MODELING IMPACT CRATERING INTO LAYERED TARGETS. L. E. Senft and S. T. Stewart, Department of Earth and Planetary Sciences, Harvard University, 20 Oxford Street, Cambridge, MA 02138 (lsenft@fas.harvard.edu & stewart@eps.harvard.edu).

**Introduction:** Impact cratering is a major geologic process that has shaped the surfaces of all of the terrestrial planets. Because crater morphology is affected by material properties that are below the surface, craters provide an ideal way to probe features that are hidden from view. In addition, because impact cratering is a process that has occurred ubiquitously throughout the solar system and throughout the solar system's history, surfaces over an entire planet and of all ages on a planet can be studied using the same methods. This allows the construction of histories and maps of the subsurface.

Layers of differing material properties are a common feature on both the Earth and Mars [1, 2, 3, 4, 5]. However, little work has been done on the effect strength layering of the target has on the impact cratering process. Studies of simple cases have shown that the effect is significant. For example, Oberbeck and Quaide experimentally studied the effect of a weak layer overlying a stronger layer, and were able to accurately estimate lunar regolith thickness based upon crater appearance [6]. Because experimental laboratory craters are limited in scale, the problem can best be studied through numerical simulations. However, existing strength models in the shock physics code CTH [7] to describe the behavior of rocks are inadequate. In this work, we (i) implement a new strength model into CTH to more accurately describe impacts into rocks, and (ii) begin to study the outcome of impacts into layered targets, including modeling selected terrestrial craters.

**Strength Model:** The new strength model for rocks that we have implemented into the shock physics code CTH is similar to the model developed by Collins et al. [8]. The model degrades shear strength as a function of pressure, temperature, and total damage. Tensile strength is degraded as a function of temperature and total damage. Note that damage is a dimensionless quantity between 0 (completely intact material) and 1 (completely fragmented material) which describes the amount of fracturing that a material has experienced. Shear and tensile damage are tracked separately. Shear damage is accumulated with integrated plastic strain, while tensile damage is accumulated according to a simple crack-growth model. Under tensile failure, void space is added to simulate fracture.

**Model Results/Validation:** We have performed a number of tests and comparisons on the strength model in order to validate its accuracy. Collins et al. [8] describe the results of a terrestrial impact producing a 20.8 km (rim diameter) crater. We perform an identical simulation and calculate similar damage and total plastic strain profiles. Furthermore, the depth of completely damaged material (approximately 6 km) falls along the trend of crater diameter versus shock damage depth as measured for terrestrial craters by Ahrens et al. [9].

We also performed simulations to compare with Ai and Ahrens’ laboratory studies of damage beneath craters [10]. Figures 1a and 1b show the results of a 0.64 cm radius copper ball vertically impacting at a velocity of 690 m/s into a granite block with dimensions of 20×20×15 cm. Figure 1a shows the calculated tensile damage produced by the impact, and Figure 1b shows the shear damage. Our results agree very well with Ai and Ahrens’ [10] laboratory results. The calculated crater shape is similar to that produced in the laboratory, and the damage profiles are similar to the observed profiles. In particular, Ai and Ahrens [10] observed tensile cracking, shown in Figure 1c, to depths of about 8 cm in their experiment. These cracks are also observed in our calculation; they extend to about 8 cm in depth and occur in nearly the same locations as seen in the experiment. Additionally, we observe a hemispherical zone of shear damage extending to depths (approximately 2.8 cm) similar to those seen experimentally (approximately 3 cm). Note that some of the damage seen along the center-lines of Figures 1a and 1b are likely overestimates resulting from problems with the cylindrical symmetry centerline boundary condition.

Finally, we compare the transient crater diameters produced by our simulations to those predicted according to pi-scaling [11]. \( \pi_0 \) is a dimensionless quantity that represents the diameter of the transient crater and \( \pi_2 \) is a dimensionless quantity that represents the kinetic energy of the impactor. As predicted, our results produce a linear trend on a plot of log (\( \pi_0 \)) versus log (\( \pi_2 \)) which flattens out at small (strength dominated) crater diameters. Our results for craters in the gravity regime fall slightly below the line predicted using competent rock scaling parameters as determined by Holsapple [11]; however, we note that our results fall closer to this line than results produced using the best old strength model in CTH (the “geo” model).
These results indicate that our strength model is able to accurately simulate the behavior of rocks during impact events over a large range of sizes.

**Terrestrial Craters in Layered Targets:** There are two well-known terrestrial craters that formed in layered targets: Lonar Crater, India and Meteor Crater, Arizona. Lonar Crater was formed when a bolide of unknown composition impacted into 600-700 m of Deccan Trap flows 15-67 thousand years ago and produced a 1.83 km rim diameter crater. At least six flows are exposed in the crater wall; each is about 10-25 m thick. In contrast to the majority of terrestrial craters, there has been little post-impact erosion at Lonar (less than 5 m of material removed from the rim height) [12, 13]. In addition, Lonar provides an excellent opportunity to study the effect of target strength layering because a stratigraphy is developed within individual Deccan Trap flows. The base of the flow is a dense and sometimes flow-banded basalt; this grades upward into a vesicular and weathered basalt which is significantly weaker than the flow bottom.

Meteor Crater, Arizona was formed about 49,000 years ago when an iron bolide impacted into a sequence of sedimentary rocks, producing a 1.2 km rim diameter crater. The sedimentary sequence intersected by the crater consists of interbedded (weaker) sandstones and (stronger) limestones [14].

We will present simulations of impacts into strength layered targets in order to model Lonar Crater and Meteor Crater. We will then compare the results to identical impacts into homogeneous targets in order to identify the effect that the layers have on the cratering process.

**Conclusions/Future Work:** We have implemented a new strength model into the shock physics code CTH and have shown that this model accurately describes the dynamic rheology of rocks during impact events. We have used the new model to produce simulations of Lonar Crater, India and Meteor Crater, Arizona. These simulations serve to (i) validate numerical simulations of impacts into layered targets, and (ii) provide a preliminary study of how layering in the target effects the impact cratering process.

In the future, we will study how layering effects impact cratering with an application to understanding Martian crater morphologies. By quantitatively comparing numerical simulations into layered targets with measurements of Martian craters, we will examine the properties of subsurface layers on Mars.


**Figure 1:** Modeled tensile damage (A) and shear damage (B) at 0.1 microseconds after the vertical impact of a 0.64 cm in radius copper sphere into a 20×20×15 cm granite block at 690 m/s compared with Ai and Ahrens’ [10] experimental results (C). Radial lines sketched in C are tensile cracks; blue hash indicates zone of shear damage.