SECTION 1 : IMPACT CRATERING (4 lectures)

1.1 Introduction

The study of impact cratering is arguably one of the most important processes operating in the solar system. Projectiles travelling at high velocities have modified, in some way, the surfaces of all solid bodies in the solar system at some point in time.

It was only in this century however, that impact cratering was accepted as being the process that caused the mainly circular lunar craters. For many years scientists dismissed the idea that projectiles could form these craters, believing that volcanic activity was the primary formation mechanism.

The history of the volcanic vs. impact origin is a fascinating one, and those interested in reading a summary should see Chapter 1, the first few pages of Melosh.

The knowledge of the impact cratering process and the underlying physics has improved drastically in the last 30 or so years. This section will highlight the main stages of impact cratering, some of the physics behind these stages and show the results of various factors which influence this process.

1.2 Cratering Mechanics

The process of impact cratering is a highly ordered one, and all craters undergo a sequence of events starting when the meteorite (projectile) first hits the target surface, and ending when the resultant debris is emplaced around the crater.

There are three stages generally recognised in the impact cratering process:

- contact and compression
- excavation
- modification

1.2.1 Compression

The process of impact cratering begins upon contact of the projectile with the target. As the projectile hits, the target is pushed, compressed and accelerated. Simultaneously, the projectile is decelerated due to the resistance to penetration of the target.

Shock waves, originating at the point (or points) of contact, travel down through the target and up through the projectile. Pressures produced are much larger than the yield strength of either the target or the projectile.

The contact and compression stage ends after the projectile has unloaded from the high pressures. Upon unloading, the projectile may melt or vaporise, perhaps producing a pool of impact melt at the bottom of the crater.

FIGURE 1.1 (Contact and compression stage)

This figure considers a vertical impact - it's the simplest case to consider. Part a) shows the point of contact and the resultant high pressure regions around it. Ignore the numbers - these are for a specific case as outlined in Melosh. Compression and distortion are taking place in both material, but the back end of the projectile is still moving at its original velocity. It will continue to do so until the shock fronts reach it, as shown in Part b). At this point, the boundary between projectile and target has been pushed down into the target by one half the original projectile diameter. More of the target is engulfed by the shock and accelerated to high speed. As the projectile is completely consumed by shocks, it flows hydrodynamically.

Part c) shows the point at which the pressures in the projectile unload. The shock wave, upon reaching the back-end of the projectile is reflected back as a rarefaction wave. As the wave travels through the projectile at the speed of sound in the compressed material it unloads the pressures in the material. It is at this point that the projectile may undergo phase transformation into a melt or vapour. This impact melt usually pools in the centre of the crater.

Once the pressures have been released, the compression stage is officially at an end, although obviously each stage merges and overlaps with another. The result of the compression stage is to convert the kinetic energy of the projectile into internal energy of both materials and to produce strong shock waves. All of this happens in the blink of an eye, formally written as

$$\tau = \frac{D}{v} \qquad \text{(Eqn 1.1)}$$

where τ = time interval of compression phase
D = diameter of the original projectile
v = impact velocity of the projectile

So, a 1km diameter projectile travelling at $10 kms^{-1}$ will undergo a compression phase lasting only a tenth of a second.

1.2.2 Excavation Stage

The excavation stage itself can be split up into two stages: 1) the expansion of the shock wave and 2) the excavation flow. Put simply, the expansion of the shock wave continues after the compression phase. As it moves, it engulfs more material but weakens as it does so, degrading to a stress wave. As it passes, the wave sets target material into motion, initiating the second of the processes, the excavation flow, which sees the main mass of material ejected from the crater.

We concentrate here on the excavation flow, since this has quite an effect on the appearance of the final ejecta blanket.

Material thrown out of the crater during the excavation stage is called ejecta. The ejecta is thrown up and away from the point of impact.

FIGURE 1.2 (The excavation flow)

The velocity vectors are known as streamlines and effectively chart the movement of material as the crater grows. Material is considered to be ejected once it rises above the level of the pre-impact surface. Note that the streamlines intersect contours of maximum pressure. This means that material ejected along a particular streamline will have contribution from all of the shock levels it intersects. But remember, the intensity of the shock decreases farther from the impact point, so the level of shock will not be the same in all materials. However, even the slowest of the ejecta will contain some highly shocked material.

Ejecta flow velocities are higher near the impact site and fall off as you go further from it, approximately as an inverse power of the distance. The maximum ejecta velocity is only between one sixth and one-tenth of the impact velocity.

So, the material ejected first, closest to the impact point has the highest velocity as takes the longest to fall back down. I.e. it is the last to be emplaced. The slower ejecta, farther from the impact point takes less time to fall until eventually material just flips over the edge. This material will form the rim of the transient crater, which is the crater formed at the end of the excavation stage.

Depth of excavation: It is important to note that the depth of excavation does not equal the depth of the transient crater. The rule of thumb currently in favour amongst impact scientists is that

$$H_{exc} \approx 1/3\, H_t \approx 0.1\, D_t \qquad \text{(Eqn 1.2)}$$

where: H_{exc} = depth of excavation
H_t = depth of the transient crater
D_t = diameter of the transient crater

So, a 100m transient crater will have excavated material from just 10m below the surface. Remember, the transient crater diameter will not be the diameter you finally observe. Transient crater diameters can be changed either during the modification stage or subsequently by wall/rim collapse due to gravity.

1.2.3 Modification Stage

The modification stage acts to alter the transient crater formed in the excavation stage. This is where central peaks and terraced walls are formed in large craters, mountain rings in basins and simple debris slumping and pooling in small craters. This stage also sees the cooling of the impact melt lining the floors and the emplacement of the ejecta blanket thrown out during the excavation phase.

FIGURE 1.3 (Modification Stage)

Simple craters are the easiest case to consider. The modification stage consists of material falling back from an unstable rim to fill the core of the crater floor. This process is known as slumping. The larger an impact crater is, the further the initial transient crater departs from gravitational stability. There is a rather well defined boundary between the modification seen in simple craters and that seen in complex craters. Smaller than around 15km, craters have a depth-diameter ratio of around 1:5, but for larger craters this ratio tails off, making them shallower. The sharp transition is probably the result of gravitational collapse as some strength threshold is exceeded.

FIGURE 1.4 (Depth to diameter ratio for fresh lunar craters)
FIGURE 1.5 (Simple to complex transition for different planets)
FIGURE 1.6 (Formation of central peaks and rings)

Is this transition diameter equal on all planets? No, surface gravity has a profound effect on this diameter. Mars is slightly off the line, probably due to the presence of volatiles in the target soil (what about Earth? Melosh doesn't mention why Earth is on the line….)

What happens to larger craters? There is an uplift at the bottom of the crater. Material is still being thrown out. The uplift increases, and we find material falling back along the steep walls of the crater. In the case of a complex crater with a peak, some of the uplift is stable and a peak remains in the central area of the crater floor. The rim of the crater does not remain stable however, and terraces form which appear to be the headscarps of huge landslides carrying material from the unstable rim into the crater. In the case of a peak ring crater, or multi-ring basin, the central uplift unstable, and falls back down. Terraces are again formed, but this time the crater has a central ring rather than a peak.

1.2.4 Ejecta blankets and Secondary Impact Craters

Very little material excavated from an impact crater escapes the gravitational field of the target planet. Most falls back to the surface and is emplaced as an ejecta blanket surrounding the crater.

The emplacement of ejecta is a very orderly process. It is shown very nicely in the terrestrial Meteor Crater in Arizona, USA.

FIGURE 1.7 (Ejecta blanket at Meteor crater, Arizona)

The ejecta blanket is also known as the continuous ejecta blanket, being thicker near the rim and thinning out as you get further away from the rim. Continuous ejecta extend approximately one crater radius from the rim of the crater more of less for any size of crater. The average radius of continuous ejecta, R_{CE}, (from the centre of the crater) is

$$R_{CE} = (2.3 \pm 0.5)R^{1.006} \qquad \text{(Eqn. 1.3)}$$

where R is the radius of the crater. There will of course be deviations from this equation when, for example, craters are excavated from strong rock. According to *Melosh*, this relation will also hold for other bodies such as Mercury, Mars and the Jovian satellites, although not everyone agrees with this.

Outside of the continuous ejecta blanket is the discontinuous ejecta, characterised by its thin and patchy nature. It is in this unit and beyond that secondary impact craters are found.

Secondaries are formed when large chunks of material are thrown out during the initial excavation period. The largest secondary crater diameter is only about 4% of the diameter of the primary on the Moon, but when that primary diameter starts to get into the 10's or 100's of km range, you get secondaries of a significant size. In fact it gets quite hard to distinguish between a primary crater of 10km and a 10km secondary of a distant crater. Fortunately there are some distinguishing features of secondaries. They often have a V-shaped ridge pointing radially away from the main crater. Secondaries also often form in clusters or chains, another distinguishing feature. When they form in chains the chevron pattern turns into a herringbone pattern. These patterns are caused as a result of the interference of the ejecta blankets of adjacent secondaries. The extent of the secondary crater field is a strong function of gravity. The higher the gravity of the target body, the closer the crater field is to the primary crater, and the higher the density of secondaries.

FIGURE 1.8 (Ejecta of a secondary impact crater)
FIGURE 1.9 (Ejecta of a chain of secondaries)

1.2.5 Oblique Impacts

In the very early days, the biggest problem most scientists had with the impact theory of lunar craters is that they were all very circular. Very few asymmetrical craters could be seen, and the experiments they carried out showed that only near-vertical projectiles could form circular craters and it was highly unlikely that all projectiles fell vertically. However, their experiments were not using hypervelocity impacts, and as we now know, the physics of hypervelocity impacts is very different to that of, say, a bullet hitting a block of wood. We know from recent experiments that only the most oblique impacts cause non-circular craters.

Because most impacts are oblique, the study of such impacts are important. Experiment has shown that a projectile must hit the surface at an angle $<10°$ from the surface in order to produce an asymmetric crater. The same is not true for the ejecta of oblique impacts. It is found that a "butterfly" shape is formed when an oblique impact occurs. A noticeable change in ejecta form can be seen in impacts with angles as high as $60°$.

FIGURE 1.10 (Ejecta patterns from oblique impacts)

As the angle of impact decreases from the vertical, ejecta first shows a preferential concentration on the downrange side. At angles <45°, a forbidden zone forms uprange where ejecta is not emplaced. This wedge increases until a forbidden zone also appears downrange (for angles <20°). This is the pattern known as the butterfly effect.

The ejecta patterns are probably formed by the elongated shock waves produced by oblique impacts and give a useful indication of the direction of travel of the original impactor. Although oblique impacts are thought to be far more common that near vertical ones, very little is known about the mechanics of such impacts. This deficiency is only now being rectified with the advent of faster, more powerful computers.

1.2.6 Atmospheric effects

Studying impact craters on the Moon is nice - there is no atmosphere to worry about. The atmosphere on Mars is thin and in some cases can be ignored, but when you start looking at bodies like Venus, atmospheric effects can no longer be ignored.

An atmosphere will act to slow the incoming projectile. Whether a projectile will remain at its high velocity depends upon the thickness of the atmosphere and the diameter and mass of the projectile. If a projectile is to penetrate an atmosphere, its diameter, D, must be :

$$D \geq 0.15 \frac{P}{\rho g \sin\theta} \qquad \text{(Eqn 1.4)}$$

where ρ = projectile density
P = surface atmospheric pressure
g = surface acceleration of gravity
θ = angle of incoming projectile

One thing to bear in mind is that this equation is concerned with penetrators which still have hypervelocity speeds. A projectile with a smaller D than allowed by this equation may still make it through the atmosphere, but will not create an impact crater as discussed so far.

Larger projectiles are not so easily slowed and will often travel at speeds exceeding Mach 50 in the denser atmospheric layers. These create shock waves in front of the projectile which can have devastating consequences itself. In 1908, Tunguska in Siberia experienced such a shock wave - 2000km^2 of forest were flattened forming a radial pattern when the shock wave hit. The projectile itself never hit the ground - it was destroyed during it's descent.

On Earth, most meteorites are expected to break up or burn up. Unless the meteorite is a particularly strong iron or stony meteorite, the following will happen.

FIGURE 1.11 (Atmospheric entry and break up of a meteoroid)

After c) the small fragments may burn up, but there may still be a shock wave travelling up to the surface causing disruption and breaking of the surface material. If the fragments do not burn up, but stay closely bunched together they will produce a single crater with a strange morphology. Alternatively if they strike the ground as separate fragments, a crater field results with a high concentration of individual craters in a small area.

1.2.7 Target Structure

As you can imagine, the target strength will have an effect on the final crater formed. However, the structure of the target will also play a role in many cases. The best studied case is when a weak layer overlies a strong one. This situation is very common on the Moon where a loose fragmented regolith layer overlies stronger material beneath. In fact, the morphology of small craters can sometimes be used to estimate the depth of the regolith layer.

FIGURE 1.12 (Effect of target material on morphology)

The morphology of the final crater depends on the ratio between the craters rim to rim diameter D and the layer thickness T_l. When $D/T_l < 4$ a normal profile is produced a). For $D/T_l < 7.5$, a central mound is formed of unexcavated material. For $D/T_l \sim 8\text{-}10$, material is excavated, revealing the floor of the stronger material. When D/T_l is greater than 10 a crater is formed in the strong material too, but the transition between the materials is marked by a bench or shelf on the wall of the crater. By using depth diameter ratios, it is possible then to work out regolith thicknesses in some areas.

1.3 General Morphology of Large Impact Craters

FIGURE 1.13 (General morphology of a complex crater)

Basins are slightly different to other large craters in that they do not contain a central peak. Instead, a central ring forms (as outlined in the modification stage). The best example of such a basin on the Moon is the Orientale basin.

Located on the western limb of the Moon, it is only fully visible from spacecraft. It is the youngest large basin on the Moon, forming around 3.8 billion years ago. Orientale is an excellent basin to study because it has not been extensively flooded by mare basalts as you see on the near-side of the Moon.

FIGURE 1.14 (Morphology of the Oriental impact basin)

The centre of the basin, inside the first ring does have some mare fill, but also contains smooth plains material known as the Maunder Formation. These smooth plains degrade as you go farther out into fractured plains, but are still known as the Maunder Formation. It's believed to be impact melt by many scientists and appears to have remained partially molten for a considerable length of time. This formation terminates at the outer Rook ring. The Rook Formation is generally found between the outer Rook ring and Cordillera scarp (ring)., although in localised areas it does extend beyond the Cordillera Scarp. It has a hummocky appearance, set in an undulating terrain. Outside the Cordillera ring, which is considered to be the topographic rim of the basin is the Hevelius Formation which has a radially lineated, swirl textured deposits. These may extend up to 500km from the rim of the basin. Secondary craters appear at the margin of this formation. The Hevelius Formation varies in thickness, as do all ejecta blankets. Some have suggested that there is evidence for ground flow occurring during the final stages of ejecta deposition. Spudis shows several figures relating to all these features.

One interesting fact about the rings of Orientale is that they are spaced according to $\sqrt{2}$D. where D is the diameter of the ring immediately inside the one being calculated. The innermost ring =320km, so work it out - there are 6 in all..

Reference List

Melosh H.J., 1996, Impact Cratering - A Geologic Process, Oxford University Press

Spudis P.D., 1993, The Geology of Multi-ring Impact Basins, Cambridge University Press