Hypervelocity Impact Crater Formation
A reference paper commissioned by RyeBrook Space
Researched and compiled in 2015

Important note: this paper has been compiled from many sources, mostly online, so referencing details have not always been available. References have been included where they could be found. The author has no wish to claim this work as his own, so if you recognise elements that are your work, please contact us so that we can correctly reference and credit you.

1. Purpose of study

Hypervelocity impact craters are among the most catastrophic processes in the Solar System. An understanding of the processes and mechanisms involved is therefore important both in order to predict the implications of such an event were it to happen on Earth in the future, and for commercial reasons, to determine how old impact craters on Earth and elsewhere in the Solar System might be exploited in the future.

This study is intended only as an overview of the process to aid understanding, rather than as an exhaustive and technically detailed account. It is hoped that it will provide the reader with an underpinning knowledge of the forces and mechanisms involved in the formation of these significant impact features.

2. Definition Lunar & Planetary Institute (date unknown)

A hypervelocity impact crater (HIC) is a structure formed by a cosmic projectile that is large enough and coherent enough to penetrate Earth's atmosphere without losing its original cosmic velocity (>11Km/sec) and striking the ground at this speed.

Of course, HICs on other bodies in the Solar System have different criteria due to the many variations in atmospheric density and gravitational value.

HICs tend to be of objects >50m in diameter for stony objects, or >20m in diameter for coherent iron objects.

Smaller objects tend to lose most of their velocity and kinetic energy in the atmosphere through disintegration and ablation, and strike the ground at only a few hundred meters/sec.

In contrast with HICs, these smaller impacts typically:

- Excavate only a pit on impact
- Have remains of the projectile in the pit
- Are less than a few tens of meters in diameter
- AKA "Penetration Pit" or "Penetration Funnel"
3. Overview of formation process Lunar & Planetary Institute (date unknown)

HICs begin to form the second the extraterrestrial object strikes the ground at its original cosmic velocity.

(i) Impact velocity is greater than the speed of sound
(ii) The crater is produced by intense shockwaves
(iii) Shockwaves radiate through target rock
(iv) Intense, transient, high pressure shockwaves
(v) High pressure waves exceed structural strength of the target rock
(vi) Shockwaves radiate from impact point at velocities greater than 10Km/sec
(vii) Shockwaves interact with ground surface and set large volumes of rock in motion
(viii) Impact crater is excavated
(ix) Excavation and modification of crater by gravity and rock mechanics is a complex and continuous process

4. Stages of formation process Lunar & Planetary Institute (date unknown)

• Contact & compression
• Excavation
• Modification

5. Contact & compression Lunar & Planetary Institute (date unknown)

• Begins the instant the leading edge of the projectile makes contact with the ground.

• The projectile is stopped in less than 1 second

• The projectile penetrates no more than 1-2 times its own diameter

• The kinetic energy is transferred to the target rock

• Shockwaves are generated at the interface between projectile and ground

• (Conversion of kinetic energy into shockwaves is poorly understood)

• The shockwave is projected out in a roughly hemispherical pattern

• A complimentary shockwave is reflected back into the projectile (Newton's 3rd Law of Motion - for every action there is an equal and opposite reaction)

• The expanding shockwave loses energy. (The expanding shock front covers increasingly larger hemispherical area, and with increasing radial distance there is a corresponding decrease in overall energy density)

• Additional energy is lost to the target rock through heating, deformation and acceleration

• Energy transfer on impact causes total melting and vaporisation of projectile and a large volume of target rock
• Excavation stops at the point where the shockwave pressure falls below the tensile integrity of the target rock, transferring to a seismic wave

At the projectile...

• The shockwave is reflected back into the projectile

• The reflected shockwave reaches the back edge of the projectile

• From here it is reflected forward into the projectile as a rarefaction or tension wave (release wave)

• Release wave unloads projectile from high shock pressures

• Heating of energy transfer leads to complete melting and vaporisation of the projectile

• The vaporised projectile may expand out of the crater as a vapour plume, and melted remainder may be violently mixed into melted and brecciated target rock

Timeframe...

• Contact and compression stage lasts less than a few seconds, regardless of the size of the crater

• The time taken for the shockwave to travel from the interface to the rear edge of the projectile is about the same time as it takes the projectile to travel one diameter at its original velocity

• This time is about 2 secs for an object of 50Km diameter, travelling at 25Km/sec

• For most impacts the entire contact and compression stage is over in less than 1 second!

6. Excavation stage (formation of the transient crater)
Lunar & Planetary Institute (date unknown)

• The actual crater is opened up by the complex interactions between expanding shockwaves and original ground surface

• Hemispherical shockwaves expand rapidly through the target rock

• Due to projectile penetration the centre of the shockwave lies below the original ground level

• Near the surface, tension in shockwaves exceeds the mechanical strength of the target rock, so fracturing and shattering of target rock occurs

• At the near-surface the tensional release wave converts some of the shockwave into kinetic energy, propelling rock outward as ejecta at high velocities

• There is a symmetric excavation flow
• In the upper levels there is upward and outward excavation

• In the lower levels there is a downward and outward excavation

• This process results in a bowl-shaped depression (transient cavity/crater)

• In the upper level ejecta travels at several Km/sec in the ejection zone

• Material is ejected beyond the rim of the final crater

• At a significant distance from the impact, ejecta travel at more than 100m/sec, so the final crater is many times larger than the projectile

• At deeper levels the release waves are lower and less fracturing and lower excavation flow rates occur, so material is driven downwards and outwards in the displacement zone

• Both zones continue to expand

• Uplift of near-surface rocks forms the transient crater rim

• Shockwaves continually lose energy by deforming and ejecting rock

• Eventually a point is reached where shockwaves can no longer displace rock

• Growth of the transient crater ceases

• There reaches a point of balance where shockwave energies no longer act, and waiting forces of gravity and rock mechanics have not yet reasserted themselves

• At this point the transient crater has reached it maximum extent

• The excavation phase ends and the modification phase begins

Timing...
• The excavation phase is quick - a 200Km crater can be excavated in less than 2 minutes!

Proportions...
• The transient crater is paraboloid

• The depth is one third of the diameter

• These proportions are the same for craters of all sizes

In reality there is an overlap between excavation and modification, with modification beginning while other parts are still being excavated.
7. **Modification** Lunar & Planetary Institute (date unknown)

- Expanding shockwaves decay into low pressure **elastic stress waves** beyond the outer rim
- These play no further role in crater development
- The crater is **immediately modified** by **gravity** and **rock mechanics**
- Modification lasts only slightly longer than excavation (less than 1 minute for a small structure)
- The **modification phase ends when things stop falling!**
- Modification has no clearly marked ending
- **Uplift** and **collapse** merge into geological mass movement of **isostatic lift, erosion** and **sedimentation**

8. **Simple and complex structures** Lunar & Planetary Institute (date unknown)

The extent to which a transient crater is modified depends on:
- Its size
- The structure of the target rock

**Small craters** - chiefly altered by collapse of the upper walls, with the shape little altered from original transient crater.

**Larger craters** - may involve major structural changes - uplift of central part of floor and major peripheral collapse around rim.

Three distinct types of impact structures can be found:
- **Simple craters**
- **Complex craters**
- **Multiring basins**
Simple craters:

- Bowl-shaped depressions
- Less than a few Km across
- Preserved shape of original transient crater
- Minor collapse of steep upper walls
- Redeposition of minor amount of ejecta in crater
- Crater diameter may increase by as much as 20%
- Depth remains largely unaffected
- **During modification**: immediately filled to perhaps half its original depth, with a mixture of *fallback* ejecta and debris
- Crater filling is called *breccia lens* or *crater fill breccia*
- Mixture of rock fragments - shocked fragments or lens of shock-melted rock (*impact melt*)
- May become eroded or covered and preserved by cap of later sedimentary fill

Complex craters:

- Larger impact structures, different and more complex in form
- Characterised by central uplift area
- Generally flat floor
- Extensive inward collapse around rim
- **Transition from** simple to complex at 4 Km in crystalline rock or 2 Km in sedimentary rock. (*these values apply only on Earth*)
- Transition value varies inversely with gravitational acceleration - different on different planets
- Very large impact events release enough energy to overcome fundamental strength of target rocks over a large volume beneath large transient crater
- Late-stage modification involves complex interactions between *shockwave effects*, *gravity* and **strength and structure of target rocks**
- Modification is characterised by outward, inward and upward movements of large volumes of sub-crater rocks
- Modification processes are poorly understood
- Deep-seated rocks beneath centre of transient craters rise to form **central uplift**
- At the same time, rocks around periphery of transient crater collapse downward to form one or more depressed rings (*ring grabens*) and a series of terraces along the centre margins of final structure.

- Geological studies have shown that the amount of actual *stratigraphic uplift (SU) = ~ 0.1D*, therefore a crater of 100-200Km diameter will have a vertical central uplift of 10-20Km
- Uplifts form in only a few minutes (instantaneous in geological terms)
- Uplifts in craters 200-300Km form in less than 15 minutes.
- The mechanism of uplift is poorly understood.

- The larger the crater, the more complicated the uplift process becomes.
- Increasing crater sizes show increasingly changing character in central uplift.
- A single central peak becomes replaced by a series of concentric rings and basins.
- There are three clear types of complex crater structures - *central peak structures, central peak-basin structures* and *peak ring basin structures*. 
• These features are characterised by formation of a basin in the central peak which leads to conversion of the peak into a ring structure.
• Critical diameters vary with planetary gravity.
• Transition from simple to complex crater occurs at 20Km diameter on the Moon.
• Transition on Earth occurs at 2-4Km.
• Transition from central peak basin to peak ring occurs at 150-200Km on the Moon.
• Transition on Earth occurs at 20-25Km.

Multi-ring Basins

• The largest impact features in the Solar System are from a few hundred to 1000Km in diameter.
• These are huge geological bullseyes.
• They consist of multiple concentric uplifted rings.
• There are intervening down-faulted valleys (ring grabens)
• These are structures with two or more internal rings in addition to outer rim structure.
• These features are produced by the impact of projectiles tens to hundreds of Kms in diameter.
• They date from the early period of the Solar System.
• Such features are best preserved on Mars, Mercury, the Moon and some jovian satellites.
• Mare Orientale on the Moon is a well-known example.
• Many do not show the classic multi-ring structure, maybe due to erosion.
• Transition on the Moon occurs at 400-600Km.
• On Earth transition is at perhaps 100Km.
• These features represent the most energetic and catastrophic impacts in the Solar System.
• Mechanisms are poorly understood - may be entirely a function of crater diameter, or there may be other special conditions.
• May be influenced by crust depth or other factors.

Fig 2: a simplified modification flow sketch showing the downward and inward radial slump from the crater rim, and the upward and outward flows of central uplift. Where the latter meet and interact, is where peak ring structures can be formed by radial displacement of uplifted material.
9. Subsequent Development of Impact Structures  
Lunar & Planetary Institute  
(date unknown)

1. Circular structure  
2. Deformed sub-crater rocks  
3. Covered with ejecta blanket  
4. Crater fill deposits

All craters are subject to geological changes:

- Erosion  
- Burial  
- Tectonic Deformation

- Impact is a near surface process  
- It is a relatively shallow process  
- Impact-produced rocks form thin units  
- A 10Km diameter crater is only a few Kms deep  
- Impact structures are especially vulnerable to erosion  
- Erosion preferentially removes ejecta blanket  
- Impact structures may get caught up in tectonic deformation with varying results  
- Horizontal compression may distort the circular shape  
- Tectonism may break up regimes of shocked rocks and disperse them as large discrete areas across the geological landscape  
- Sufficient tectonism and metamorphism could destroy even large impact structures and make them unrecognisable

10. Peak Ring Formation in Large Impact Structures  
Morgan et al 2000

Studies of the 200Km diameter Chicxulub crater in Mexico have revealed the kinematics of central uplift and peak ring formation in large crater collapse.

The seismic data reveal downward and inward radial collapse of the transient crater cavity in the outer crater, and upward and outward collapse within the centrally uplifted region. Peak rings are formed by the interference between these two flow regimes, and involve significant radial transport of material.

11. Economic Potential of Impact Craters  
Westbroek & Stewart 1996

From a commercial point of view, impact craters on Earth have been linked to economic deposits of various materials of value.

- Impact crater materials have been exploited for decades  
- Only recently have revenues been formally inventoried  
- 140 known terrestrial impact craters  
- 17 being actively exploited  
- Current estimated annual revenues of >$12 billion
Deposit types:

**Progenetic** - the effect of the impact redistributing native deposits, allowing them to be more easily retrieved. e.g. Gold and Uranium.

**Syngenetic** - originate during or shortly after impact, and attributed to the direct deposition of energy into target rocks causing change and melting. e.g. Cu-Ni

**Epigenetic** - deposits formed after impact and generally attributed to hydrothermal action, formation of enclosed basins with isolated sedimentation or flow of fluids into structural traps associated with craters. e.g. Hydrocarbons.

12. **Oblique Impacts** Poelchau 2010

Although obliques impacts generally still form circular craters, they are characterised by asymmetric, non-radial distribution of ejecta blanket.

At a deeper level, there can be found an internal structure signal of deformed rock in crater rims.

The non-radial signal of the ejecta blanket can be used to determine the direction of impact.

**Radial Corner Faults** and **inter-thrust wedges** may contribute to polygonal craters.

Non-radial central uplift features are also a strong indication of an oblique impact.

There are a few examples of elliptical craters.

• The statistic chances of a 90 degree impact are impossible.
• The most common angle of impact is 45 degrees. (Half of all impacts should strike at 45 degrees.
• The proportion of oblique impacts does not fit with nearly all observed craters being circular.
• Only around 5% of craters are elliptical. (Aspect ratio 1:2).
• Explained by high impact velocity and delivery of shockwave.
• Leads to significant asymmetry in oblique impact.

![Fig 3: a simple sketch of oblique impacts, showing the asymmetric distribution of the ejecta blanket. (left) oblique impact. (right) highly oblique impact. The arrows indicate the direction of impact.](image)
Conclusion:

Hypervelocity impact crater formation is a process that is more complex than it might at first appear. There is still a great deal that we do not understand, and future research will improve our understanding of the kinematics and mechanics behind the complex features that we observe in some craters. Much laboratory work is being done, trying to create impact crater analogues that can be observed under hyper-slow motion video imagery, to gain a better insight into the physics involved.

Despite its complexity, when the mechanics of impact crater formation is understood in its basic form, it is highly intuitive and can be easily visualised when observing real specimens of impact features both on Earth and on other bodies within our solar system. The purpose of this work has been to facilitate this underpinning understanding in the reader.

Hypervelocity impacts are catastrophic and energetic events, and the prospect of such a process occurring her on Earth is concerning. For this reason, there has been much interest in Near Earth Objects (NEOs) in recent years. The Chelyabinsk fireball incident of 15 February 2013, brought home the possibilities of a catastrophic impact, even this late in the evolution of the Solar System. The World's eyes were all watching an NEO in a close pass of the Earth, when this unexpected and undetected object crashed to Earth while our backs were turned!

A knowledge of the kinematics, mechanics and energy exchanges of hypervelocity impacts will help us to prepare through the development of theoretical scenarios, thus enabling us to formulate emergency plans. This is a developing area of space science, where there is currently much work to be done.

It also emerges that there are commercial potentials in the exploitation of impact craters, both her on Earth, and on other bodies within the Solar System at some point in the future. Those organisations and companies that currently specialise in this field on Earth, might one day become leaders in the same processes off-Earth, and there is certainly benefit in exploration and examination of extra-terrestrial impact structures.

Ryebrook Space hopes to develop into both areas - NEB detection, monitoring and mitigation; and impact structure exploitation. This work has been compiled to help inform commercial decision-making for our business and scientific teams, by providing an underpinning, albeit basic knowledge of impact structure formation and characteristics. It forms the standard document of reference for our business associates.