Designing Craters:
Creating a Deep Impact

Current Scientific Thinking About Cratering

APPENDIX B: BACKGROUND SCIENCE FOR TEACHERS

Meteor Crater, University of Arizona

The iron nickel meteorite that created Meteor Crater in Arizona over 50,000 years ago weighed several hundred tons and struck the Earth at a velocity of 40,000 miles per hour. In a fraction of second, the meteorite was brought to a halt by the surface of the Earth, and its kinetic energy was transferred and converted into other forms. Within ten seconds, a 1.2-kilometers wide (3/4 of a mile), 174-meters deep (570-feet) crater had been excavated on the desert floor. The universe conserves energy, and it is this energy conservation, this need to deal with a large amount of incoming kinetic energy, that drives the process of cratering. Any moving body has kinetic energy. This energy is the product of its mass and the velocity squared (Kinetic Energy = $1/2mv^2$). The Meteor Crater impactor struck the Earth with an equivalent explosive force greater than 20 million tons of TNT. The crust of the Earth must somehow deal with this massive amount of energy when a meteor slams into its surface. The familiar crater formation is the result of the energy exchange. The kinetic energy of the impactor determines the amount of energy involved, but the material properties of the impacted body determine how the surface will respond to that energy.

When you drop an object at a low velocity on to a surface, such as dropping a pen onto the carpet or a dish on the kitchen tile, the energy of the impact may be passed through the target as a pressure or sound wave without permanently disturbing the target surface. A large portion of the energy is reflected back into the object itself, causing the pen to bounce or the dish to shatter. The surface absorbs little of the energy, its molecules are compressed and released elastically, returning to their original positions after the compression by the impacting body is released. Cratering experiments conducted in the classroom are low energy impacts. We use surfaces of loose particles such as flour and sand that are easily moved to simulate the effect that larger energies have on surfaces such as rock. The surfaces in our experiments are not significantly structurally altered; the particles are just moved into new positions by the energy of the impact.

However, when larger impacts take place, the surface may not be able to bounce back so easily. The amount of energy in large impacts is so great that the compression of the surface by the impactor creates pressures beyond what the material can absorb in any elastic way. Every material has a limit, known as its yield strength, beyond which its material will be permanently altered by stress. Material subjected to pressures greater than its yield strength will crack, melt, and undergo other transformations.

Solar System scale impacts transfer energy in shock waves, which function differently than the pressure and transverse waves with which we are familiar. In a pressure wave, or sound wave, the molecules of the material vibrate and then return to their original position. A shock wave, on the other hand, is a front that moves through the rock at supersonic speeds structurally altering the rock through which it passes.

Cratering is often divided into three phases for ease of discussion, although all three phases flow from one into the next and part of the impactor and target can be in one phase, while another has already moved on to the next. The first phase is referred to as the contact and compression phase. The impactor hits the surface, accelerating the surface material downward while the target's resistance to penetration slows the impactor. Material in the contact zone is compressed, material outside is uncompressed, and the line between them, the shock wave, moves forward. The shock wave moves outward into the target body and a similar shock wave also moves back into the projectile. The pressure of this wave is often far beyond the yield strength of the impactor. The impactor can be vaporized by the energy carried in this wave. This stage is considered over once the projectile has stopped moving and the shock front has moved completely through the projectile. This usually takes only fractions of seconds. The initial compression of the surface can push materials around the side of the impactor, causing them to squirt out of the sides at a high velocity. This effect is known as “jetting.”

The second stage is excavation. In this stage, the shock wave continues to travel outward through the target material, losing energy to the transformation of rocks as it travels outward. The shock wave leaves the material behind it in motion. A second wave, the rarefraction wave, arises from the release of the high pressure of the shock wave as it moves past the material. The interactions of this wave and the motion of the material following the passage of the shock wave combine to form the excavation flow field, the motion that carriers material away into lower pressure areas and forms the crater behind.

The final stage of an impact event is referred to as modification. This begins after the crater has been fully excavated and the shock wave has been attenuated by the target body. During modification, gravity pulls loose particles down the walls of the crater. Large craters can have entire sections of the wall slide down, pooling on to the crater floor, or forming features known as slump terraces.

Most of what we know about the cratering process comes from our studies of planetary impacts (including the Earth), explosion weapons testing, theoretical models, and laboratory experiments. Even though small in scale, laboratory studies allow the isolation of variables. Theoretical studies allow extrapolation and comparisons with craters found on the Earth and other planets allow for the testing of these extrapolations. One of the earliest scaling laws developed from weapons tests in the 1940s and 1950s found that the crater diameter is proportional to the cube root of the kinetic energy for hard targets. Laboratory experiments later revealed that crater diameter is proportional to the quarter to sixth root of a combination of energy and momentum for craters limited by gravity (very large craters and craters in sand).

A more detailed form of scaling treats the diameter of the crater as a function of a number variables; impact velocity, projectile density, target density, the yield strength of the target, gravity, and projectile mass and the effect of an atmosphere. The relationship between these variables is determined by holding all variables but one of interest fixed. To a minor extent, this is the sort of modeling demonstrated in Activity 3 (or the Predict section): Predicting Crater Size. From the relationships discovered with this form of modeling, we find that we can predict crater size fairly well if the density of the impactor and the target bodies are similar. Calculations are also easier to make if the impact is “gravity dominated” as opposed to “strength dominated”, meaning that the gravitational force pulling the impactor down is significantly larger than the material strength of the target that is resisting that downward motion. The porosity of the material may also be important in predicting crater size. In a highly porous material, energy goes into the compression of the pores, and the shock wave is attenuated more quickly.

Another factor of importance in cratering is the angle of impact. This is also a factor where the differences between low energy impacts, such as those in classroom experiments, and high energy Solar System scale impacts are clear. In low energy impacts, as the angle of impact moves away from vertical, the shape of the crater becomes elliptical. High energy impacts still create a spherical shock wave, and therefore a circular crater, although the intensity of that shock is lessened and the crater will not have as great a depth. This discrepancy between the classroom model and the Solar System scale reality is important to point out to your students and is discussed in Activity 4 (or the Compare section): Cratering in the Classroom, the Lab, and the Solar System.

How does all of this apply to the specific problem of cratering on Comet Tempel 1? The list of variables gives us some insight into the problem. We can control the projectile density, the impact velocity, and the projectile mass. Ideally, to determine what values to choose for those factors, we would like to know the target controlled variables – target density, gravity, yield strength, and porosity. However, these things are not well known. In fact, the driving purpose of the experiment is to learn these and other characteristics of the comet from watching the crater formation. The challenge is to use what we do know about the comet to choose an impactor configuration that will help us get the most new information out of the impact. We have a general range for the size of the comet and some ideas about density. We can make guesses about yield strength from what we know of the materials that compose the comet's surface. Ground-based observations of the comet conducted by both professional and amateur astronomers in the years leading up to the mission will hopefully yield more information about the comet's rotation period and the size of the nucleus. Pooling all of this information together allows the mission design team to design an impactor and schedule an impact that will hopefully provide us with a lot of new information about the composition and structure of comets.

References:

For more information on cratering, see the chapters on cratering in the two books listed below

Beatty, J. Kelly et al (Ed.) The New Solar System.
Cambridge University Press, 1998.

Weissman, Paul R. et al. (Ed.) Encyclopedia of the
Solar System. Academic Press, San Diego, 1998.