

SUMMARY OF SESSION ON EFFECTS OF TARGET PROPERTIES ON THE CRATERING PROCESS, FRIDAY, FEBRUARY 7, 1:30 P.M.

Summary by Kevin Housen

Discovery of how the size and shape of a crater depends on the properties of the material it forms in has been elusive, primarily because of the complicated constitutive behavior of most geological materials. For example, the strength of rocks and ice is known to be both scale and rate dependent, thus complicating the comparison of laboratory results with the much larger structures formed on planetary surfaces. Realistic numerical simulations must include the effects of rate-dependent brittle fracture, pressure-dependent yield, dilatation, thermal softening, pore-space compaction, etc. Most current numerical models only consider some of these mechanisms and with varying degrees of sophistication. Therefore, we presently have only an incomplete picture of how cratering depends on the mechanical properties of the target material. Fortunately, there is a diverse set of data that can be applied to this problem, including laboratory experiments of impact and explosion cratering, field tests that have formed explosion craters over a half kilometer in diameter, results of code calculations, and observations of the great variety of craters formed on planetary and satellite surfaces. This session of the conference was aimed at gleaning what we can from these various sources of information.

Results of laboratory and field cratering tests were reviewed by Kevin Housen. He noted that most geological materials follow a Mohr-Coulomb type of behavior, in which the shear strength is the sum of the cohesion and a frictional component, $P \tan \phi$, where P is the pressure and ϕ is the angle of internal friction. Small craters, for which the overburden pressure is negligible, are therefore determined by cohesion. This is the case for terrestrial craters up to a few tens of meters diameter in rock. Formation of small craters in rock or ice is complicated by the fact that the cohesion is both scale and rate dependent, as clearly illustrated by explosive cratering tests at various sizes, and by dynamic strength measurements. The situation for large craters is somewhat simpler, because crater size depends primarily on the target density and friction angle, which together with the gravitational acceleration form the frictional component of the shear strength. From scaling arguments, Housen noted that the dependence on target density can be determined by controlled experiments which vary only the impactor density. Numerous impact

experiments have collectively varied this parameter by more than a factor of 1000 and have shown that the cratered mass is independent of target density. That is, the crater volume is inversely proportional to target density. Experiments in various materials show that crater volume varies by a factor of several when the friction angle is varied over the range typically observed for geological materials, i.e. 25° to 60°. This was shown to be consistent with the range in crater size typically observed in explosive field tests conducted in a variety of materials.

Paul Schenk discussed observations of crater populations on planetary surfaces in the context of how material properties affect crater shape and the transition from simple to complex structures. Schenk noted that the pioneering work of Pike, that showed crater depth to be approximately one-fifth the crater diameter. This relation holds for craters on the Moon, Mercury and Mars (terrestrial craters experience considerable erosion and Venusian impacts are significantly affected by the atmosphere). Preliminary analyses of icy satellites based on Voyager data indicated craters in ice are about 70% the depth of craters in rock. Subsequent analyses of higher-resolution Galileo imagery revised this conclusion and now show similar depth/diameter ratios for rock and ice. However, the transition from simple to complex structures occurs at much smaller diameters in ice than in rock, which probably reflects the lower strength of ice. Observations of the transition diameters on icy satellites show that the transition diameter is inversely proportional to gravitational acceleration. Silicate bodies also exhibit an inverse relationship, but the exact dependence is less certain.

The significant effects of target layering were also noted. In particular the unusual, very shallow, complex structures observed on Europa may be related to the presence of an ocean beneath a thin icy shell. On the Moon, terraces and central peaks occur in smaller craters on the layered volcanic mare deposits than in the highlands. This could reflect differences in mechanical strength or possibly layering.

A particular type of layering of interest for Earth and Mars is the case of impacts in marine locations. Jens Ormö presented a summary of his research on the Lockne crater in central Sweden. The idea is to use the observed geology and morphology of a ma-

rine-target crater along with numerical simulations to infer the water depth at the time of impact. Ormö summarized some of the main features at Lockne, including a 7.5 km crater in the crystalline basement rock, surrounded by a 3 km wide brim of fractured overturned basement rock. The upper ~40m of sedimentary rock that originally overlaid the basement was stripped away before the deposition of the flap, presumably by the outward movement of the transient crater formed in the water layer. In collaboration with Valery Shuvalov, numerical simulations were performed for impacts into granite overlain by various thicknesses of water layers. A water layer that is too thin is unable to flow over the rim of the central crater and therefore cannot reproduce the evidence of resurge observed at Lockne. Additionally a thin layer does not strip away enough of the surface material prior to the deposition of the flap. Conversely, a water layer that is too thick results in a crater that is too small and reduces the amount of material in the flap. Ormö found that the paleo-water depth at Lockne must have been greater than about 500m, possibly as large as 1000 m.

Codes, such as SOVA used by Ormö and Shuvalov, used in numerical simulations have progressed significantly over the past decade, both in terms of material models and the numerical methods used. Dave Crawford described some recent modifications to the Sandia code CTH, which now includes adaptive mesh refinement (AMR). AMR methods can significantly reduce run times by refining the computational mesh only where high resolution is needed. He gave examples of applications including a 3D model of an impact in aluminum and a finely resolved model of an impact on Eros using the shape model determined from the NEAR Laser Rangefinder measurements. He also demonstrated the use of AMR methods to study shock propagation in heterogeneous materials. These calculations can be used to help understand impact processes in discontinuous media, with obvious applications to the study of rubble-pile asteroids.

Another adaptive-meshing code (SAGE), developed at Los Alamos and SAIC, was described by Galen Gisler. He presented the results of large-body (0.25-10 km) impacts in marine environments. In the larger impacts, collapse of the transient water cavity and jet produced tsunamis up to 1 km in height.

The effect of target properties on melting was addressed by Gordon Osinski. His talk considered the question of whether sedimentary rocks undergo melting in impact events. He noted that even though the

volumes of material shocked to pressures sufficient for melting are about the same for sedimentary targets and crystalline rocks, it is often assumed that impacts into the sedimentary targets generate much less melt. For example, it has been generally accepted that impacts into carbonate-rich targets do not generate much melt because the carbonates decompose and devolatilize to yield CO₂ and CaO or MgO. Osinski presented the results of field observations at the 24-km diameter Haughton impact structure that formed in a 1.8 km thick layer of sedimentary rocks overlying Precambrian metamorphic basement material. He summarized evidence that crater-fill deposits, which originally comprised as much as 12 km³, are impact melt rocks. This volume is comparable to that of melt sheets observed in similar-size craters in crystalline target materials. Osinski, and collaborators John Spray and Richard Grieve have concluded that impacts into sedimentary materials may generate significant volumes of melt and that the amount of CO₂ released into the atmosphere may be much less than previously thought.

One of the goals of field and remote-sensing studies of large craters has been to deduce the initial conditions of an impact event from the observed characteristics of a crater. One example is to use the observed crater size and volume of impact melt, along with scaling relationships, experimental crater data or code calculations to determine the size and velocity of the impactor. Keith Holsapple discussed this problem and noted that its solution is rendered nearly impossible by a unique property of hypervelocity impacts that has, ironically, greatly expanded our understanding of impact processes. Measurements of many of the observables of impact cratering have shown that, to a very good approximation, the impactor is a point source. As such, the impactor velocity and mass are not important separately, but only through a specific power-law combination. Consequently, the important measures of an impact crater, such as its size, melt volume, ejecta blanket, etc, are all determined by the same point source. Any combination of these measures can only determine the power-law combination of size and mass. Their values cannot be determined separately. Holsapple noted that the point source does not strictly apply close in to the impact, where much of the melt is generated. But even in this case, the solution for impactor mass and velocity is highly non-robust. Factors of two variation in the melt volume result in several decades of uncertainty in impact velocity.