Impact Craters:

The “Evolutionary Leader”

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Abstract

Impact cratering is by far the most fundamental and widespread geologic process shaping the surfaces of solid bodies in the Solar System, and before it was even intimately associated with the formation and evolution of planets, satellites and small bodies. For instance, an early very large impact of Mars-sized object striking the differentiated proto-Earth has been proposed to be responsible for the origin of the Moon, whose surface was reshaped by a later, heavy bombardment.

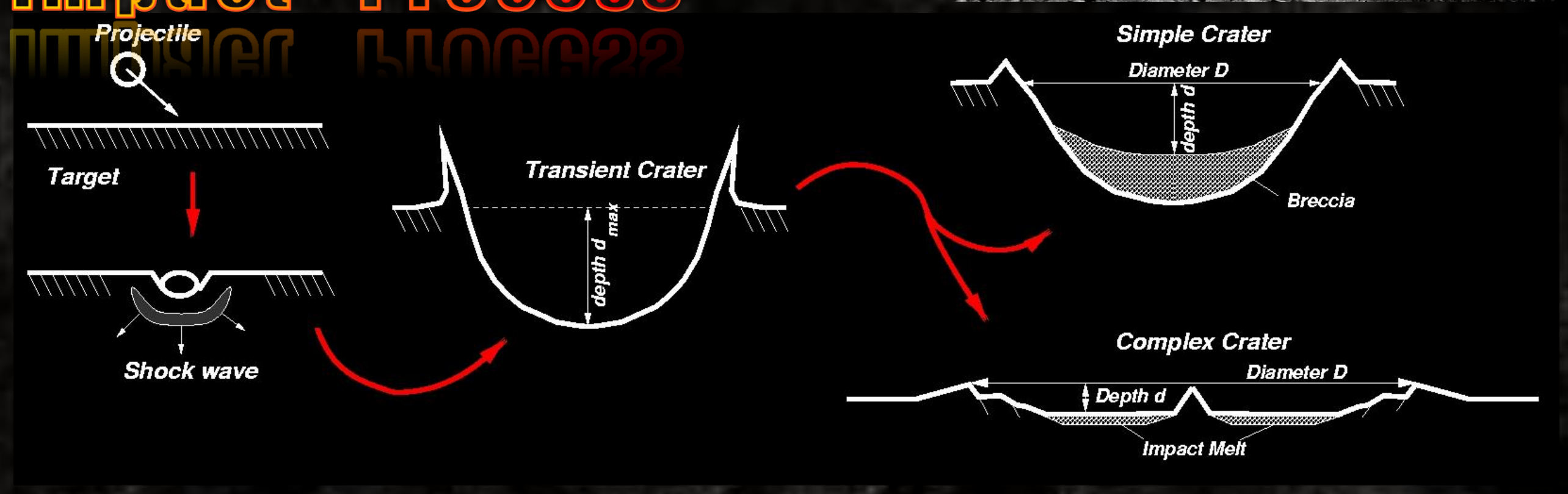
On the other hand, the analysis of large and small-scale deformation features related to Lunar impact craters, including rings, rims, peaks, faults fractures and antipodal deformation structures, is essential for the understanding of impact tectonics, whose study is otherwise difficult on the few, heavily degraded or almost completely buried, Earth craters.

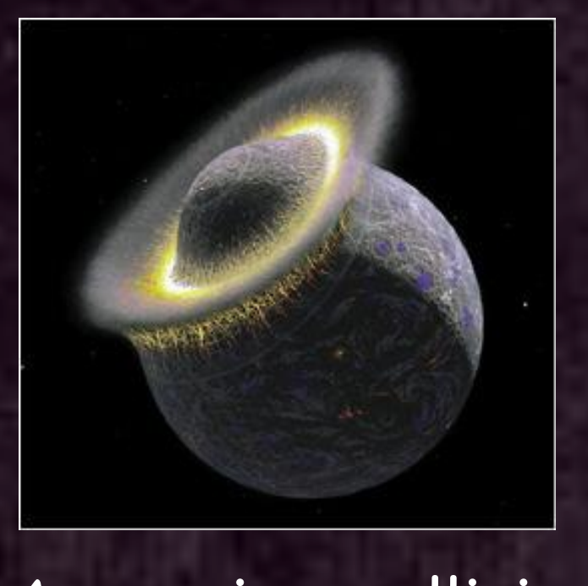
Craters are also of paramount importance to assess the mineralogical zoning of the upper hundred meters of the crust or even the composition of lunar mantle. In addition, the morphology of craters is also of great value for tectonic studies since craters readily record deformation processes and fault displacements; at the same time, studies of impact processes and Crater Size-Frequency Distributions can shed light on the rheology of the target itself (*Holsapple & Housen, 2007; Massironi 2009*).

Last, but not the least, since impact craters population on a surface unit directly correlates with the time the unit was exposed to space, the cratering record is crucial for assessing the evolution of the impact flux, ages and even the thickness of geological units on planetary surfaces (*Neukum 2001; Marchi 2009*).

In this work, we would like to focus on the impact crater process and its role in the understanding of the evolution of our natural satellite.

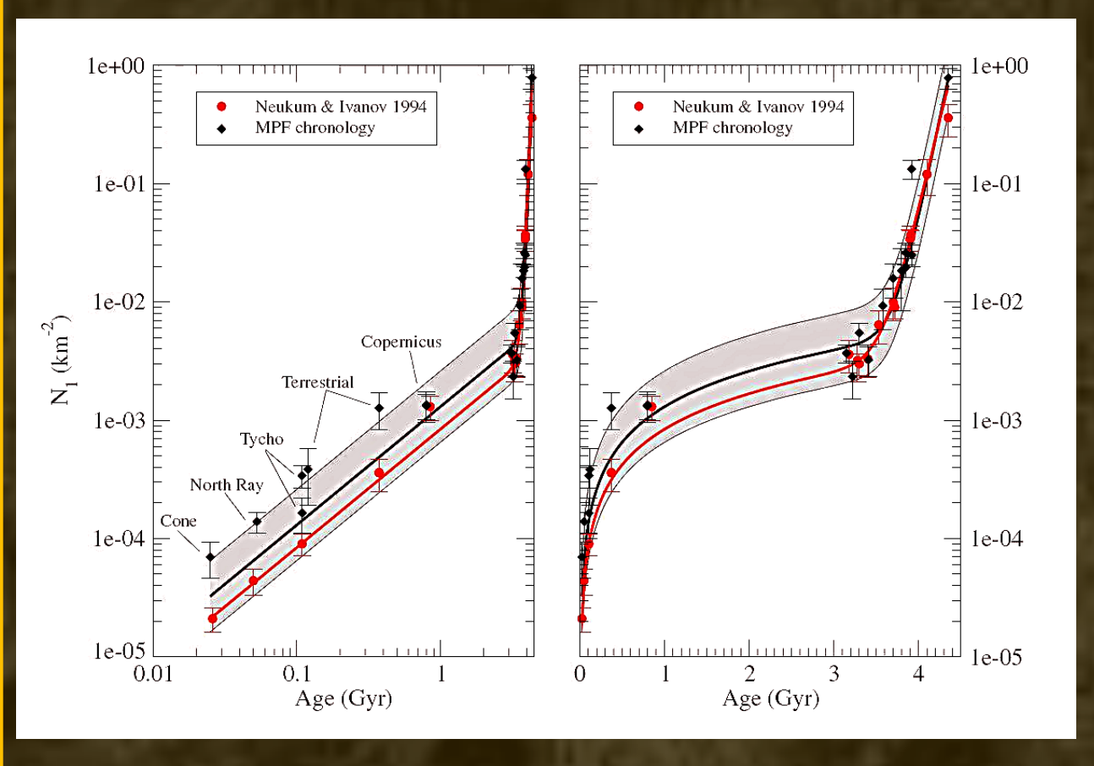
Impact Process





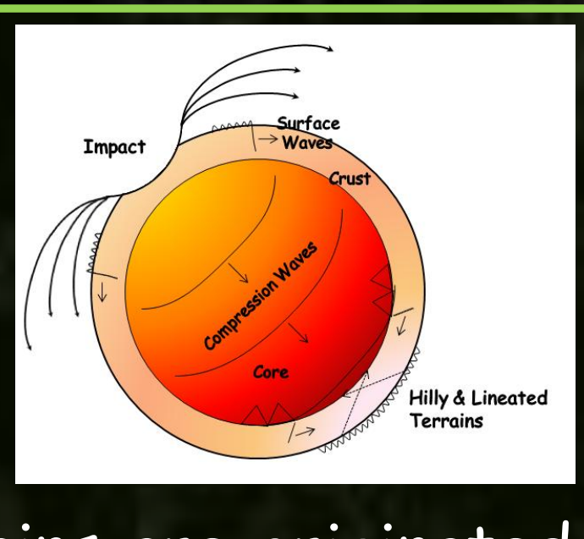
The origin of the Moon in now attributed to a collision between the proto-Earth and a Mars-size object, ~4.5 Gyr ago, near the end of accretion period. The “giant impact” theory has overcome the other theories of lunar origin (capture, fission, and co-accretion) because it is the only one to provide a simple explanation for the Moon’s chemistry, as revealed in the lunar samples.

A grazing collision vaporized a large quantity of the proto-Earth’s mantle, along with a comparable quantity of the projectile. While most of the mass of the projectile merged with the Earth, one or two lunar masses of vapor condensed into dust in stable Keplerian orbits around the Earth and later accumulated together to form the Moon (*Melosh, 2011*).



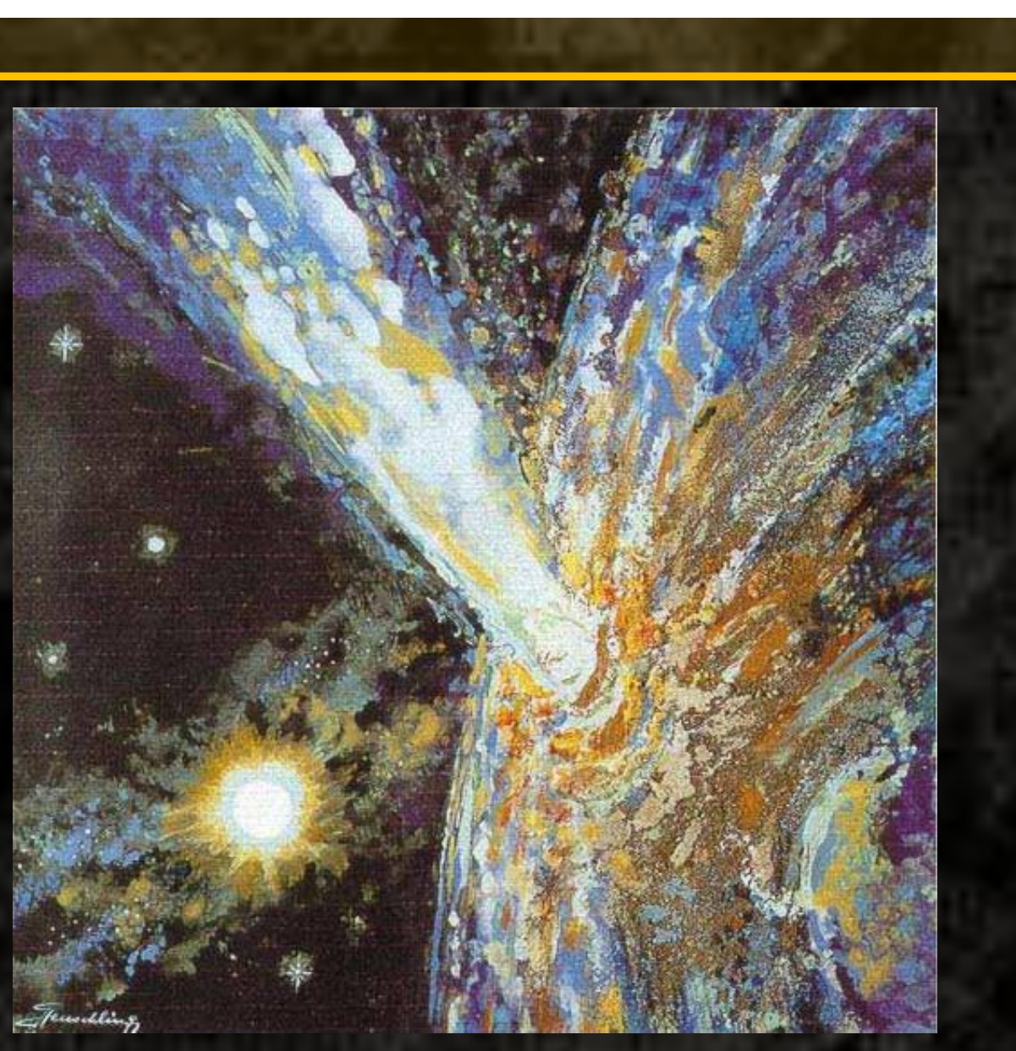
Cratering studies provide a fundamental tool for the age determination of the Moon and planetary surfaces., based on the assumption that craters form randomly and were accumulated through time at known average rates as a function of size.

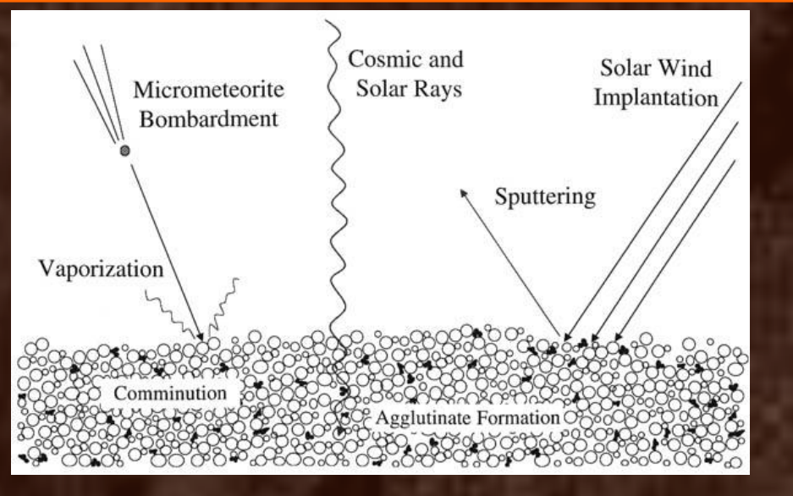
One among the most recent models is based on the impactor size and velocity distributions, derived from dynamical models describing the evolution of MBAs and NEOs, and then converted into the crater Model Production Function (MPF, *Marchi et al., 2009*) through the *H&H (2007)* scaling law. The absolute model chronology is finally attained through the calibration with the known radiometric ages of the lunar samples.



Extremely large impact structures on the planets and satellites seem to have affected the entire tectonic framework of those bodies. For example, Caloris basin on Mercury is believed to have affected large areas surrounding the basin and also to have caused a great amount of fracturing and surface disruption at its antipode.

A possible explanation is that these hilly and lineated terrains are originated by seismic waves focusing at the antipodal regions with respect to the impact (*Strom & Sprague, 2003*).





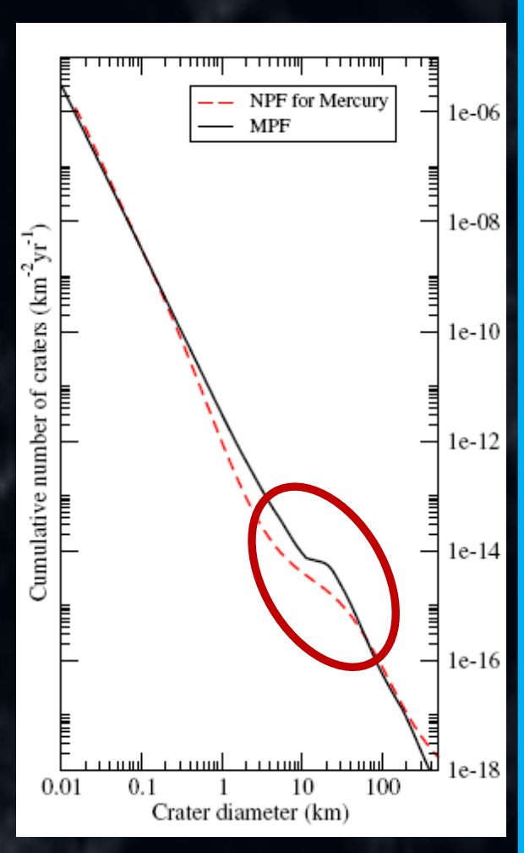
A long history of bombardment caused the lunar surface to have been ground up into fragments ranging from huge boulders to powder. The charcoal-gray, powdery rocky debris, called regolith, ranges from 4 to 5 m on the mare to perhaps 20 m deep in the highlands (*Bart et al., 2011*). Beneath the regolith is a region of fractured bedrock referred to as the megaregolith.

Spectrally, the lunar regolith is much darker than fresh rock of the same composition. Mineral fragments in the regolith are riddled with tracks produced by energetic cosmic rays, and solar wind gases are implanted below the surfaces of many grains. Although the Moon’s interior seems to be nearly devoid of water, recent remote spectral observations have detected OH and H_2O molecules produced as solar wind protons bond chemically with oxygen in silicate minerals on the surface (*Sunshine et al., 2009*). Neutrons liberated by primary cosmic rays penetrate many meters into the surface, creating exotic isotopes whose presence records the relentless irradiation and permits the total duration of exposure to be determined (*Melosh, 2011*).

H&H (2007)
Holsapple & Housen (2007)

$$D = kL\left[\frac{gL}{2v_\perp^2}\left(\frac{\rho}{\delta}\right)^{\frac{2\nu}{\mu}} + \left(\frac{Y}{\rho v_\perp^2}\right)^{\frac{2+\mu}{2\mu}}\left(\frac{\rho}{\delta}\right)^{\frac{\nu(2+\mu)}{\mu}}\right]^{-\frac{\mu}{2+\mu}}$$

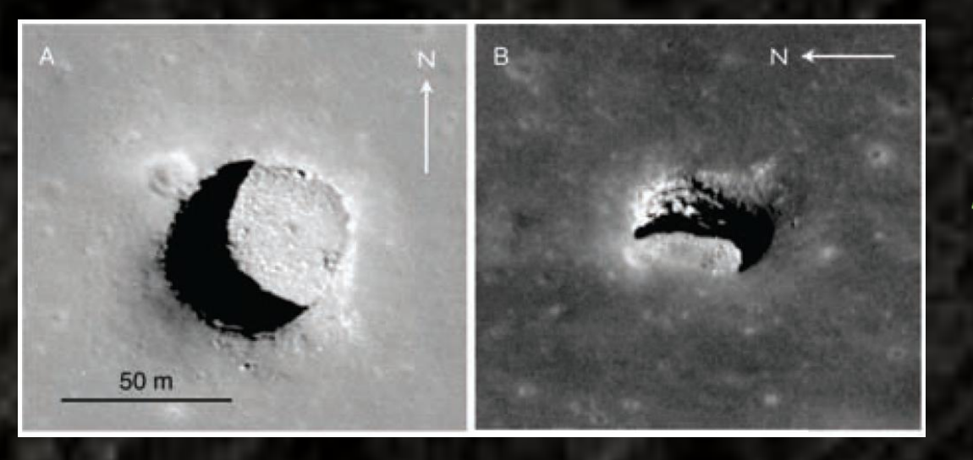
Cohesive soil   Hard rock



Several crater counts show a distinct “kink” in the shape of cumulative crater-SFD for crater diameters lower than 20 km. In some regions of the Moon (e.g., Mare Crisium and Mare Tranquillitatis), this inflection is due to the partial superposition of two geological units of different age (*Neukum & Horn, 1976*). On the other hand, if such lava flows emplacement has not intervened, such inflection is related to the rheological layering of the studied portion of the crust, and more in details to the transition between cohesive to hard rock soils.

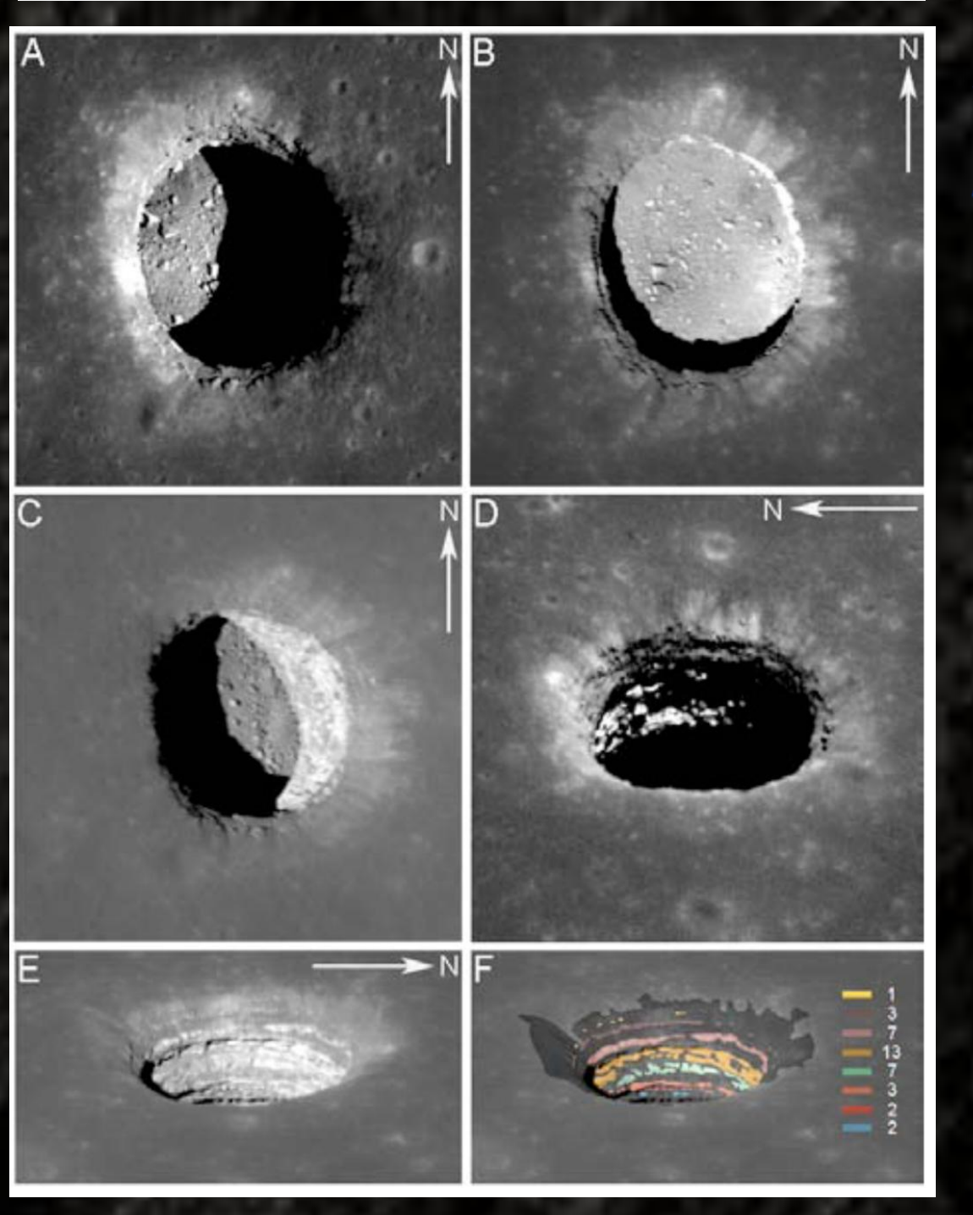
The MPF curves (*Marchi et al., 2009*) keep the S-inflection due to transition in the target’s crustal properties through the adoption of the scaling law in the formulation by *H&H (2007)*.

… And something new?!



Marius Hills skylight

Diameter = 52.5 m
t = 28 m



Mare Tranquillitatis skylight

Diameter = 91.5 m
t = 47 m

Ashley et al. (2011)

Skylights

Skylights are opening on lava tubes (*Calvari & Pinkerton, 1999*) and they could originate as collapse of the lava tubes ceiling caused by random meteoroids impacts (e.g., *Coombs and Hawke, 1992*).

We consider this hypothesis to compare crater-geometry argumentations and numerical modelling results to analyze the conditions of the collapse of lava tubes’ roofs.

Lava tubes

Lava tubes are, following the definition of *Kauahikaua et al. (1998)*, "roofed conduit through which molten lava travels away from its vent“. They form when a lava channel flow develops by radiative cooling a solid crust whereas the lava stream beneath is still liquid and flowing away from the feeding vent (e.g. *Greeley, 1970, 1987; Keszthelyi, 1995*).

iSALE: Numerical Modelling

iSALE (Simplified Arbitrary Lagrangian Eulerian) is a multi-material, multi-rheology code modified after the SALE hydrocode (*Amsden et al. 1980*) since the early 1990s. Improvements to the code have spread into many topics, to include up to three target material, various equations of state, a variety of constitutive models along with the introduction of a porous-compaction model (*Melosh et al., 1992; Ivanov et al., 1997; Collins et al., 2004; Wünnemann et al., 2006*). It is well-tested against other hydrocodes (*Pierazzo et al., 2008*).

The dynamics of a continuous media is described by a set of differential equations established through the principles of conservation of momentum, mass and energy from a macrosopic point of view.

In addition, two further equations are needed.

An Equation of State to describe the thermodynamic state of a given material over a wide range of pressures, internal energies and densities.

A Strength Model to describe the response of a material to stresses that induce deviatoric deformations or changes of shape. It combines the concepts of:

- Elasticity (strain proportional to stress)
- Plasticity (elastic until yield stress)
- Fluid flow (strain rate a function of stress)

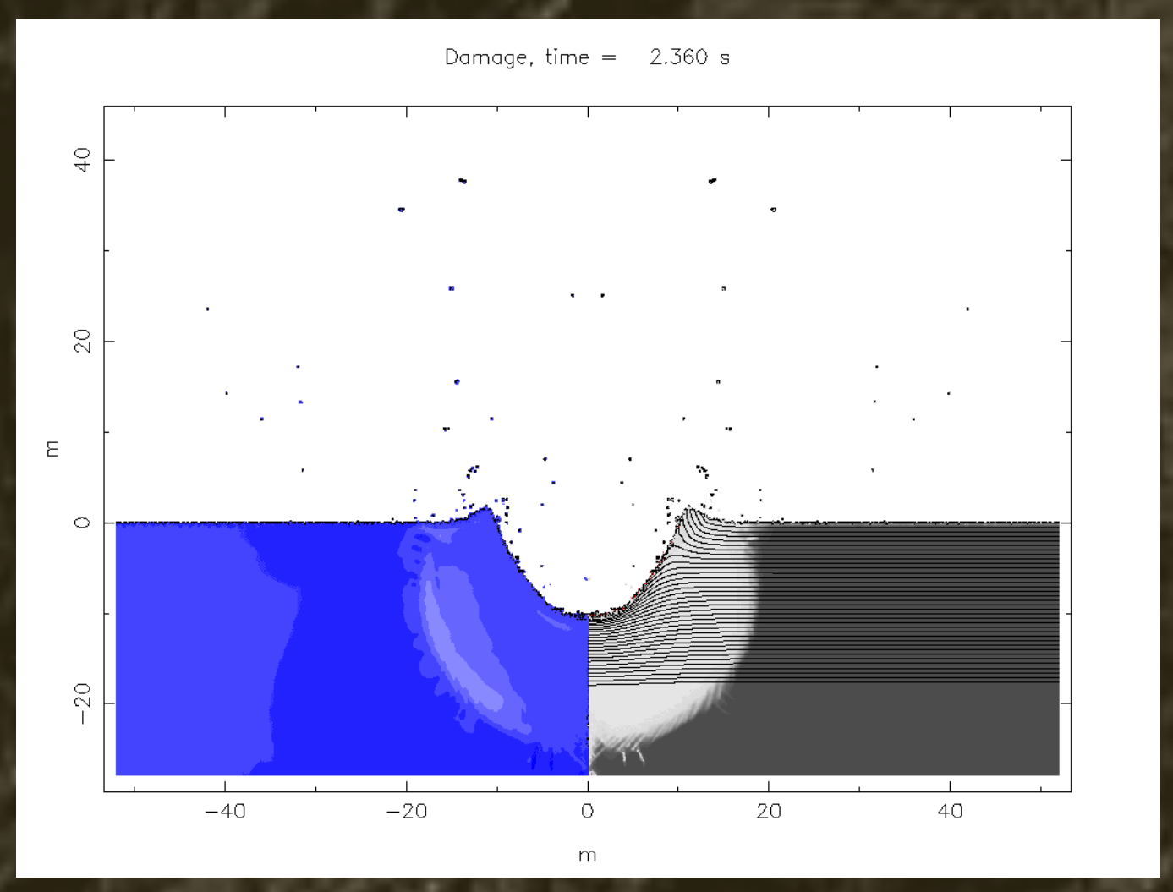
Crater Geometry

Hörz (1985) sustained that lava tubes roofs should be at least two times larger than the larger crater depth to not collapse, on the basis of ballistic penetration mechanics and associated spallation processes at the roof’s ceiling of a slab-like target:

$$t = K \cdot 0.25 \cdot D, \text{ where } K=2 \qquad \text{Eq. (H85)}$$

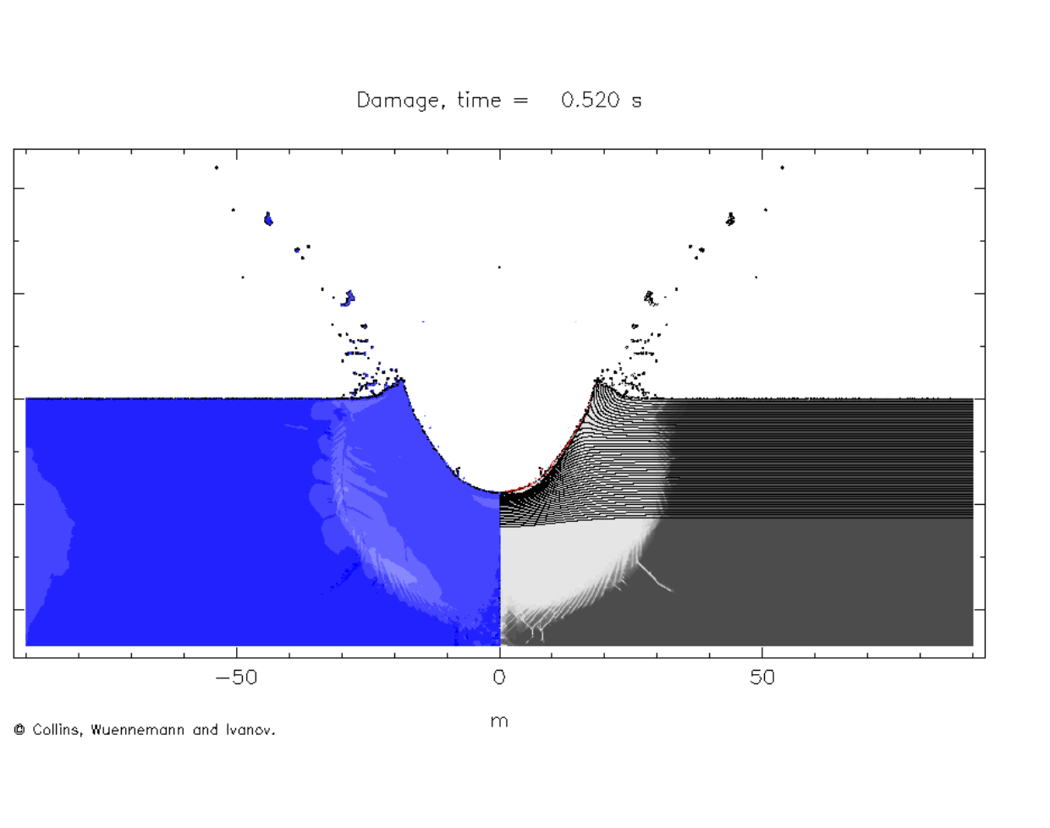
Numerical Modelling

An asteroidal-like projectile strikes perpendicularly at 18 km/s a slab-like target. In both cases, we used basalt, which is described by the ANEOS equation of state and the standard rock strength model.



Marius Hills skylight

Projectile Radius = 1.2 m
Crater Diameter = 23 m



Mare Tranquillitatis skylight

Projectile Radius = 2 m
Crater Diameter = 38 m

The thicknesses at both Marius Hills and Mare Tranquillitatis skylights are higher than the value for the minimum thickness predicted by Eq. (H85) to have uncollapsed lava tubes roofs. However, LROC images clearly show the presence of collapse. This collapse is also sustained by the results of numerical models on the formation of impact craters standing at the origin of the studied skylights. In fact, the maximum extent of the damaged area below the craters is well beyond the thickness of the target. Hence, we modelled various impacts, with the aim to derive the maximum crater, the damaged area of which is totally included within the target. Applying the outcomes of such simulations to Eq. (H85), we found that K should be ~5.

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