
impact directly into PMMA, in agreement with experiments.

[28] Figures 7 and 8 show time sequences from AVGR
experiments and equivalent CTH model results for a 1a-
and 2a-thick surface ice layer, respectively. The model variables
shown are plastic strain (middle) and pressure (right). Most
damage forms behind the shock wave and is basically
finished forming well before the rarefaction off the bottom
surface returns. Damage begins while the material is still
under compression, before the unloading behind the shock
wave (based on the companion numerical model). Just as in
the experiments, the damage grows asymmetrically. The CTH
comparison in Figure 8 predicts a fairly substantial central
damage zone. In contrast, inspection of the resulting damage
in the AVGR experiment shows a hollow, arcuate damage
region downrange. While the general extent of damage in the
model matches that in the experiment, the location and
structure do not: the central, sub-impact damage zone is
absent in the experiment.
Second, a series of laboratory-scale models isolated how a specific layer type or thickness affected the peak pressures experienced by, and energy deposited into, the substrate. Four separate cases were examined: a) no layer, impact directly into PMMA; b) a one-projectile-diameter (1a) thick Plasticine layer on top of the PMMA; c) a 1a-thick ice layer on top of the PMMA; and d) a 2a-thick ice layer on top of the PMMA. All four cases used a 0.635-cm Pyrex projectile impacting at 5 km/s at an angle of 30° above the horizontal. The yield strength for PMMA was taken to be 120 MPa, and failure in the PMMA occurred at 10% plastic strain. As in the experiments, the model includes a Styrofoam block below the PMMA block. Figure 9 shows a comparison of plastic strain accumulated in the substrate 50 μsec after impact, following the completion of damage formation. As expected, the surface layers act to mitigate damage, and in agreement with the experiments, the Plasticine layer shields the subsurface better than an equivalent ice layer. These simulations demonstrate that the primary zone of damage in the experiments is due to large amounts of plastic strain, not purely tensile failure, although the specific expressions of failure are not matched.

Peak pressure with depth can be easily tracked in numerical models. Figure 10 and Table 3 document the peak-pressure decay with depth for each of the four lab-scale model geometries illustrated in Figure 9. Mass-less Eulerian tracers at specific locations within the PMMA substrate tracked the peak pressures (Figure 10). Unsurprisingly, the case with no surface layer exhibits the highest peak pressures. In general, the peak pressure magnitude is also greater downrange than directly beneath the impact point as a result of the downrange-directed shock wave. Further, a thicker layer shields the subsurface from damage (reduced peak pressures) better than a thinner layer does for a given material (ice in this case). A 10% lower impedance in the surface layer compared to PMMA (i.e., an ice layer) results in the peak pressure dropping by ~43%, whereas a ~30% lower impedance (Plasticine) results in the peak pressure dropping.

Figure 5. Evolution of the subsurface damage through time for an impact directly into a planar PMMA target. Impact by a 0.635-cm Pyrex projectile at 5.5 km/s. Impact angle: 30° above horizontal. The white lines show the top and bottom of the target block, 6.35-cm apart. The size of the projectile is shown for scale. The three main damage regions described in the text are shown: the main damage zone, the downrange “tongue” and the tensile failure at the base of the block.
by 27% at a depth equivalent to 1.5 projectile diameters. By three projectile diameters, the presence of a 1a-thick ice layer causes a 35% decrease in peak pressure and a 1a-thick Plasticine layer results in a 43% decrease. These results indicate that a thin Plasticine layer (one projectile diameter) at the surface is enough to significantly reduce the peak pressures in the substrate (see, for example, Figures 2 or 3) with subsurface damage significantly reduced below the impact but accentuated farther downrange. A one-diameter-thick layer of Plasticine is a more effective shield than a two-diameter-thick layer of ice.

3.3. Large-Scale Models

Large-scale models provide insights for interpreting the cratering record. Three different cases were examined: 1) 1-km diameter dunite sphere impacting into a basaltic substrate; 2) 1-km dunite sphere impacting into a 1-km thick sediment layer on top of a basaltic substrate; and 3) 1-km dunite sphere impacting into a 1-km thick ice layer on top of a basaltic substrate. All three cases used a speed of 15 km/s and an impact angle of 30° (above the horizontal). Figure 11 shows pressure contours 1 s after impact for each case. The top images show material isosurfaces overlain with pressure values, whereas the middle and bottom rows show pressure contours perpendicular to the trajectory and parallel to the trajectory, respectively. The low-impedance sediment (represented here by a Plasticine layer) and ice layers act to shield the competent basalt substrate. Peak pressures and the extent to which material is shocked are reduced.

In the model simulations, mass-less Eulerian particles track the evolution of pressure with distance from the impact point (shown schematically in Figure 12) with the resulting pressure decay shown in Figure 13. Figures 13a and 13b show maximum pressure with depth, directly below the point of first contact. The vertical, dashed black line indicates the location of layer-basalt interface for the two different layered cases. The impact directly into the bedrock has the highest peak pressure, but decays to a value approximately equal to that of ice. The presence of a sediment layer significantly reduces the pressure magnitude far from the impact point (Figure 13b). Downrange from the impact point, this difference increases drastically (Figure 13c). Pressure evolution through time at a point directly beneath the impact point and 1-km deep in the substrate are shown in Figure 13c. Not only does it take much longer for the material to experience the peak pressure, but the pressure is also very much reduced. This again shows that sedimentary layers more efficiently shield the substrate than do ice layers. Specifically, Table 4 shows peak pressure magnitudes from the CTH simulations shown in Figure 11. An 85% lower impedance (ice above bedrock) results in the peak pressure dropping from ~12 GPa to ~5.5 GPa (reduced by 55%), whereas a 90% lower
Figure 7. One-to-one comparison of an AVGR experiment to an equivalent CTH calculation. Size of projectile and trajectory are marked for reference. (left) Time sequence showing evolution of damage from a 0.635-cm Pyrex projectile impacting into a 0.635-cm (1a) ice layer over PMMA target. Impact velocity: 5.7 km/s, impact angle: 30° from the horizontal. (middle) Corresponding CTH calculation showing plastic strain. Failure occurs at 10% plastic strain, which is marked by a black line on the colorbar and is outlined by a black contour in the images. (right) Corresponding pressure contours. Positive values and warm colors indicate compression, while negative values and cold colors indicate tension.
Figure 8. One-to-one comparison between an AVGR experiment and an equivalent CTH calculation. Projectile size and trajectory are marked for reference. (left) Time sequence showing evolution of damage from a 0.635-cm Pyrex projectile impacting into a 1.27-cm (2a) ice layer over PMMA target. Impact velocity: 5.4 km/s, impact angle: 30° from the horizontal. (middle) Corresponding CTH calculation showing plastic strain. Failure occurs at 10% plastic strain, which is marked by a black line on the colorbar and is outlined by a black contour in the images. (right) Corresponding pressure contours. Positive values and warm colors indicate compression, while negative values and cold colors indicate tension.
impedance (sediment above bedrock) results in the peak pressure dropping from 12 GPa to \( \frac{24}{3} \) GPa (reduced by 70%) near the surface of the bedrock. This difference increases markedly with distance from the impact point.

4. Discussion

[34] In summary, both experimental and numerical results reveal that even a relatively thin (1–2\(a\)) low-impedance surface layer significantly reduces subsurface damage in the target for an oblique impact. Both the overall damage zone and crater size are reduced (even non-existent in some cases). Thicker layers more effectively shield the underlying competent substrate, but even a layer on the order of 1-projectile-diameter has measurable effects (for a 30° impact). Laboratory experiments into layers of Plasticine, pumice powder and ice overlying planar PMMA targets show subsurface damage structures distinct from those due to an impact directly into PMMA. Companion CTH models demonstrate that these differences (morphology and extent) are due to reduced peak shock pressures in the substrate as significant amounts of energy are absorbed/scattered in, or directed along, the surface layer.

[35] The three large-scale simulations illustrate what might remain following post-impact modification and erosion of a layered surface. Masking the surface layer provides visualization for the eroded surface. Figure 14 shows the plastic strain experienced by the substrate 1 s after impact for the three large-scale CTH models. Here, the substrate surface is shown at an equal height for all three geometries. These results are early in the cratering process, but note that the depth of the crater here is similar to the maximum depth of modification [Elbeshausen et al., 2009, Figure 1]. Figure 14 allows comparison between an impact into basalt (Figures 14a and 14d), into a 1-km-thick sedimentary layer (Figures 14b and 14e), and into a 1-km-thick ice layer (Figures 14c and 14f). The surface layer and approximate crater have been masked to show the level of strain in the substrate following post-impact modification and erosion. These results illustrate how an oblique impact into a low-impedance surface layer can mitigate shock damage in crystalline basement rocks, thereby complicating assessment of the initial crater size, if not confirmation of an impact structure. For example, quartz begins to display shock features at pressures above the HEL (between 5 and 7 GPa), and remains in the low-pressure regime until \( \sim 35 \) GPa [Stöffler and Langenhorst, 1994]. The lowest pressure regime occurs before the change from \( \alpha \)-quartz to high-pressure phases, within a range from 5 to 14 GPa. Weakly (or ambiguous) shocked minerals within a structural disturbance can weaken the identification of an impact structure.

[36] Qualitatively, Figure 14 can also be compared to the results in Senft and Stewart [2008], which indicated that vertical impacts into an ice-over-basalt target resulted in slightly deeper craters when compared to vertical impacts directly into basalt. The models in the present study, however, indicate that this effect is less pronounced for oblique impacts.
Craters into layered targets are only marginally deeper than a crater directly into basalt when measured from the pre-impact surface. Following erosion, the exposed surface would now be the layer-bedrock interface; consequently, this depth is relevant for our applications. An impact directly into basalt will produce a crater significantly deeper than a crater produced in a low-impedance layer (either ice or sediment) over basalt for the same impactor conditions when measured from a depth equivalent to the layer-bedrock interface. This is likely a result of the surface layer absorbing and scattering a greater percentage of the initial impact energy for an oblique impact (Figure 15).

The Rock Elm structure in Wisconsin, USA illustrates the possible role of low-impedance surface sediments. French et al. [2004] identified quartz exhibiting features characteristic of shock levels between 5 and 10 GPa in the central region, well within the low-pressure regime. French et al. [2004] used crater-scaling to conclude that a crater the size of Rock Elm could have formed from a stony meteorite approximately 200 m in diameter impacting the surface at 30 km/s at an angle of 45° (4 × 10^18 J). Our large-scale CTH simulations, however, predict a larger projectile with 4 × 10^22 J (Table 4) in order to produce the same transient crater depth.

Simulations with a surficial low-impedance layer mitigate peak pressure in the substrate enough to remain within the low-pressure regime, and, more specifically, within the 5–10 GPa range. The geology of the Rock Elm structure includes several hundreds of meters of sediments over the crystalline Precambrian basement [French et al., 2004]. The estimates for projectile size and pre-impact stratigraphy by French et al. represent a low-impedance layer with a thickness of 2–3a overlying more competent bedrock, which is a geometry comparable to the experiments and small-scale models considered here. The large-scale models examined here, however, evaluate a 1-km projectile impacting obliquely into a 1a-thick sedimentary layer, which is significantly larger than the estimates in French et al. [2004], but results in similar pressure magnitudes. This suggests that the impactor in this case may have been much larger than 200-m in diameter if it impacted at an oblique angle because of the shielding provided by the surface layer. These results suggest one possible explanation for the absence of highly shocked material within the impact structure: the sediments scattered.

**Figure 10.** Peak pressure with depth for the four different model geometries seen in Figure 9. All four models were for a 0.635-cm Pyrex projectile impacting at 5 km/s and 30° above the horizontal. (top) Peak pressure with depth, directly below the impact point. (middle) Peak pressure with depth 1 cm downrange from the impact point. (bottom) Peak pressure with depth 2 cm downrange from the impact point.

<table>
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<tr>
<th>Location</th>
<th>Depth (cm)</th>
<th>No Layer (Mpa)</th>
<th>1a Ice (Mpa)</th>
<th>2a Ice (Mpa)</th>
<th>1a Plasticine (Mpa)</th>
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<td>226</td>
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<td>151</td>
<td>134</td>
<td>118</td>
<td>83</td>
</tr>
</tbody>
</table>

*aDepths are taken from the PMMA surface directly below the impact point, 1 cm downrange, and 2 cm downrange.

Craters into layered targets are only marginally deeper than a crater directly into basalt when measured from the pre-impact surface. Following erosion, the exposed surface would now be the layer-bedrock interface; consequently, this depth is relevant for our applications. An impact directly into basalt will produce a crater significantly deeper than a crater produced in a low-impedance layer (either ice or sediment) over basalt for the same impactor conditions when measured from a depth equivalent to the layer-bedrock interface. This is likely a result of the surface layer absorbing and scattering a greater percentage of the initial impact energy for an oblique impact (Figure 15).
Figure 11. Planetary scale models showing pressure contours at 1 s after impact. Projectile: 1-km dunite sphere. Impact angle: 30°. Impact velocity: 15 km/s. Projectile size is shown for comparison. Three different cases are shown: (left) Impact directly into basaltic substrate. (middle) Impact into 1-km thick sedimentary layer over basaltic substrate. (right) Impact into 1-km thick ice layer over basaltic substrate.
and absorbed a significant amount of the impact energy from an oblique impact. Thus, the underlying competent rocks were shocked to weaker pressure. In the case of Rock Elm, up to 300 m of this sediment has since been eroded, reducing the remnant crater size [French et al., 2004].

The water depth at time of the Rock Elm impact event is unknown; so, it has been neglected in the models. Nevertheless, the effect of water-saturated sediments is instructive. Wet sediments typically have densities ranging from 1.9 to 2.4 kg/m$^3$. This is higher than the density of dry sediments (1.69 kg/m$^3$) used in our models, and would act to increase the acoustic impedance of the surface layer by up to $\approx 70\%$. This could possibly, in turn, decrease the shielding effects. However, the difference between the wet sediment impedance ($\approx 3.4$–$4$) and the impedance of the underlying bedrock ($\approx 17$) is still significant, so it is unlikely to alter the results seen here.

Numerical models also can be used to better understand energy deposition following an impact. Specifically, a simulated $30^\circ$ impact at $\approx 5.5$ km/s matches the laboratory experiments using a layered target (Figure 15). The model reveals that approximately $70$–$75\%$ of the initial energy of the system is deposited into the $2a$-thick Plasticine layer (here, $1.27$ cm thick). Over time, this averages out to $\approx 60$–$70\%$ of the total internal energy localized in the Plasticine layer. Very little of the initial kinetic or final internal energy is deposited into the competent substrate. The reduction in subsurface damage is one manifestation of the energy being absorbed/scattered in the surface layer.

In general, inadequate spatial resolution can affect the results of numerical experiments. Specifically, a low-resolution, 3D simulation will reduce the intensity of the recorded peak shock pressure because the shock parameters are averaged over the cell volume. Thus, higher resolution results in smaller cell volume and sharper shock boundaries. For 3D CTH simulations, Pierazzo [2006] showed that a resolution of 5 cells per projectile radius (cppr) results in a $20\%$ lower measured peak pressure than the same simulation with 20 cppr. The peak pressures measured in these simulations, therefore, must be considered a lower estimate. However, because equivalent resolution is used for comparison models (i.e., laboratory-scale models with differing layers), the relative values are still comparable. Further, the key observations of energy coupling and damage reduction are essentially unchanged by absolute magnitude of peak pressure.

Laboratory experiments reveal that the pumice is an effective shield when compared with ice or other, non-porous sediments (Figures 2 and 3). This increased shielding may be an effect of pore-space collapse as the shock wave travels through the pumice layer, or it may reflect a transformation of impact energy into kinetic energy of the ejecta (for pumice) rather than internal energy of deformation (for ice or Plasticine). However, the CTH simulations considered in this study do not include porosity, and therefore may overestimate peak pressures (which may also offset resolution effects). In a porous rock, peak pressures may decay more quickly than in a crystalline rock, and so the values presented here may provide a worst-case scenario. The interaction of porosity and resolution effects has not yet been quantified.

Some discrepancies do still remain between the observed damage in the target in experiments versus damage predicted by the numerical models. First, the simulations do not fully capture the complete damage zone because neither the downrange “tongue” nor the full spall region are seen in any simulation, even though the overall central region damage is of similar extent. Second, a two-projectile-diameter thick Plasticine layer in the laboratory experiments did not produce any subsurface damage (Figure 2e). A two-projectile-diameter thick ice layer, however, did result in very minimal damage (Figure 2f), which may be due to edge effects. The CTH simulations, however, predicted damage in both cases; hence, the model over-predicts the extent of the damage zone. This implies that damage may be even more reduced in both small- and large-scale simulations than what is currently seen in the figures (e.g., Figures 7–9, 11, and 14). This might be due to several factors. First, it is likely that projectile failure is not being accurately modeled in

Figure 12. Schematic locations of selected Eulerian tracer particles within large-scale layered and unlayered CTH models.
these simulations. Previous experimental work [Schultz and Gault, 1990a, 1990b] revealed that, for oblique impacts, a significant portion of the projectile energy (up to 50%, dependent on velocity) is decoupled from the initial impact by decapitation of the projectile. This is especially pronounced at low angles (5°–15°). If this process is not fully captured in the simulation, the initial amount of energy being coupled to the target may be too high, resulting in an excess of damage. Second, these impacts cannot be treated as a point source; rather, the impactor transfers energy through continued penetration and successive impacts by pieces of the disrupted projectile [e.g., Schultz and Anderson, 1996]. In laboratory experiments using layered targets, a low-impedance layer shields the substrate from the complete

Figure 13. Pressure decay for large-scale CTH models of layered and unlayered targets. Three cases are examined: 1) 1-km dunite sphere impacting into basalt target; 2) 1-km dunite sphere impacting into a 1-km thick sediment layer overlying basaltic bedrock; and 3) 1-km dunite sphere impacting into a 1-km thick ice layer over basaltic bedrock. All three impacts were at 30° and 15 km/s. (a and b) Peak pressure with distance from the impact point for each case. (c) Pressure with time for each case. Surface layers delay the arrival of the shock wave, and significantly reduce the peak pressure. (d) Peak pressure with depth, 1 km downrange from the impact point. Peak pressures are higher downrange than directly below the impact point for oblique impacts. Note that the vertical dashed line shows the depth of the basalt-layer interface.

<table>
<thead>
<tr>
<th>Layer</th>
<th>Impedance (ρ kg/m³)</th>
<th>Depth Beneath Rock Surface (km)</th>
<th>Distance From Impact Point (km)</th>
<th>Peak P (Gpa)</th>
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</thead>
<tbody>
<tr>
<td>None</td>
<td>~1.7</td>
<td>1</td>
<td>1</td>
<td>11.95</td>
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<td>Dry sediment</td>
<td>2.366</td>
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<td>2</td>
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<tr>
<td>Ice</td>
<td>2.89</td>
<td>1</td>
<td>2</td>
<td>5.57</td>
</tr>
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</table>

Table 4. Peak Pressure With Depth for Large-Scale Layered CTH Models
Figure 14. Strain contours for 1-km impact into three separate geometries described in Figure 11. The substrate surfaces are shown at an equal elevation here, and the 1a-thick surface layer and approximate crater size at 1 s after impact have been masked to show what the subsurface might “look like” following post-impact erosion. The dashed line indicates the depth of the crater for an impact directly into basalt. (a) Impact directly into basalt. (b) Impact into a 1-km thick sediment layer over basalt. (c) Impact into a 1-km thick ice layer over basalt. (d) Vertical impact directly into basalt. (e) Vertical impact into 1-km thick sediment layer over basalt. (f) Vertical impact into 1-km thick ice layer over basalt. Though the surface layers provide some shielding at high impact angles, resulting in shallower crater depths, the effect of the low-impedance surface layer is more pronounced for oblique impacts.
process of energy and momentum transfer; this has not been observed in the lab-scale simulations.

5. Conclusion

[44] Laboratory experiments coupled with 3D CTH models show that, for a layered target, surface layers with thicknesses approaching the projectile diameter act as effective “flack jackets” by shielding the underlying target material and absorbing or scattering significant portions (~70%) of the impact energy for a 30° impact. Numerical simulations reveal that this reduced (and often shallow) damage is due to shear failure, rather than purely tensile processes. Moreover, here we find that one-projectile-diameter-thick sedimentary or ice layers at the surface reduces peak pressures (and damage) within the substrate by ~60–70%, with sedimentary layers more effective in shielding than an ice layer. Both approaches indicate that a sufficiently thick, low-impedance layer may mitigate expressions of shocked minerals in the substrate within large-scale craters even though a structural response occurs. One example of this is the Rock Elm impact structure, which will be examined in much more detail in a future study.

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References


Figure 15. Internal energy partitioning following impact into a 1.27-cm Plasticine layer. Projectile: 0.635-cm Pyrex sphere, impact angle: 30°, impact velocity: 5.45 km/s; 1:1 comparison to AVGR experiment #110107. Approximately 70% of the energy is coupled into the surface layer, while only ~10% is transmitted into the PMMA substrate.


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