Cráteres e Impactos

- Historia del conocimiento sobre cráteres e impactos
- Energía y presión de los impactos
- Mecánica de Cráteres
- Estructura y tipos de cráteres
- Leyes de Craterización
- Meteoritos e impactitas
- Criterios para la Identificación de Cráteres
- Consecuencias ambientales de los impactos
- Conteo de cráteres
- El evento de Carancas: ejemplo de Geología Planetaria

Practicas:

  - Google Earth - cráteres
  - Conteo de cráteres y ajuste de curvas de edad
  - Virtual Lab: Visualización de secciones finas de meteoritos

Cut & Paste

- **Impact Cratering Seminar – H. Jay Melosh**
- **Geology and Geophysics of the Solar System – Shane Byrne**
- **Impact Cratering – Virginia Pasek**

- **Explorer's Guide to Impact Craters! http://www.psi.edu/explorecraters/**
- **Terrestrial Impact Structures: Observation and Modeling - Gordon Osinski**
- **Environmental Effects of Impact Events - Elisabetta Pierazzo**
- **Traces of Catastrophe: A Handbook of Shock-Metamorphic Effects in Terrestrial Meteorite Impact Structures – Bevan French – Smithsonian Institution**
- **Effects of Material Properties on Cratering - Kevin Housen - The Boeing Co.**
- **Sedimentary rocks in Finnish impact structures -pre-impact or post-impact? - J.Kohonen and M. Vaarma -** ***Geological Survey of Finland***

DEPARTMENT OF PLANETARY SCIENCES
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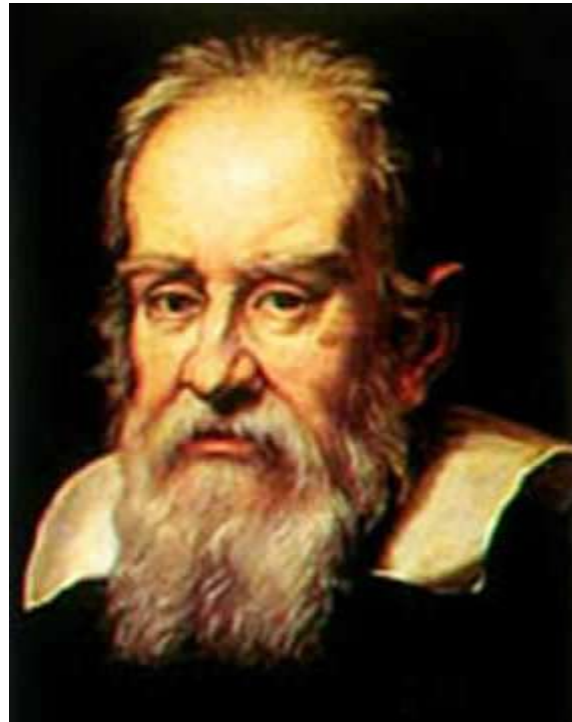
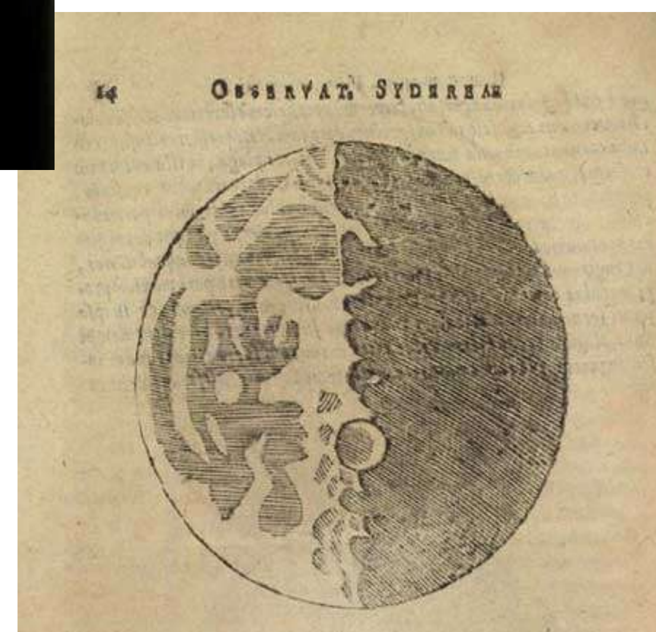
History about impact craters

The study of impact craters has a well-defined beginning: 1610


SIDEREVS
NVNCIVS
MAGNA, LONGEQVE ADMIRABILIA
Spectacula pandens, suspiciendaque proponens
vnicuique, præsertim verò
PHILOSOPHIS, atq; ASTRONOMIS, quæ à
GALILEO GALILEO
PATRITIO FLORENTINO
Patauini Gymnasij Publico Mathematico
PERSPICILLI
Nuper à se reperti beneficio sunt obseruata in LVNÆ FACIE, FIXIS IN-
NVMERIS, LACTEO CIRCVLO, STELLIS NEBVLOSIS,
Apprime verò in
QVATVOR PLANETIS
Circa IOVIS Stellam disparibus interuallis, atque periodis, celeri-
tate mirabili circumuolutis; quos, nemini in hanc vsque
diem cognitos, nouissimè Author depræ-
hendit primus; atque
MEDICEA SIDERA
NVNCVPANDOS DECREVIT.

VENETIIS, Apud Thomam Baglionum. M DC X.
Superiorum Permissu, & Priuilegio.

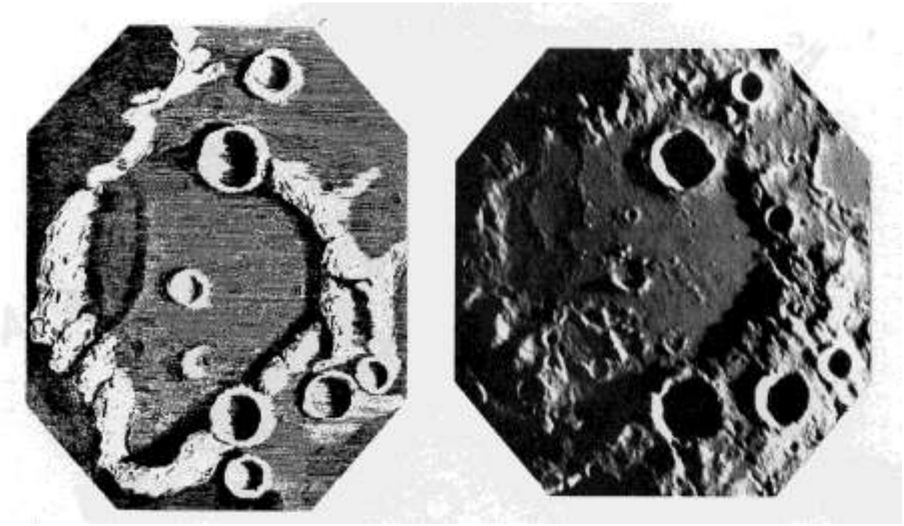




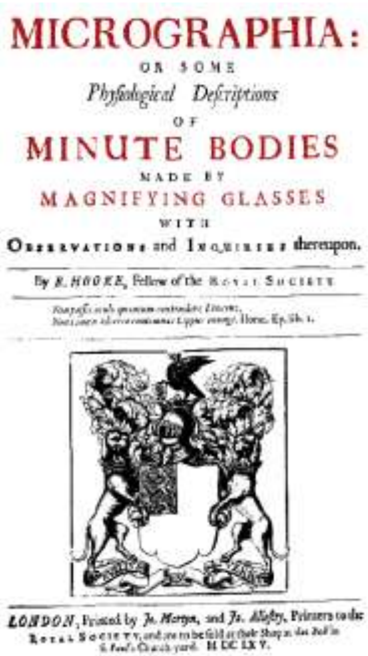
Galileo's small telescope and limited field of view did not permit him to view the entire moon at once, so his global maps were distorted

- **Nevertheless, he recognized a pervasive landform that he termed "spots"**
- **He described them as circular, rimmed depressions**
- **But declined to speculate on their origin**

Robert Hooke had a better telescope in 1665

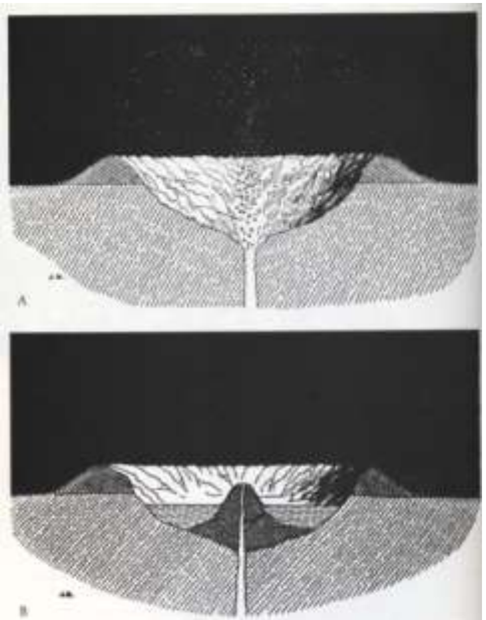


Hooke make good drawings of Hipparchus and speculated on the origin of the lunar "pits".


MICROGRAPHIA:
OR SOME
Physiological Descriptions
OF
MINUTE BODIES
MADE BY
MAGNIFYING GLASSES
WITH
OBSERVATIONS and INQUIRIES thereupon.

By *R. HOOKE*, Fellow of the ROYAL SOCIETY

LONDON, Printed by *Jo. Martyn*, and *Ja. Allestry*, Printers to the ROYAL SOCIETY, and are to be sold at their Shop at the *Bell* in S. *Paul's* Church-yard. M DC LX V.



3 Nasmyth and Carpenter's (a) "Fountain" and (b) the resulting crater

- **Hooke considered impact, but dismissed it because he could not imagine a source for the impactors. In the end, he opted for a volcanic origin, based on his study of "boiling" alabaster (gypsum)**

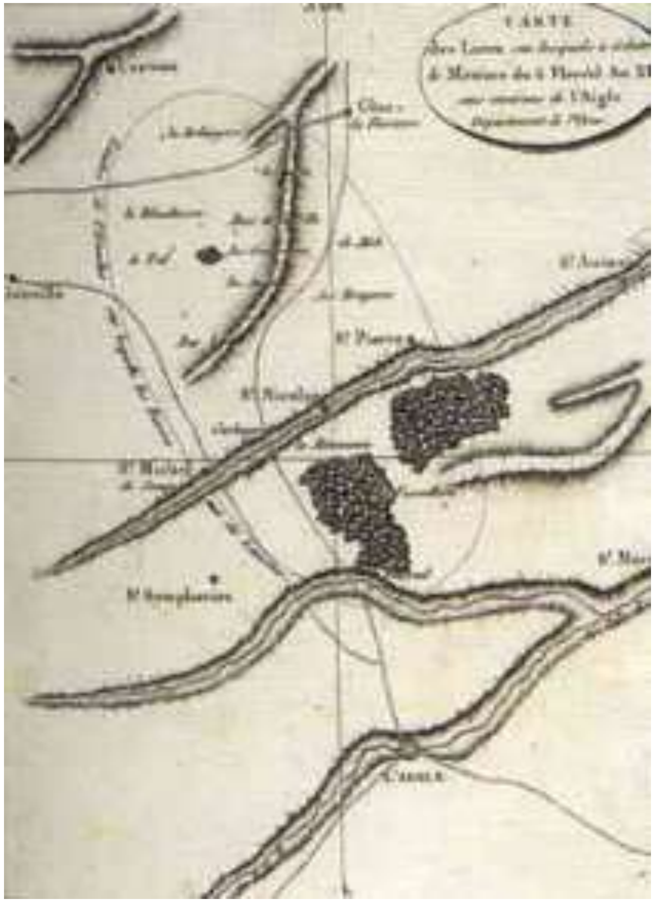
- **For the next 300 years astronomers accepted this origin.**

The word “crater” was coined by German Astronomer Schröter

SELENOTOPOGRAPHISCHE
FRAGMENTE
GENAUERN KENNTNISS DER MONDFLÄCHE,
JOHANN HIERONYMUS SCHROETER

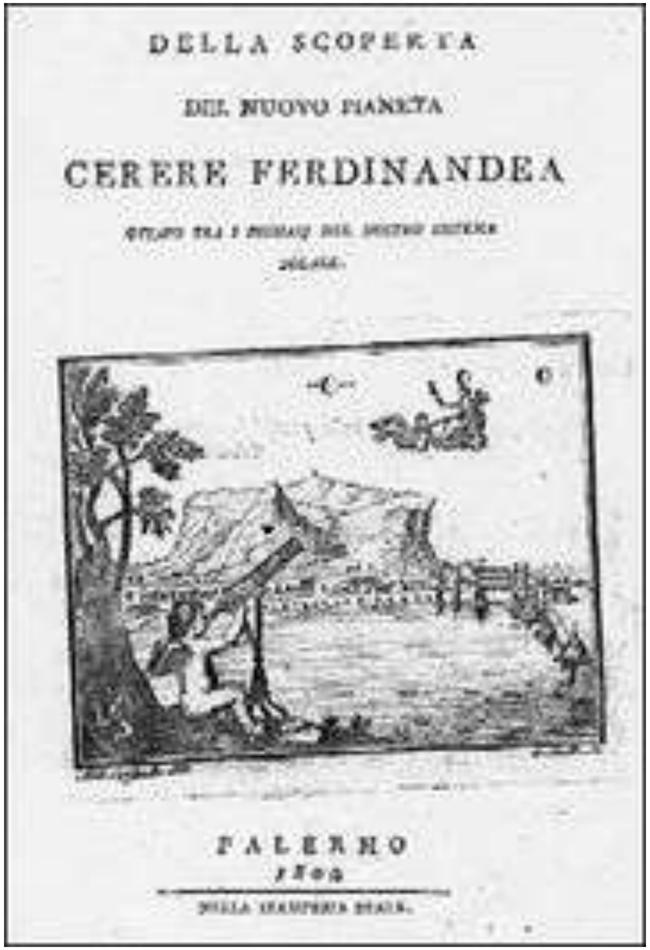
- He also described “Schrörter’s rule” that states that the volume of a crater’s rim equals (approximately) the volume of the crater itself.
- But he still believed that craters are volcanic in origin.

In 1794 Ernst Chladni argued that meteorites were real phenomena, not just peasant's fables of rocks falling from the sky



….A proposal that was greeted with scorn, but opinions were revised after a large fall at L'Aigle in 1803

Furthermore, the “void” of space was partly filled when on Jan. 1, 1801 Piazzi discovered Ceres from Palermo, Sicily



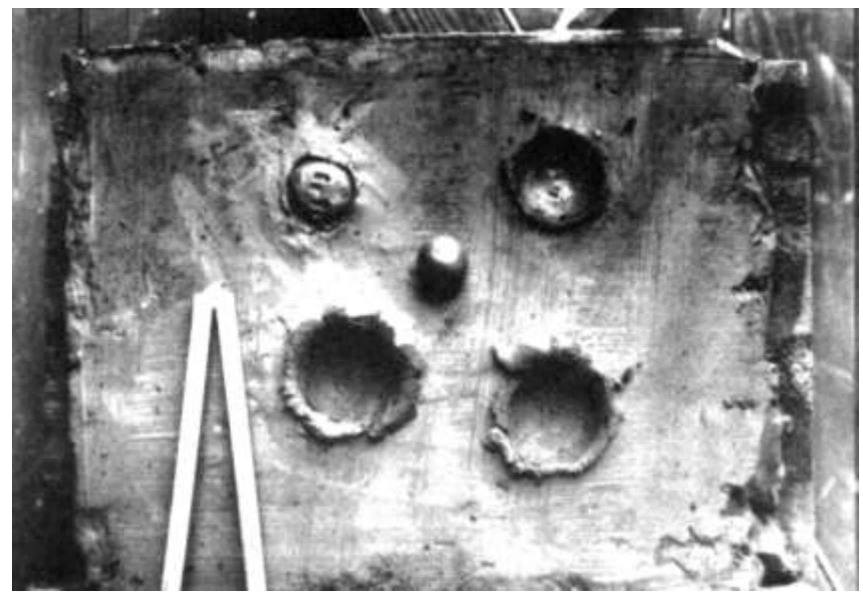
By ~1850 there were ~50 discovered asteroids between Mars and Jupiter

Near Earth Asteroids (NEAs)

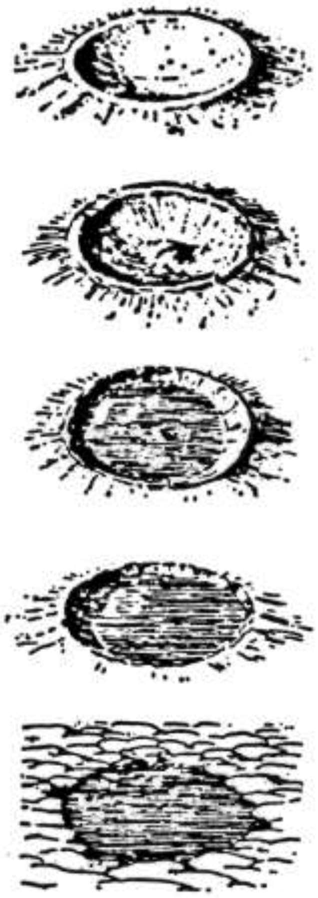
$q < 1.3$ UA

- **1932 - (1862) Apollo ($q < 1$, $a > 1$)**
  - (1221) Amor ($1 < q < 1.3$, $a > 1$)
- **1976 - (2062) Aten ($a < 1$, $Q > 1$)**

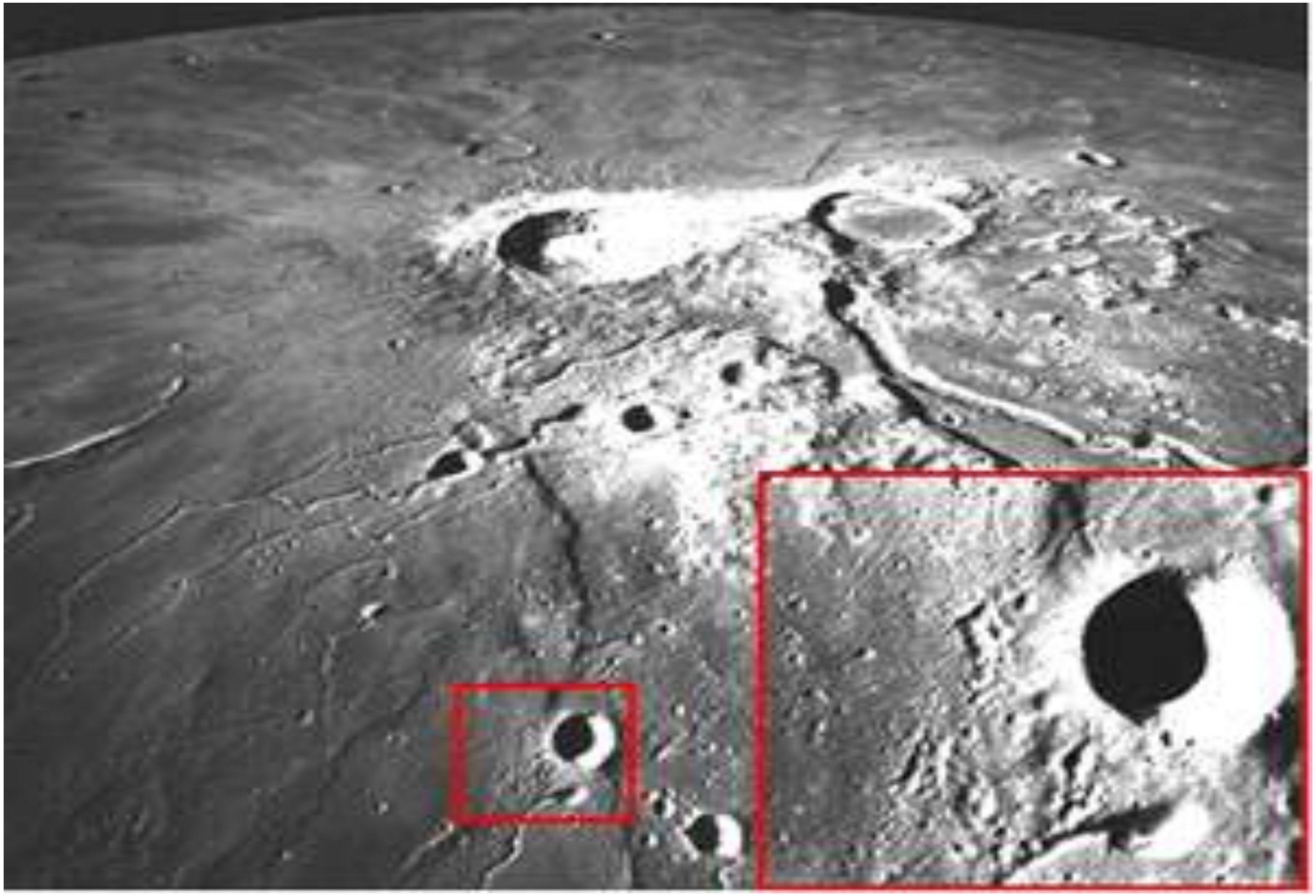
In 1893 American Geologist G. K. Gilbert proposed an impact origin for lunar craters



Gilbert established a size-morphology progression for craters

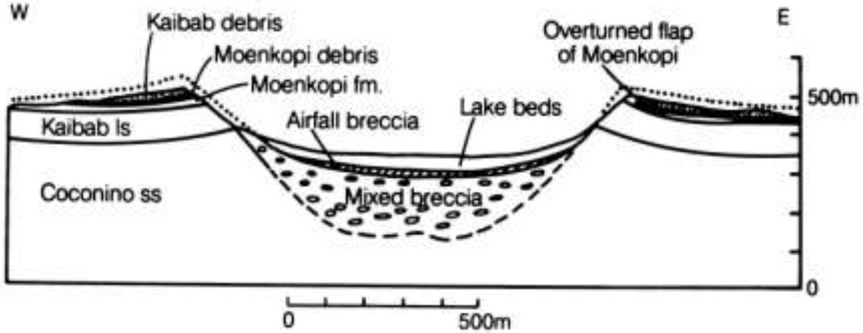


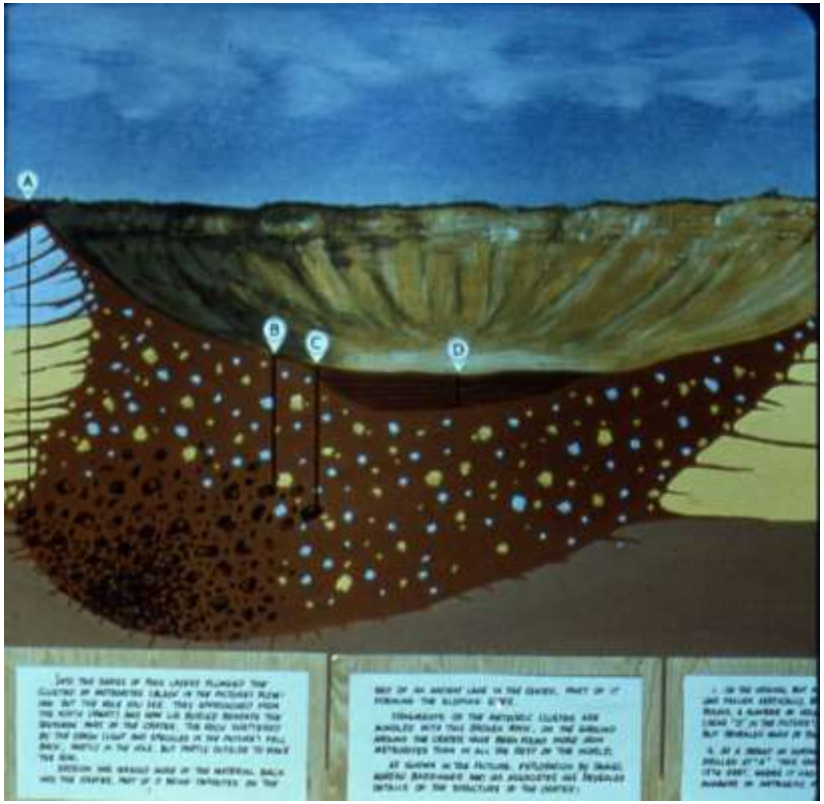
- Small craters are simple bowls
- Larger craters have central peaks and wreaths of terraces
- Craters are of different ages: Some are fresh, others old and degraded



Crater Aristarco, Moon

The first impact crater recognized on Earth was the Arizona Meteor crater

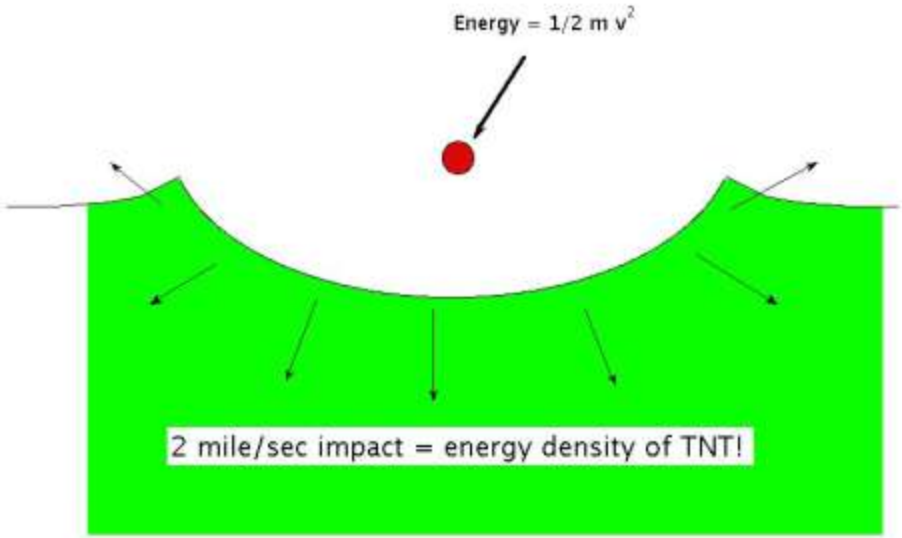


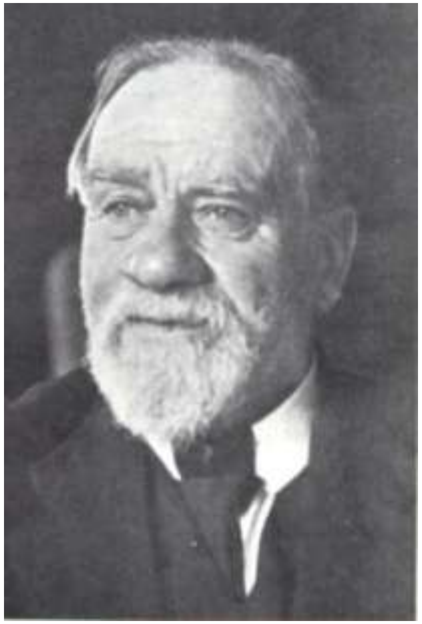


D. M. Barringer established a meteoritic origin in 1906, but until the end of his life he believed that the iron meteorite that created the crater was buried beneath its floor

Astronomers at the time had an excellent argument against the impact origin of lunar craters--too many are circular (only about 4% elliptical)

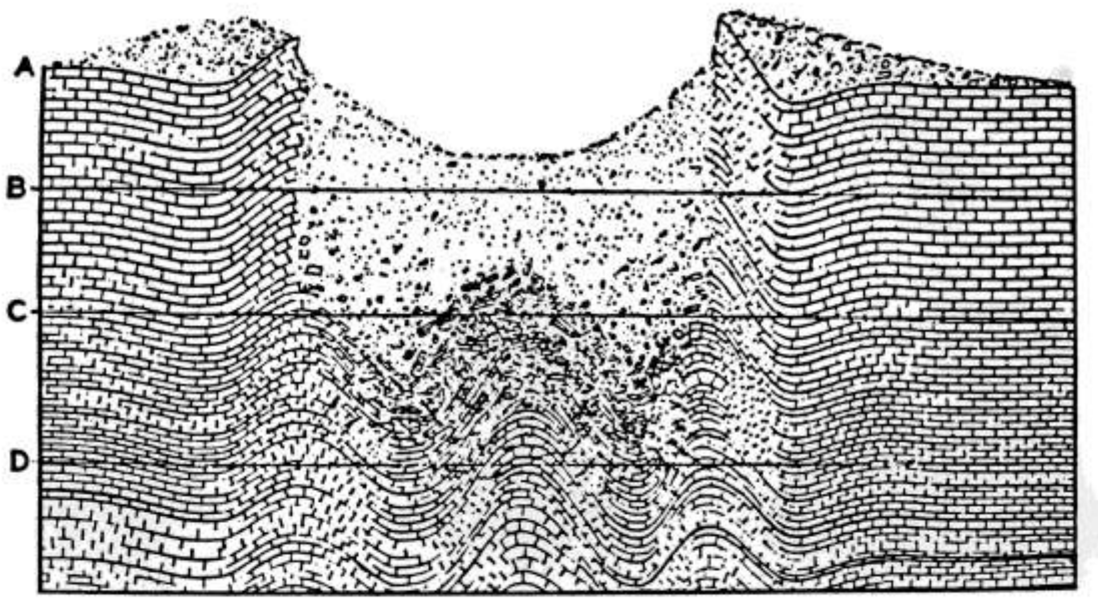
Impact-Explosion Analogy





In the early 20th century, a number of workers realized that a high-speed impact resembled an explosion. Öpik (1916), Ives (1919), Moulton (1929) and Gifford (1924) all promoted this idea. Gifford's arguments eventually carried the day.

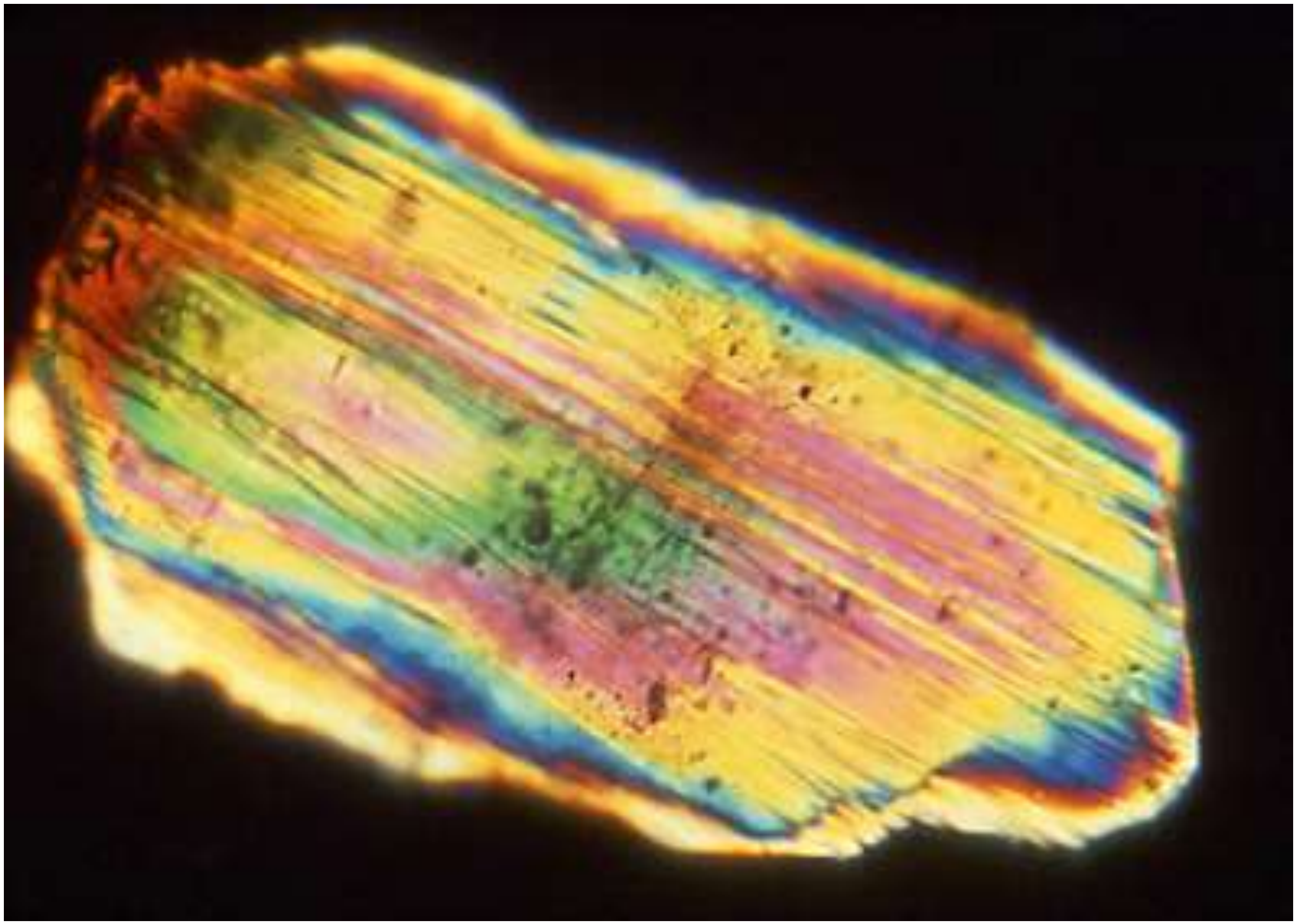
“Crypto-Volcanic” Structures



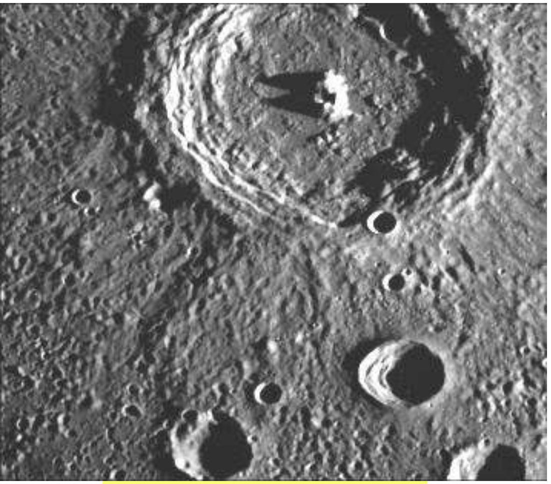
Geologists Boone and Albritton re-interpreted “Crypto-Volcanic structures as impacts in 1937 and defined the geologic characteristics of impact craters

In 1964 Robert Dietz proposed the first shock-metamorphic feature diagnostic of impact: Shatter Cones

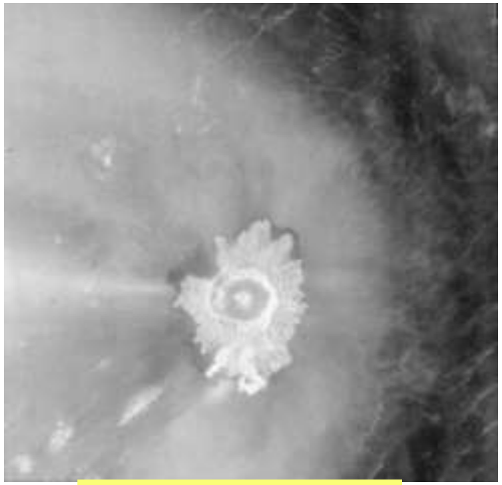
High pressure polymorphs and shock features in quartz followed quickly



- Where do we find craters? – Everywhere!
  - Cratering is the one geologic process that every solid solar system body experiences…



Mercury



Venus

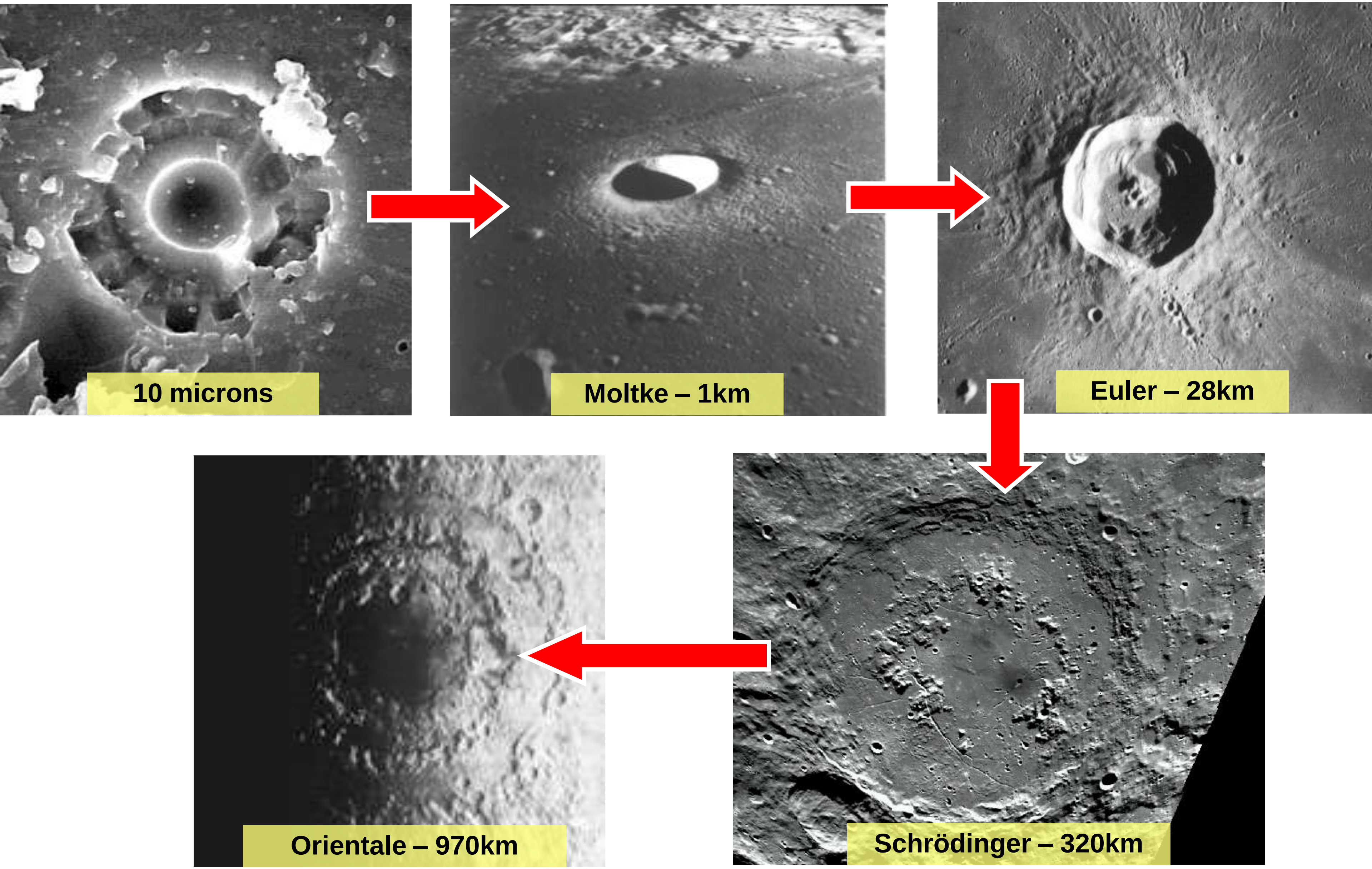
Moon

Earth

Mars

Asteroids

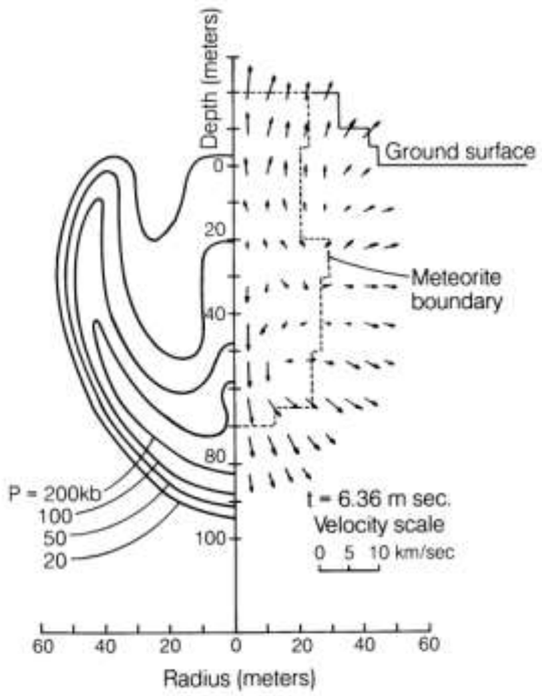
- Morphology changes as craters get bigger
  - Pit → Bowl Shape→ Central Peak → Central Peak Ring → Multi-ring Basin



Studies of cratering were advanced by three areas of research:

Nuclear weapons effects,

Numerical simulations of impacts and explosions,



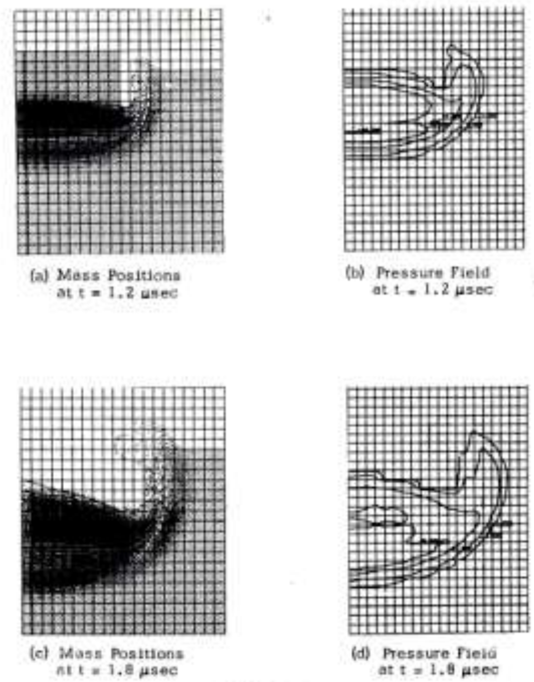


FIGURE 2-1
FORMATION AND DETACHMENT
OF SHOCK SYSTEM
Aluminum into Iron at 72 km/sec
(Case 8056)

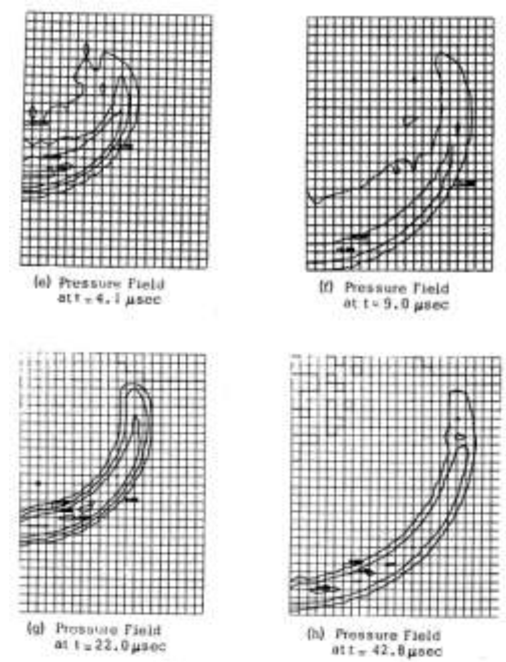
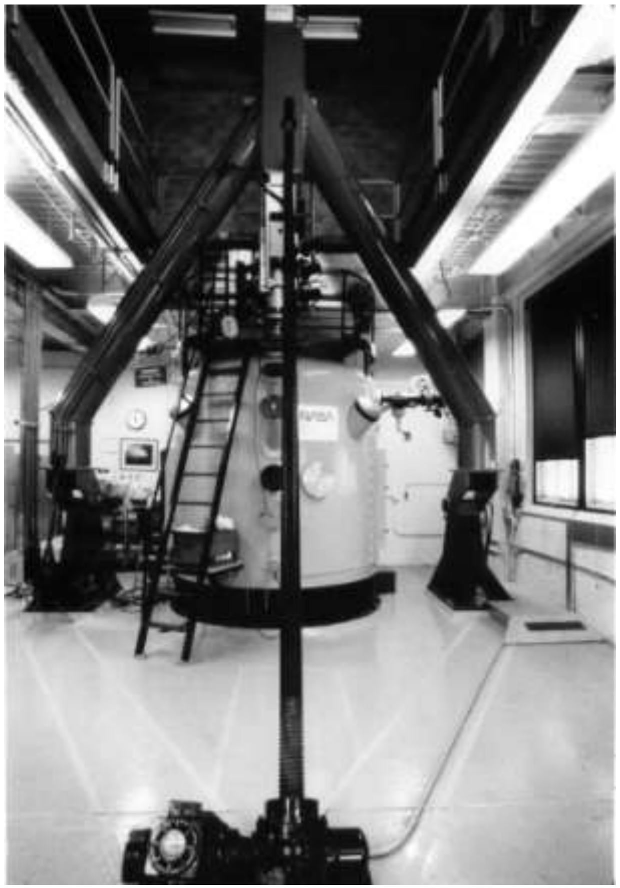
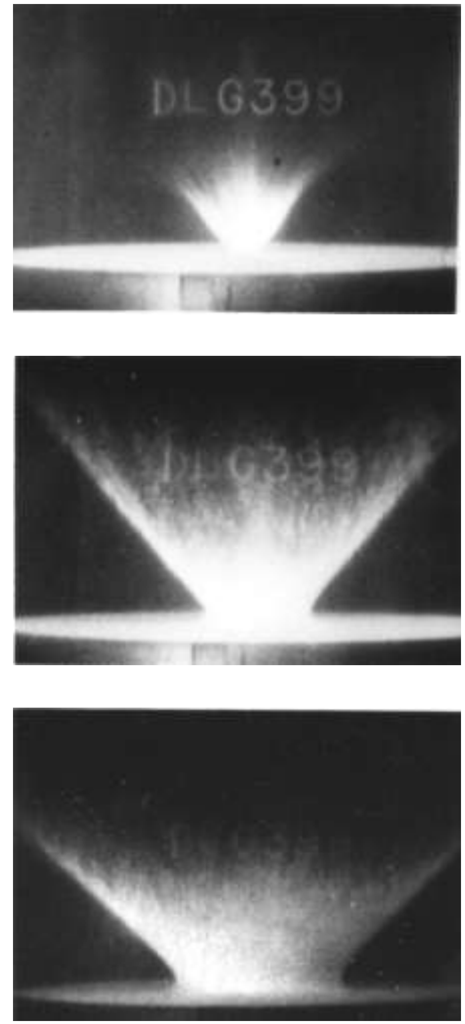


FIGURE 2-1 (Con't)
FORMATION AND DETACHMENT
OF SHOCK SYSTEM
Aluminum into Iron at 72 km/sec
(Case 8056)

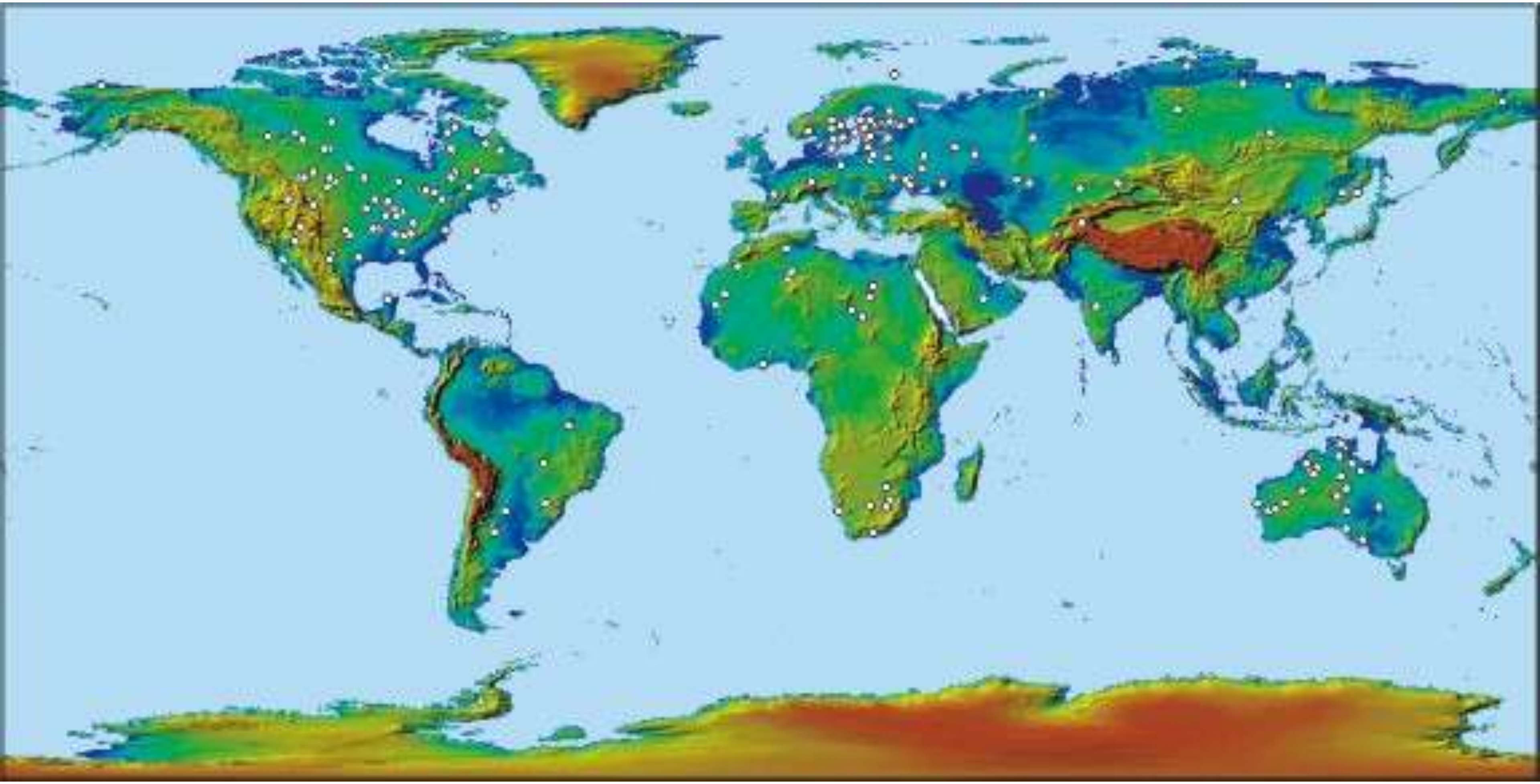
…and experimental studies of the impact process



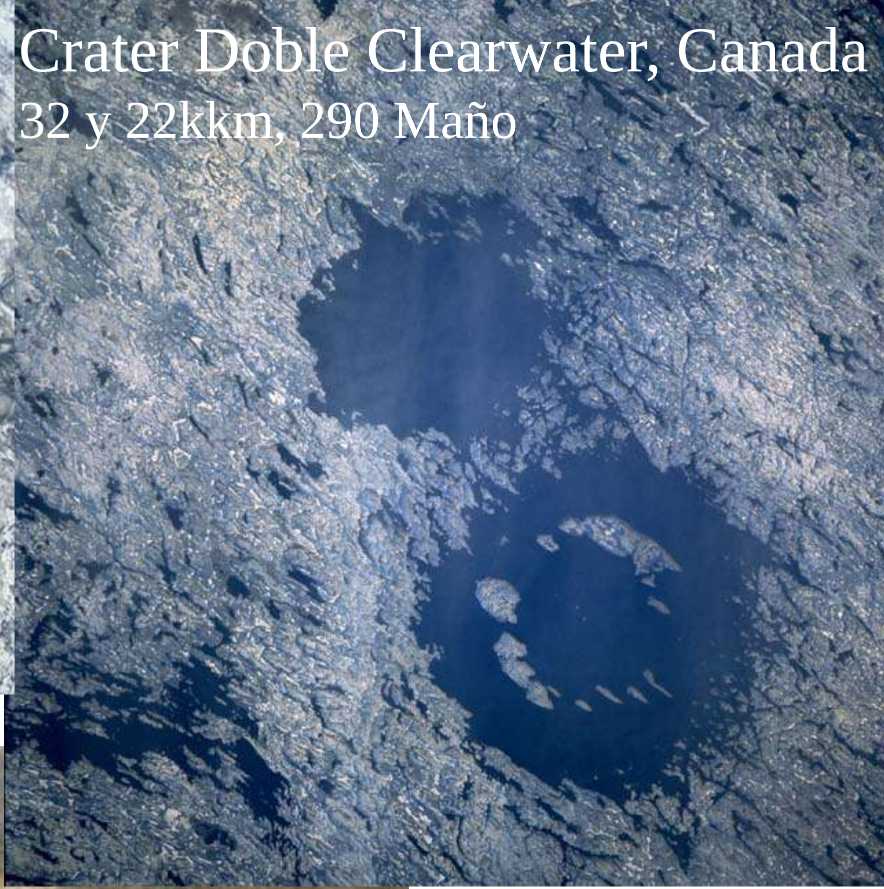



04:03:22 11:47 1:30 00:04:18

Impact craters on Earth are sparse




Cráter Manicouagan, Canada
100 km, 212 Maño


Crater Doble Clearwater, Canada
32 y 22kkm, 290 Maño


Cráter Meteórico Barringer, Arizona
1.2 km, 49.000 año

Velocity, energy and pressure of impacts

Impact Energy

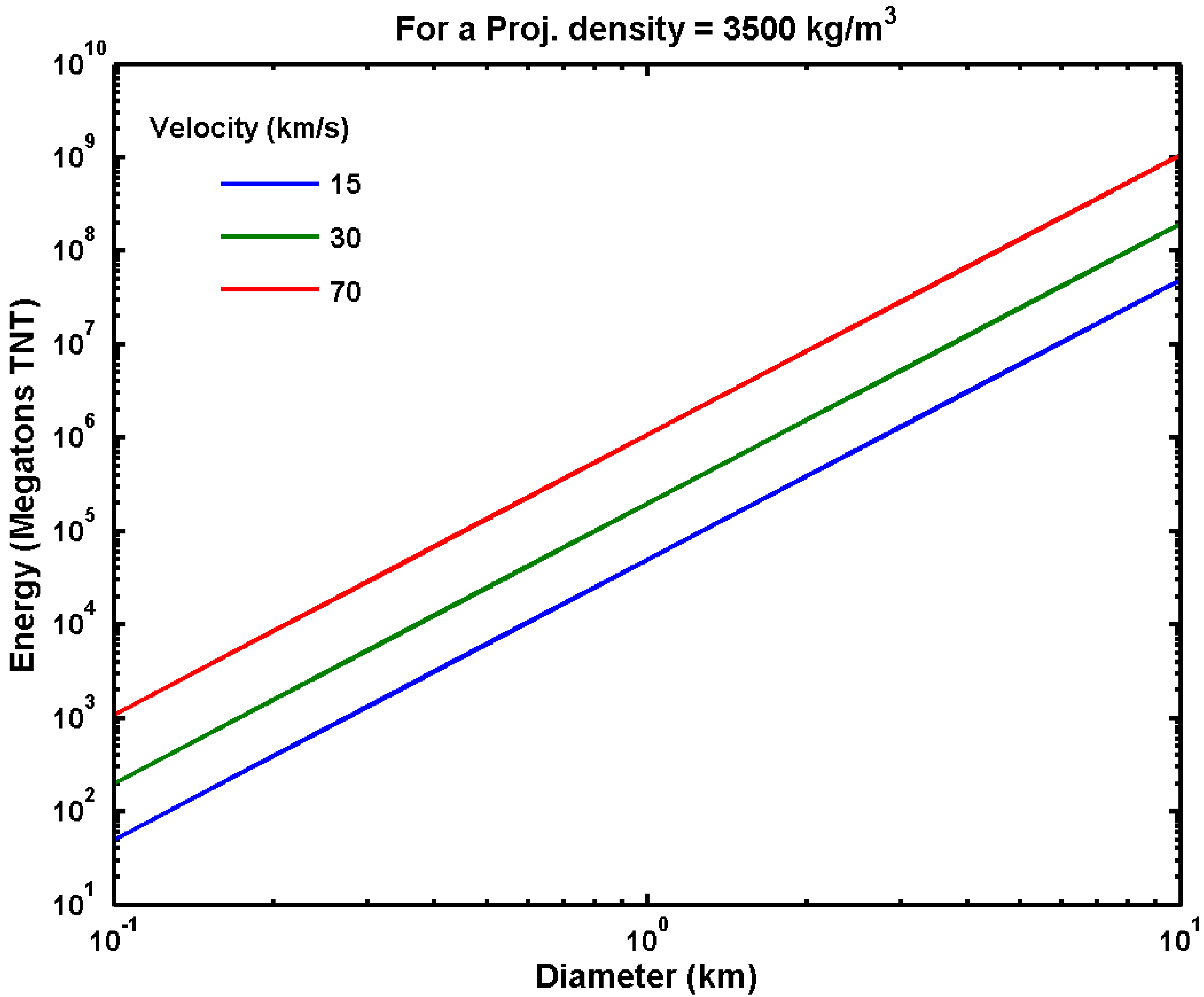
- How much energy does an impact deliver?
- Projectile energy is all kinetic
  - Most sensitive to size of object
  - Size-frequency distribution is a power law
    - Slope close to -2
    - Expected from fragmentation mechanics

$$E = \tfrac{1}{2} mv^2 = \frac{2\pi}{3} \rho r^3 v^2$$

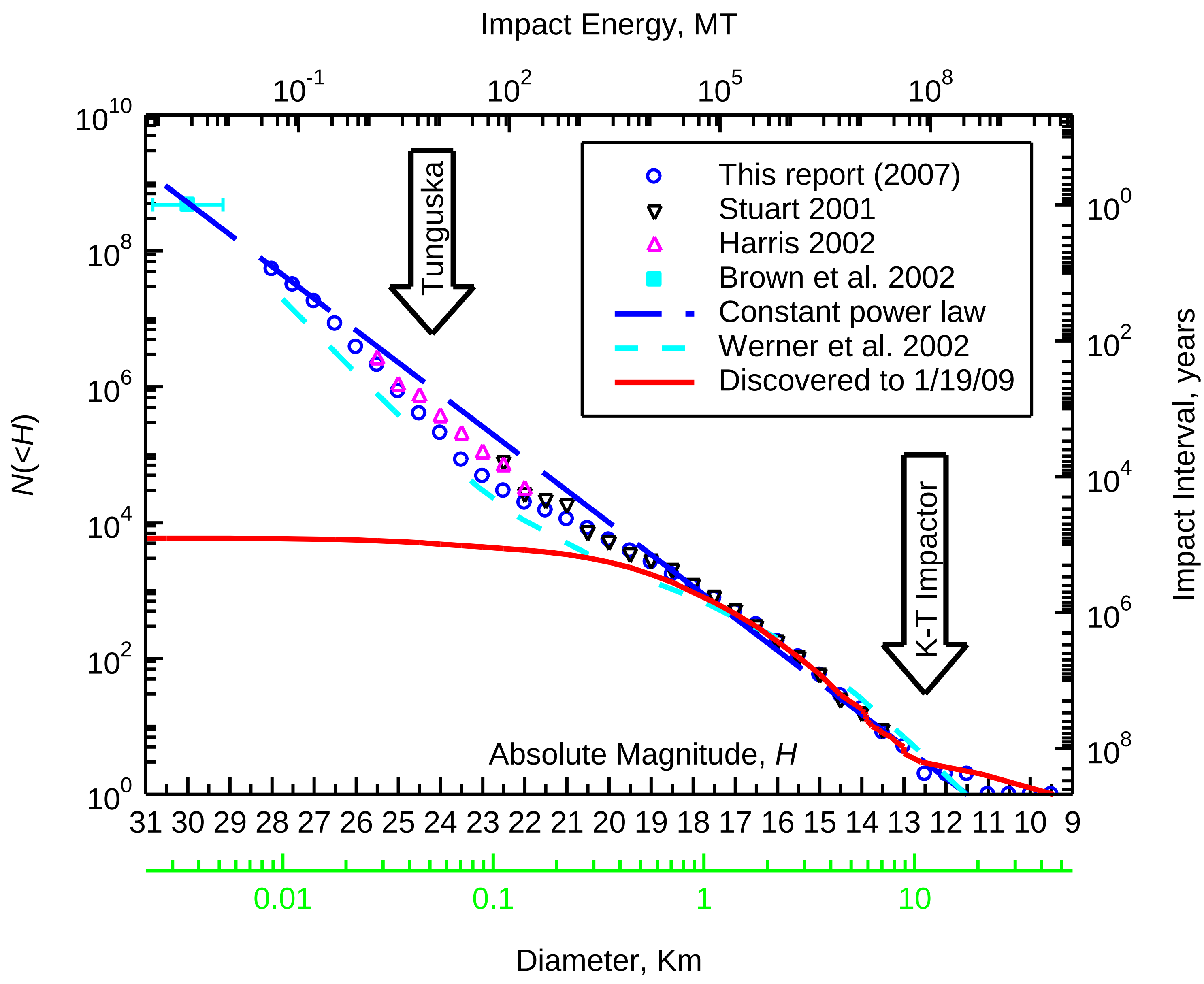
1 ton TNT = 4.18 x 10^9 Joules

Impact Velocity

- **Minimum impacting velocity is the surface escape velocity** $$V_{esc} = \sqrt{GM_p / R_p}$$
- **Lowest impact velocity ~ escape velocity (~11 km s^{-1} for Earth)**
- **Orbital velocity of the impacting body itself** $$V_{orb} = \sqrt{GM_* \left(\frac{2}{r} - \frac{1}{a} \right)}$$
- **Planet's orbital velocity around the sun (~30 km s^{-1} for Earth)**
- **Highest velocity from a head-on collision with a body falling from infinity**
    - **Long-period comet**
    - **~78 km s^{-1} for the Earth**
    - **~50 times the energy of the minimum velocity case**
- **A 1km rocky body at 12 kms^{-1} would have an energy of ~ 10^{20}J**
    - **~20,000 Mega-Tons of TNT**
    - **Largest bomb ever detonated ~50 Mega-Tons (USSR, 1961)**
    - **Recent earthquake in Peru (7.9 on Richter scale) released ~10 Mega-Tons of TNT equivalent**

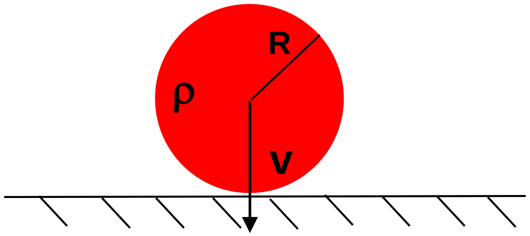

For a Proj. density = 3500 kg/m3
Velocity (km/s)
15
30
70
Energy (Megatons TNT)
Diameter (km)
10^10
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10^1
10^-1
10^0
10^1

Cumulative Population



Impact Pressure

Simple estimate: the projectile is completely stopped in 2R.



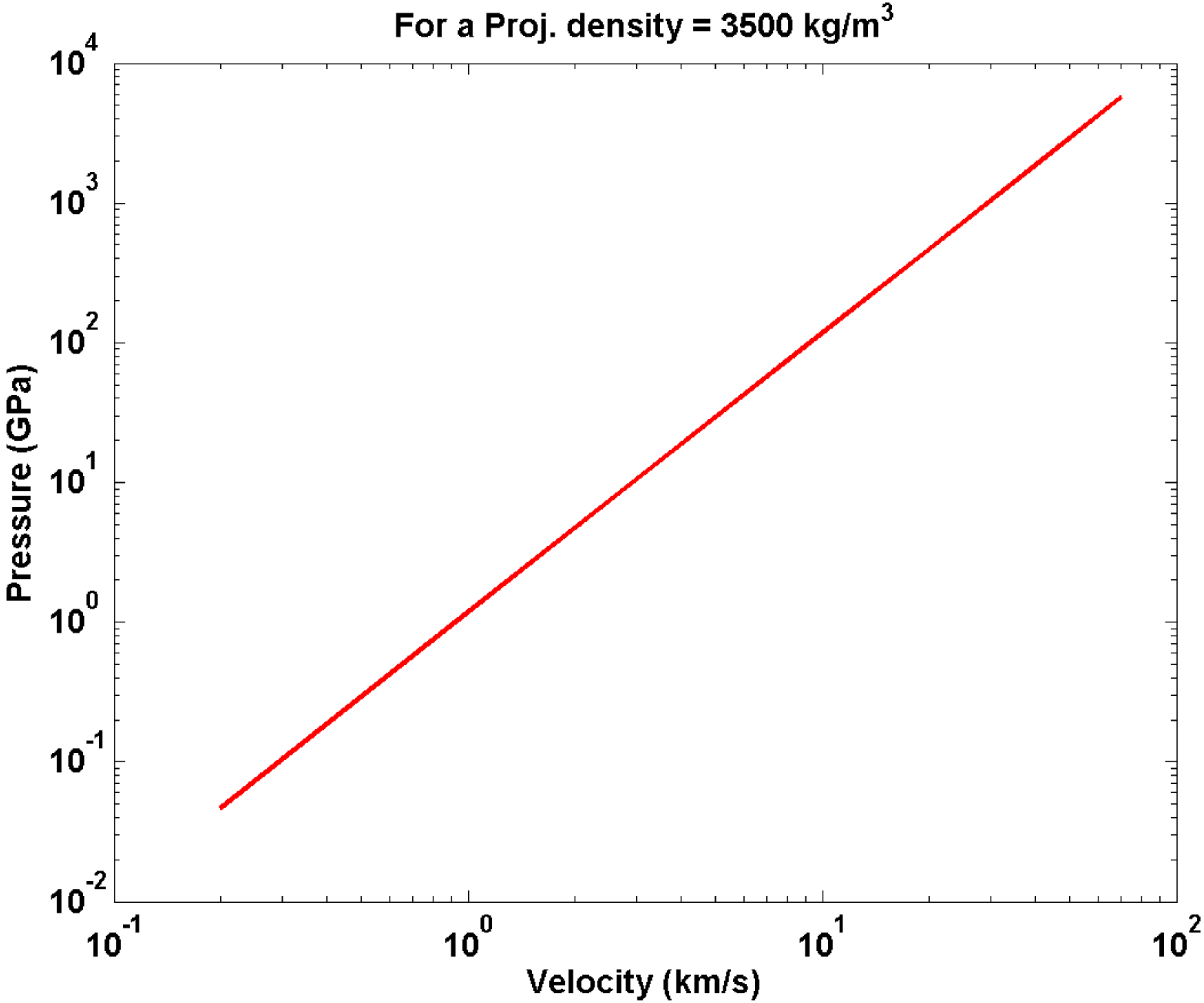
$$P = \frac{F}{A} \qquad F = m\,a \qquad A = \pi R^2$$

$$m = \frac{4\pi}{3}\rho R^3$$

$$a = \frac{\Delta v}{\Delta t} = \frac{v_{imp}}{\sqrt{\frac{4R}{a}}} = \sqrt{\frac{a}{4R}}\,v_{imp} \quad \Rightarrow \quad a = \frac{v_{imp}^2}{4R}$$

$$2R = \Delta x = \tfrac{1}{2} a\,\Delta t^2 \quad \Rightarrow \quad \Delta t = \sqrt{\frac{4R}{a}}$$

$$\Rightarrow \quad P = \frac{ma}{\pi R^2} = \frac{4\pi\rho R^3 v_{imp}^2}{3\pi R^2\, 4R} = \frac{1}{3}\rho\, v_{imp}^2$$



For a Proj. density = 3500 kg/m^3
Pressure (GPa)
Velocity (km/s)
10^4
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-1
10^0
10^1
10^2

Cratering Mechanics

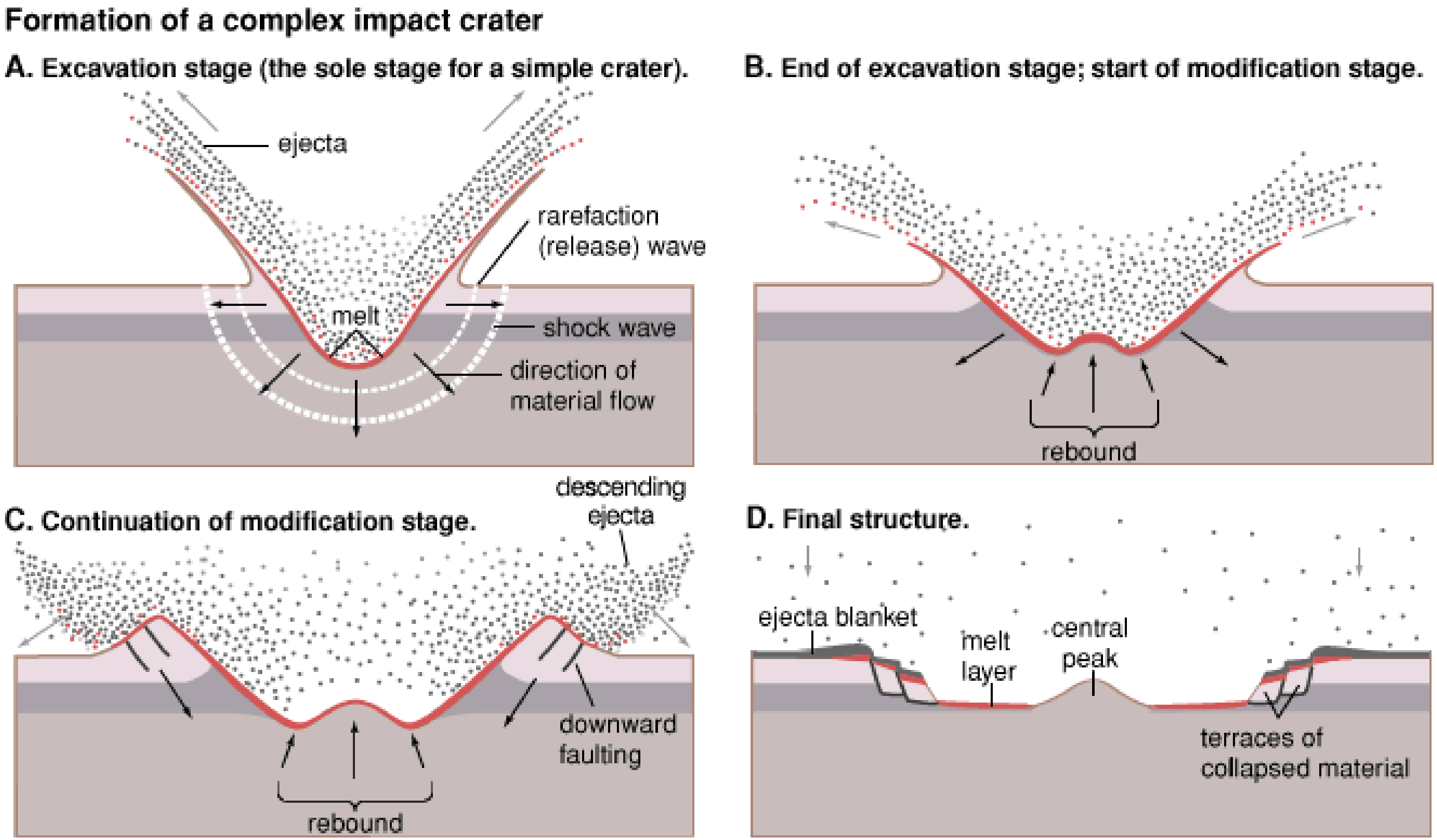
- Contact & Compression
- Excavation
- Modification

Cratering Mechanics

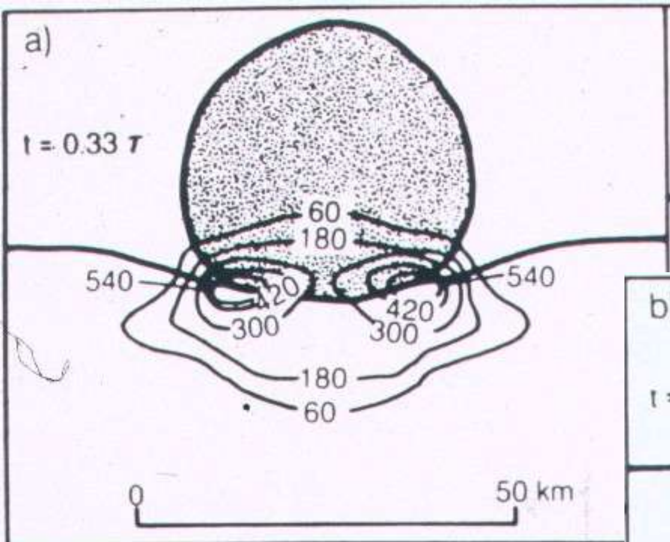
The impact cratering process is divided into three basic stages:

- Contact and Compression
- Excavation of the crater
- Modification (collapse) of the crater

(not a real division, just a convenient one)

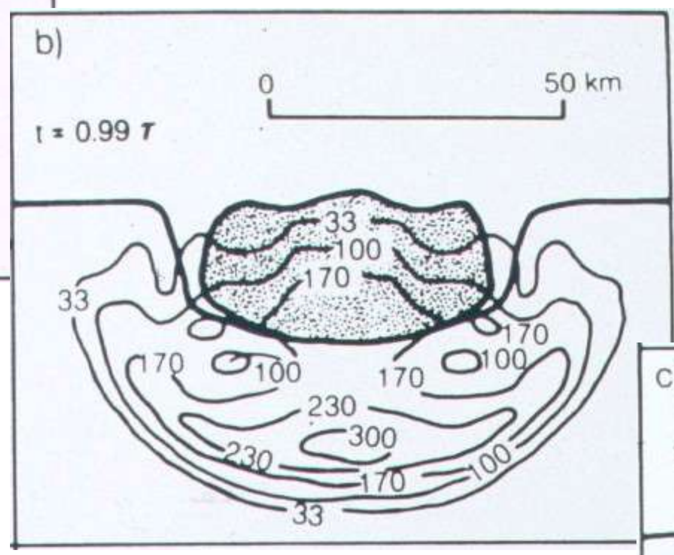

Formation of a complex impact crater
A. Excavation stage (the sole stage for a simple crater).
ejecta
rarefaction (release) wave
melt
shock wave
direction of material flow
B. End of excavation stage; start of modification stage.
rebound
C. Continuation of modification stage.
descending ejecta
downward faulting
rebound
D. Final structure.
ejecta blanket
melt layer
central peak
terraces of collapsed material

Contact & Compression

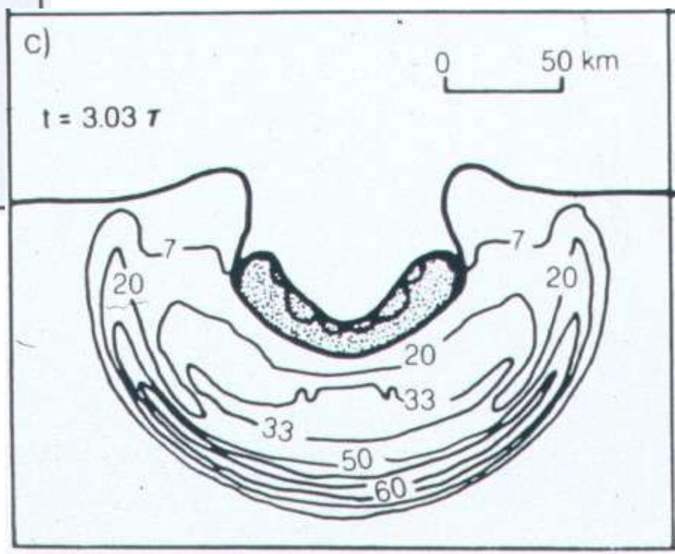


(O'Keefe & Ahrens, 1975)

Begins when the projectile contacts the target surface

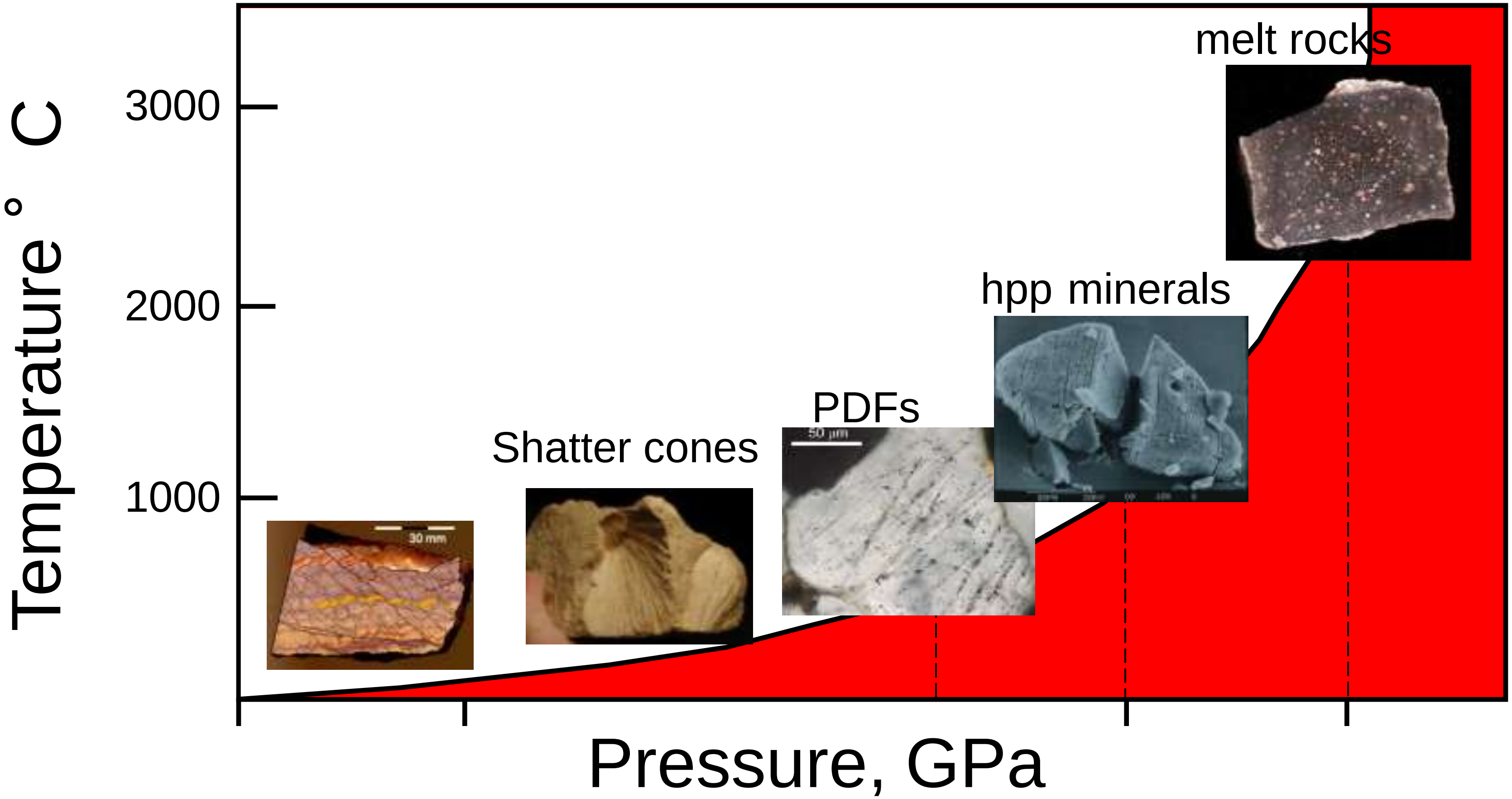


Fast moving projectile compresses target material along its path



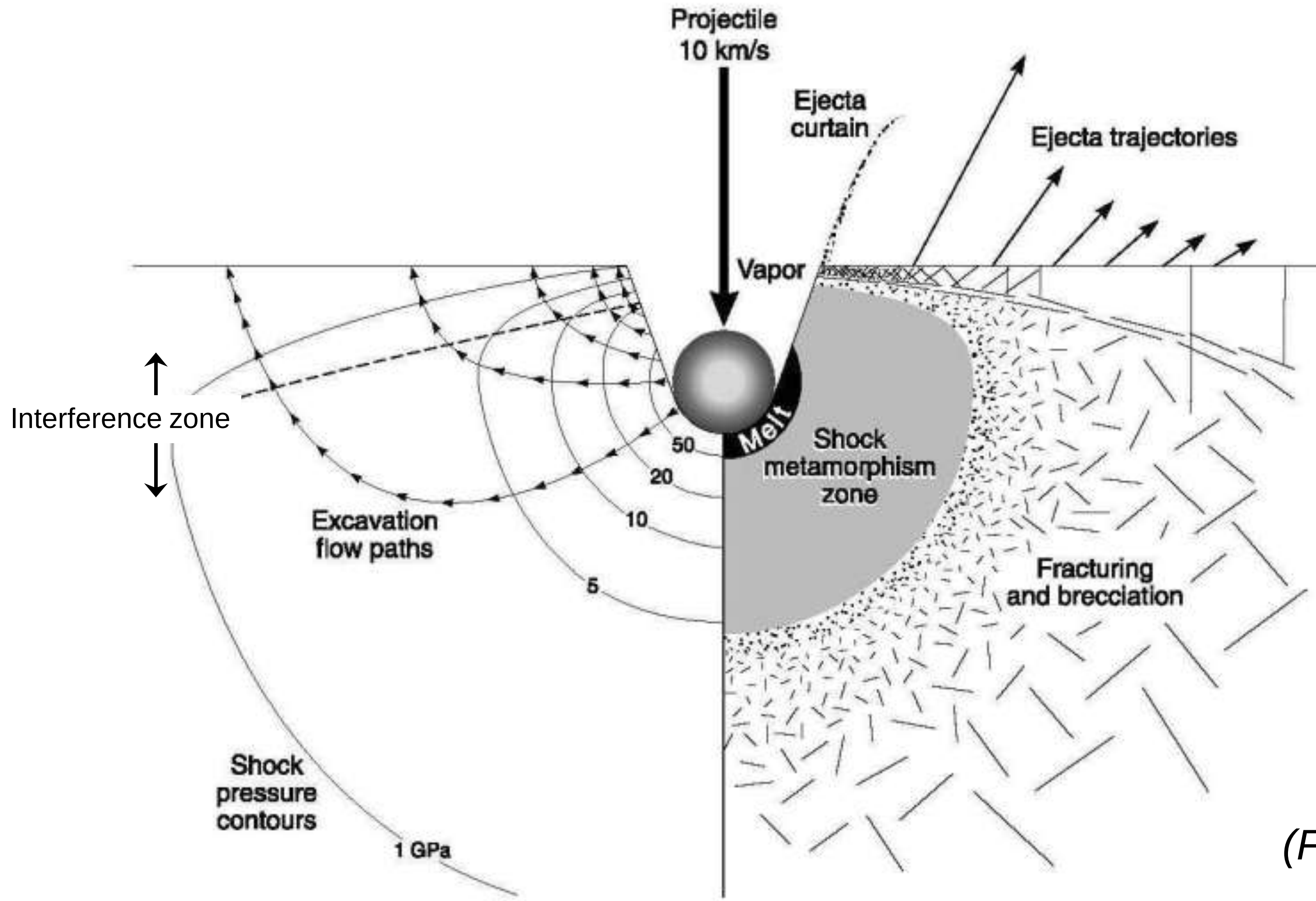
At the same time target's resistance to penetration decelerates the projectile

Shock barometry is well calibrated in experimental studies



Shock features in minerals/rocks tell us something about the thermodynamic conditions the material was exposed to

Excavation Schematic



(French, 1998)

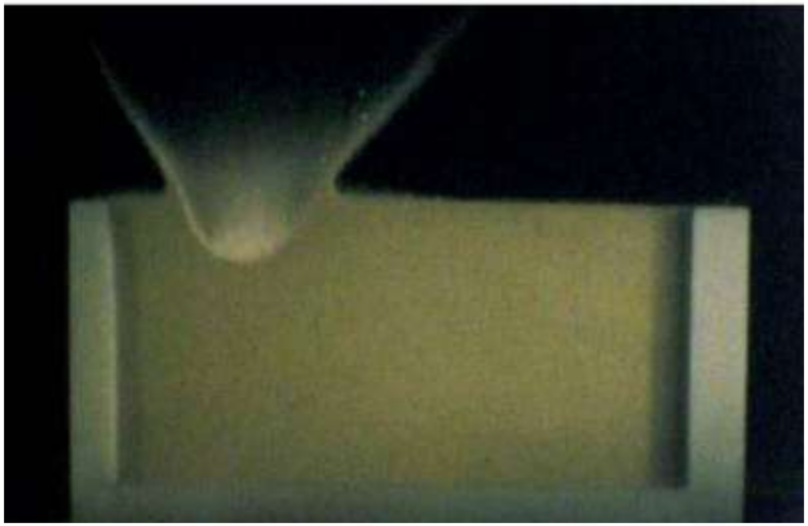
Shock wave appears to radiate from below the target surface (parallel with shallow burial explosions). Shock wave distribution provides a way to determine amount of melting and vaporization.

After the passage of the shock/rarefaction wave, material has a residual velocity, ~(1/3 ÷1/5)u_P, away from the impact point

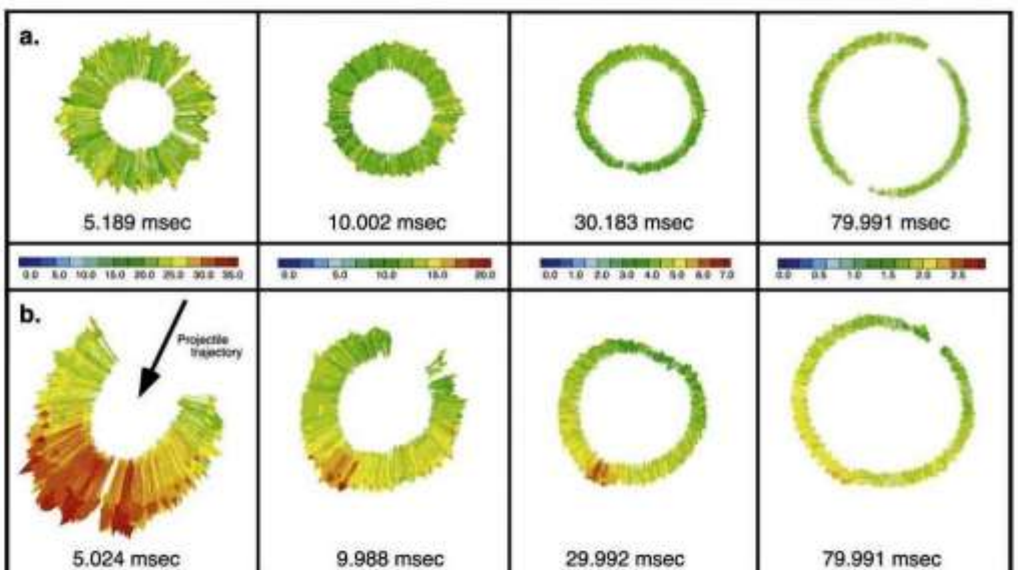
Ejecta Curtain

2D laboratory experiments show that the ejecta curtain forms an inverted cone that expands with time

Ejecta Curtain in Oblique Impacts



Oblique impacts also create an ejecta curtain with a similar inverted cone shape



And again, the use of a laser allows to measure particles speed, angle and position over time during cratering

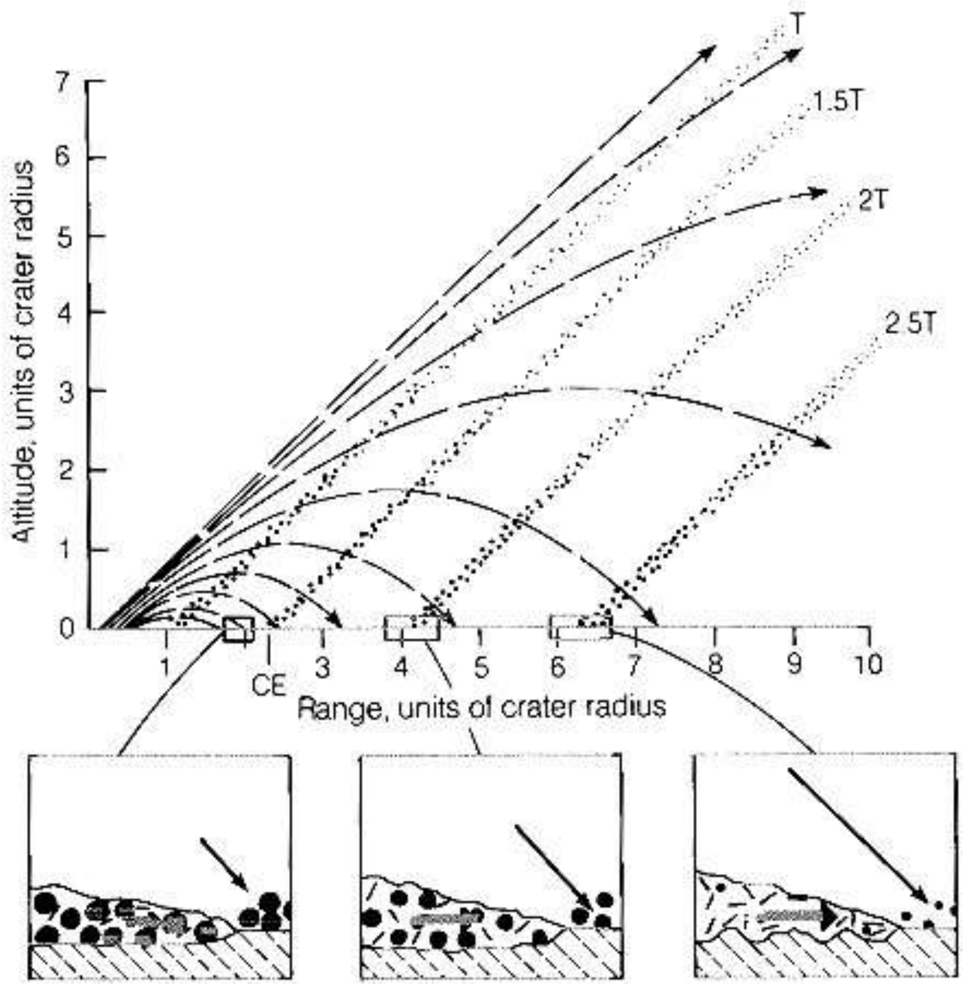
(Anderson et al., 2003)

Ejection

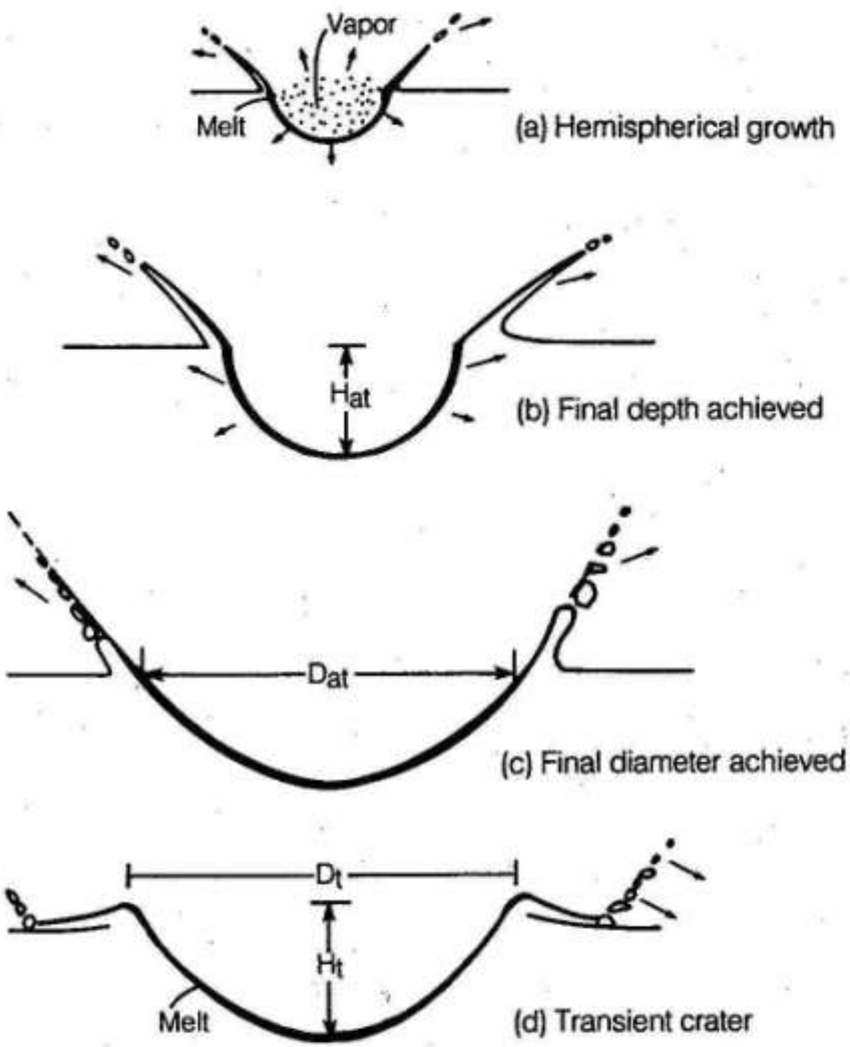
- Material begins to move out of the crater
- Material forms an inverted cone shape
  - Fastest material from crater center
  - Slowest material at edge forms overturned flap
  - Ballistic trajectories
  - Material escapes if ejected faster than escape velocity

$$v_e = \sqrt{GM_P / R_P}$$

  - Craters on asteroids generally don't have ejecta blankets



Crater Growth



An hemispherical cavity grows at a steadily decreasing rate

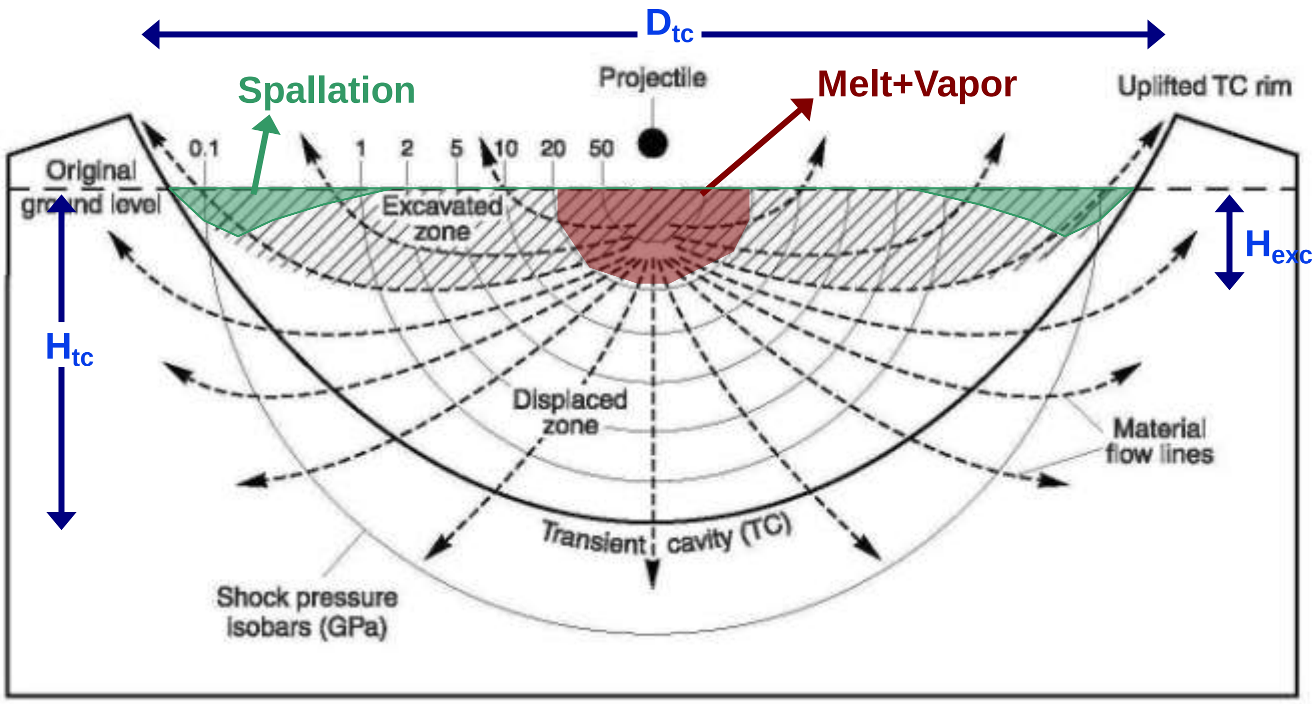
Maximum depth is reached when material strength and increasing lithostatic pressure from surrounding rock halt the growing vertical motion

Resistance to crater growth is lower near the surface and the crater continues growing in width until material velocity does not allow ejection anymore

↪ **Transient Crater**

Transient Crater and Excavation

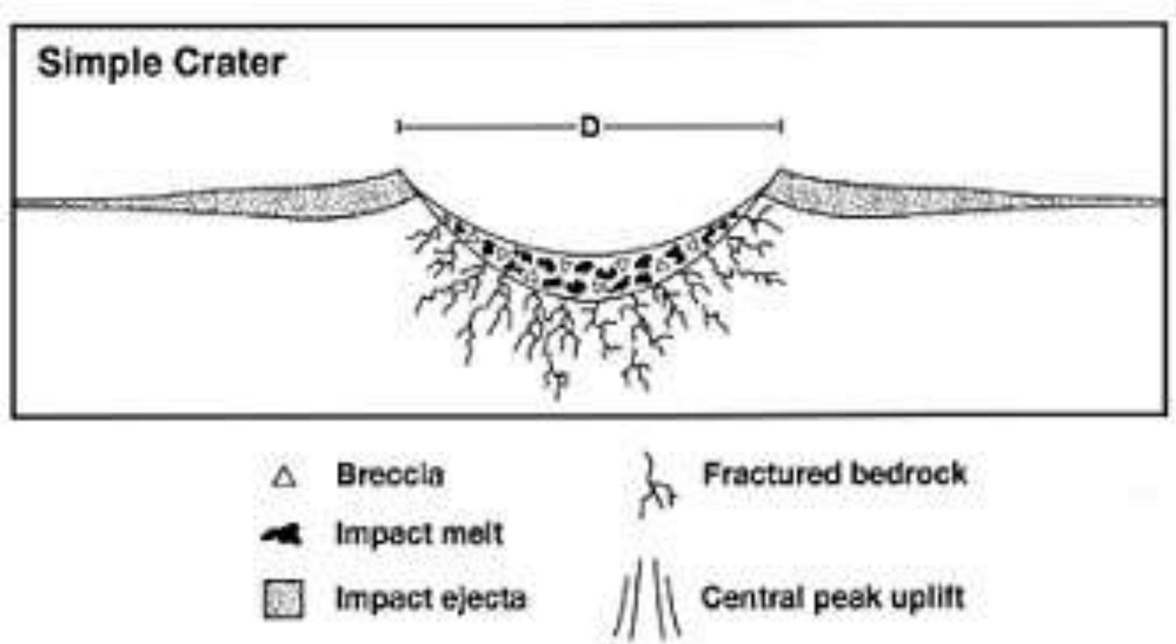
"Transient Crater is generally used to refer to the idealized theoretical construct defined by the maximum extent to which excavation proceeds in every direction" (*Turtle et al., 2005*)

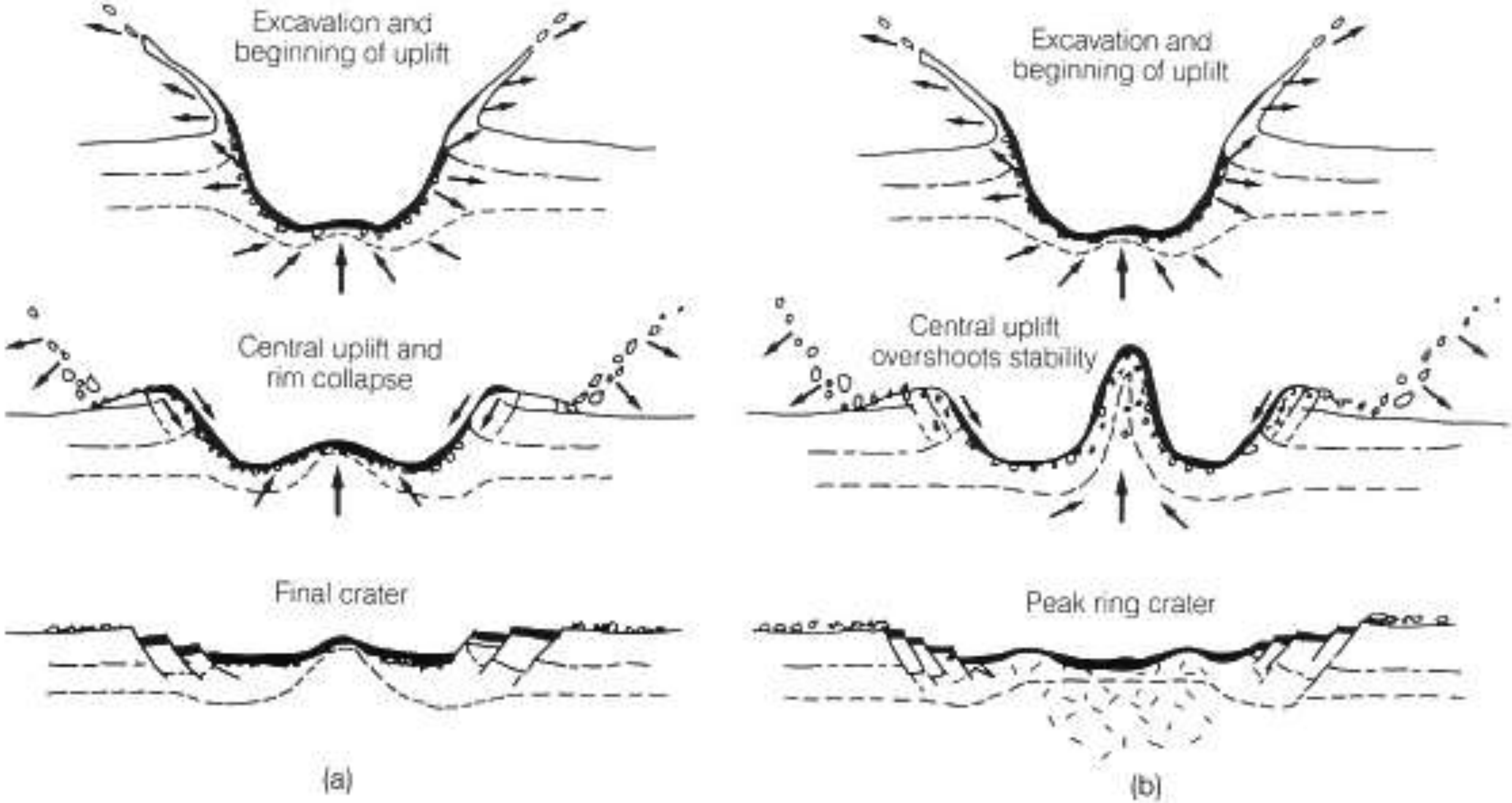


$$H_{tc} \cong \left(\tfrac{1}{4} \div \tfrac{1}{3}\right) D_{tc} \qquad H_{Exc} \cong \tfrac{1}{3} H_{tc} \cong \tfrac{1}{10} D_{tc}$$

Collapse and Modification Stage

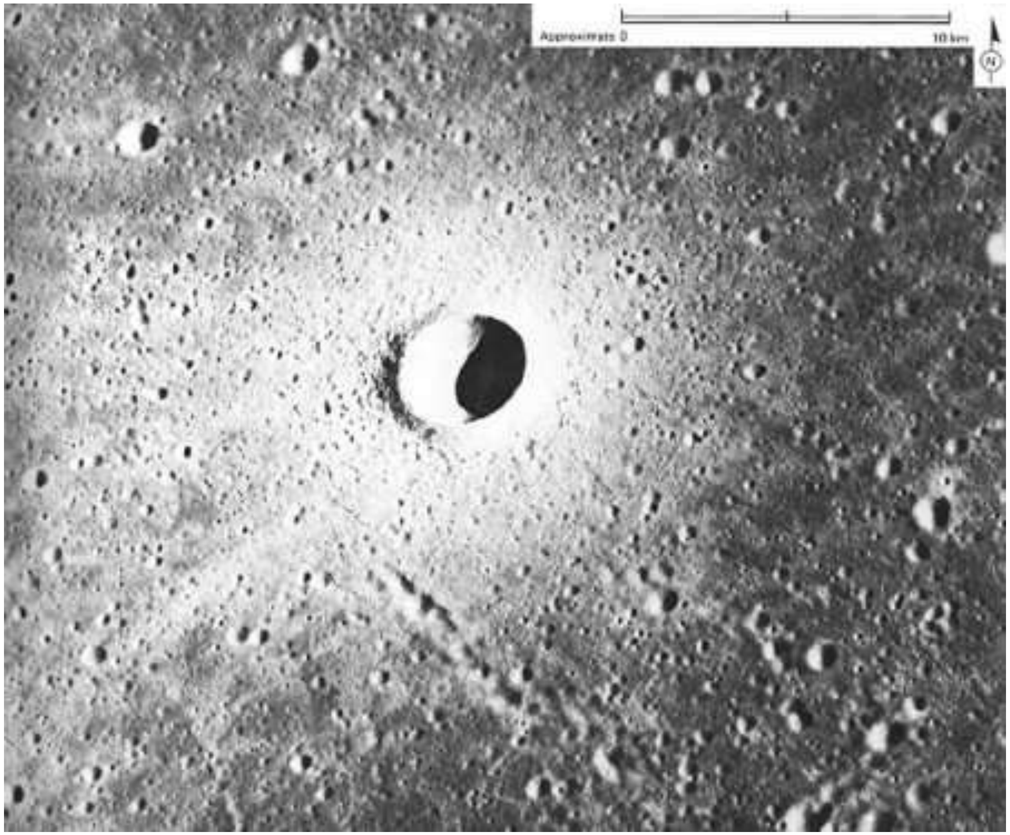
- Previous stages produces a hemispherical transient crater
- Simple craters collapse from d/D of ~1/3 to ~1/5
  - Bottom of crater filled with breccia
  - Extensive cracking to great depths
- Peak versus peak-ring in complex craters
  - Central peak rebounds in complex craters
  - Peak can overshoot and collapse forming a peak-ring
  - Rim collapses so final crater is wider than transient bowl
  - Final d/D < 0.1

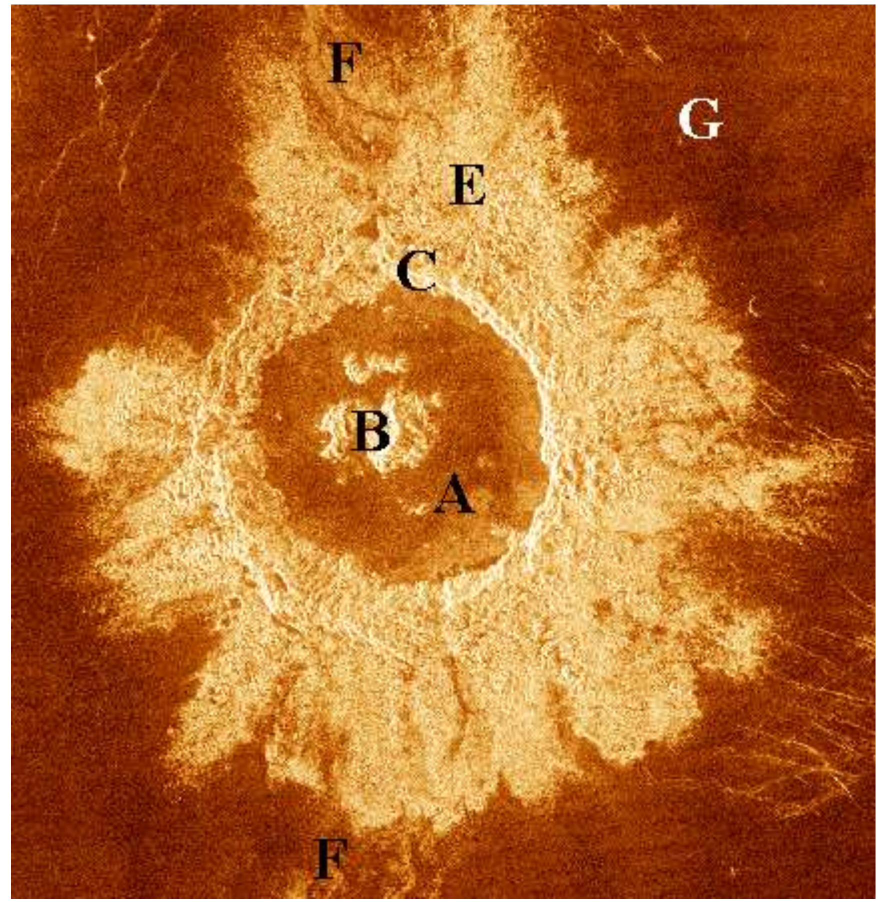




Excavation and beginning of uplift
Central uplift and rim collapse
Final crater
(a)
Excavation and beginning of uplift
Central uplift overshoots stability
Peak ring crater
(b)

Ejecta blanket

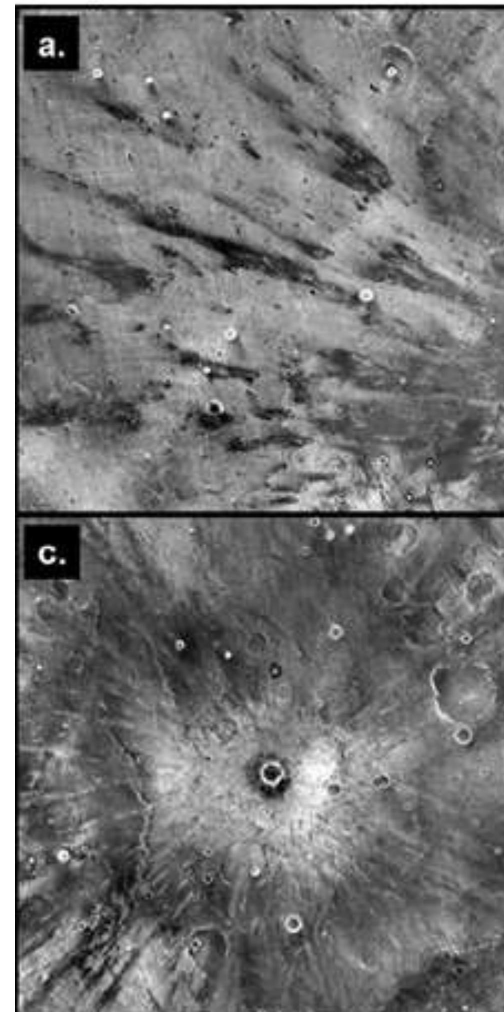




Crater rays

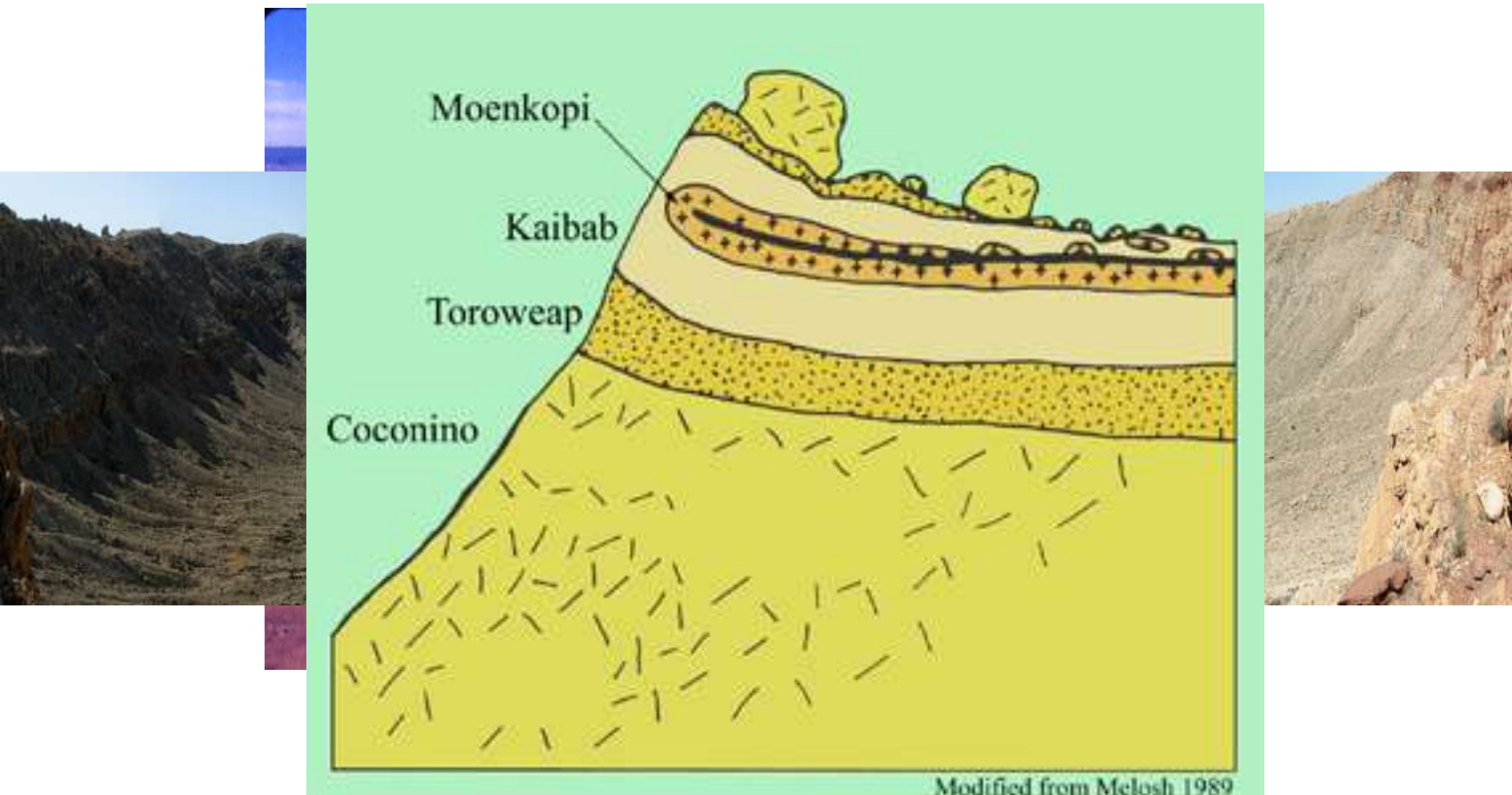
Gratteri

THEMIS
Nighttime Thermal Infrared



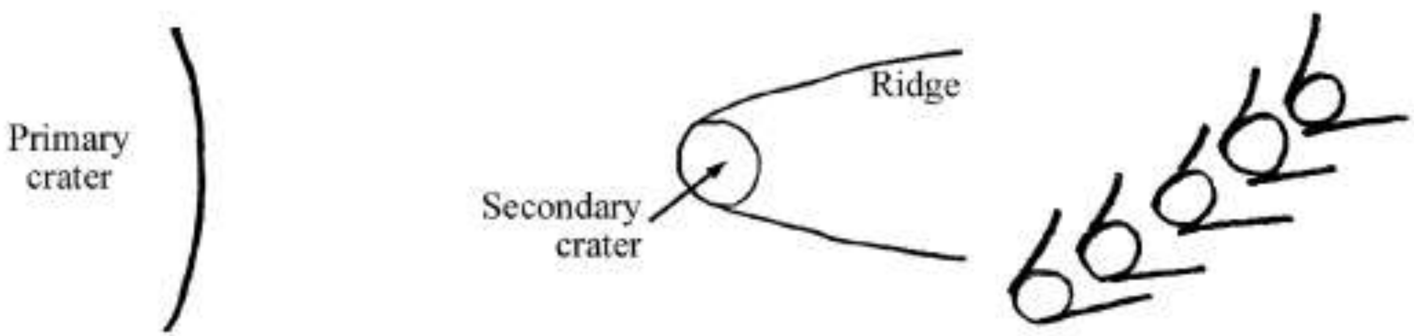
Reversed stratigraphy

Meteor crater (1.2km)

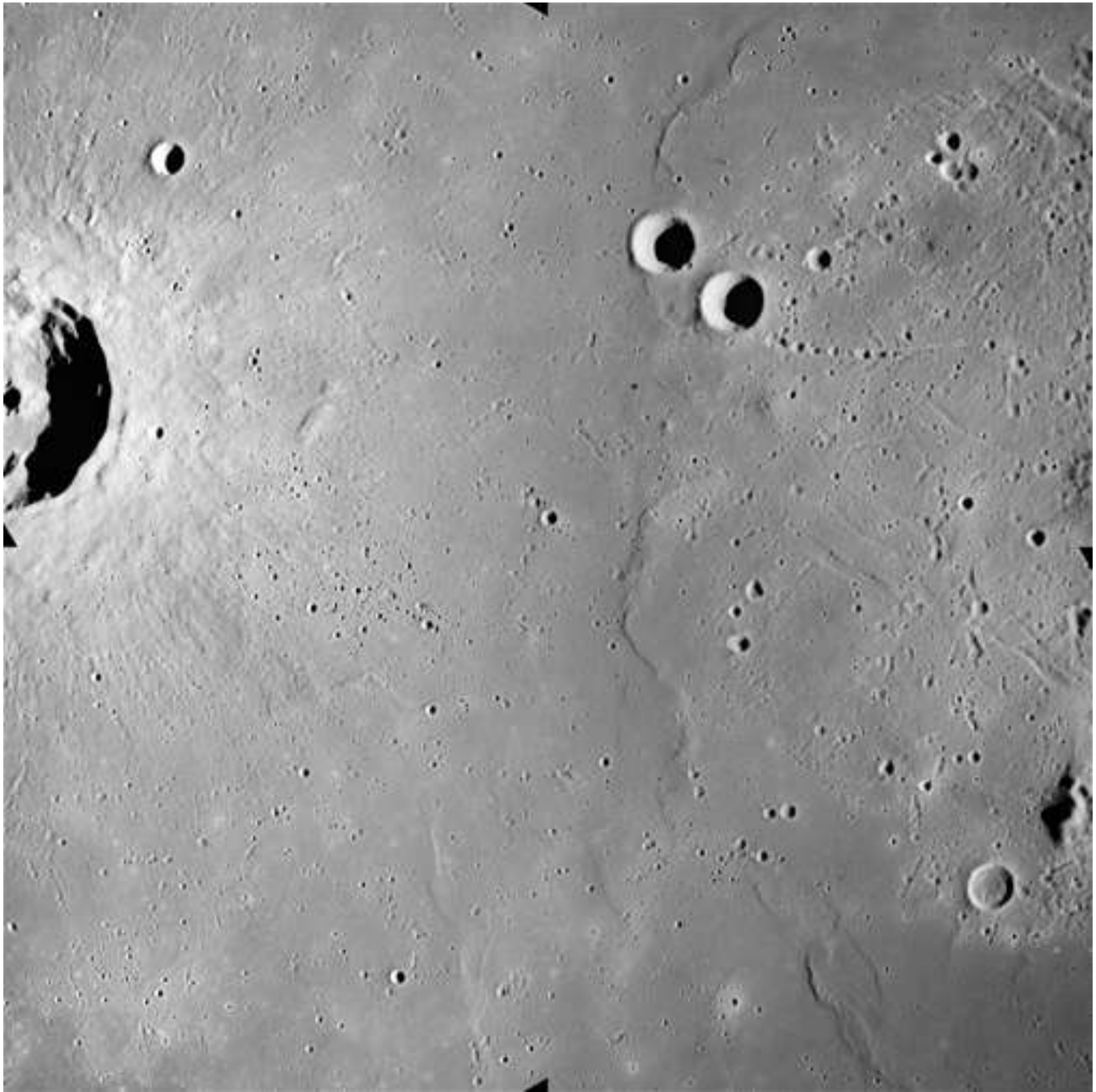


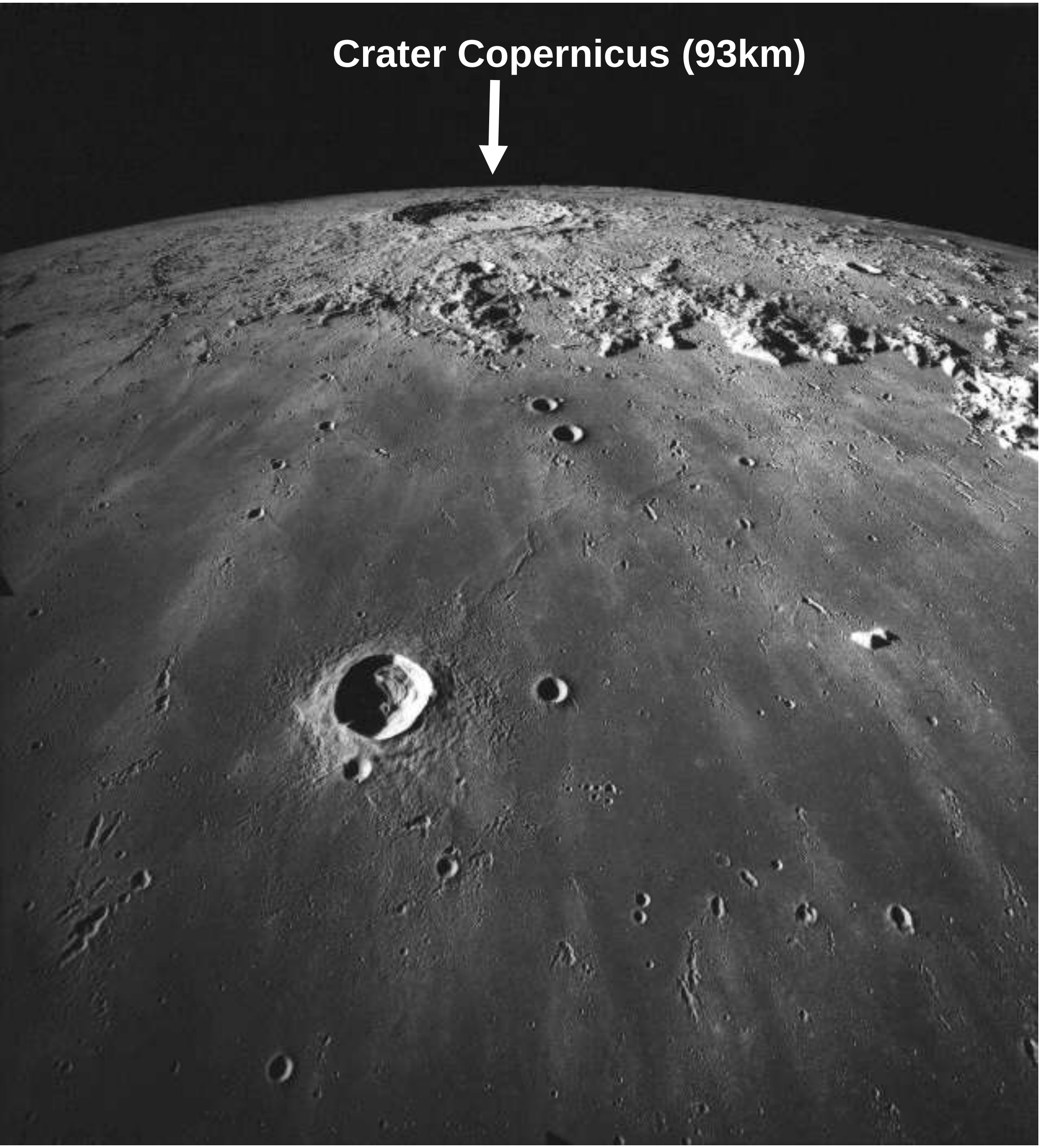
Secondary craters

- In the discontinuous ejecta and beyond that secondary impact craters are found.
- Secondaries are formed when large chunks of material are thrown out during the initial excavation period.
  - often have a V-shaped ridge pointing radially away from the main crater.
  - often form in clusters or chains, another distinguishing feature.



Crater Timocharis , Moon (33km)





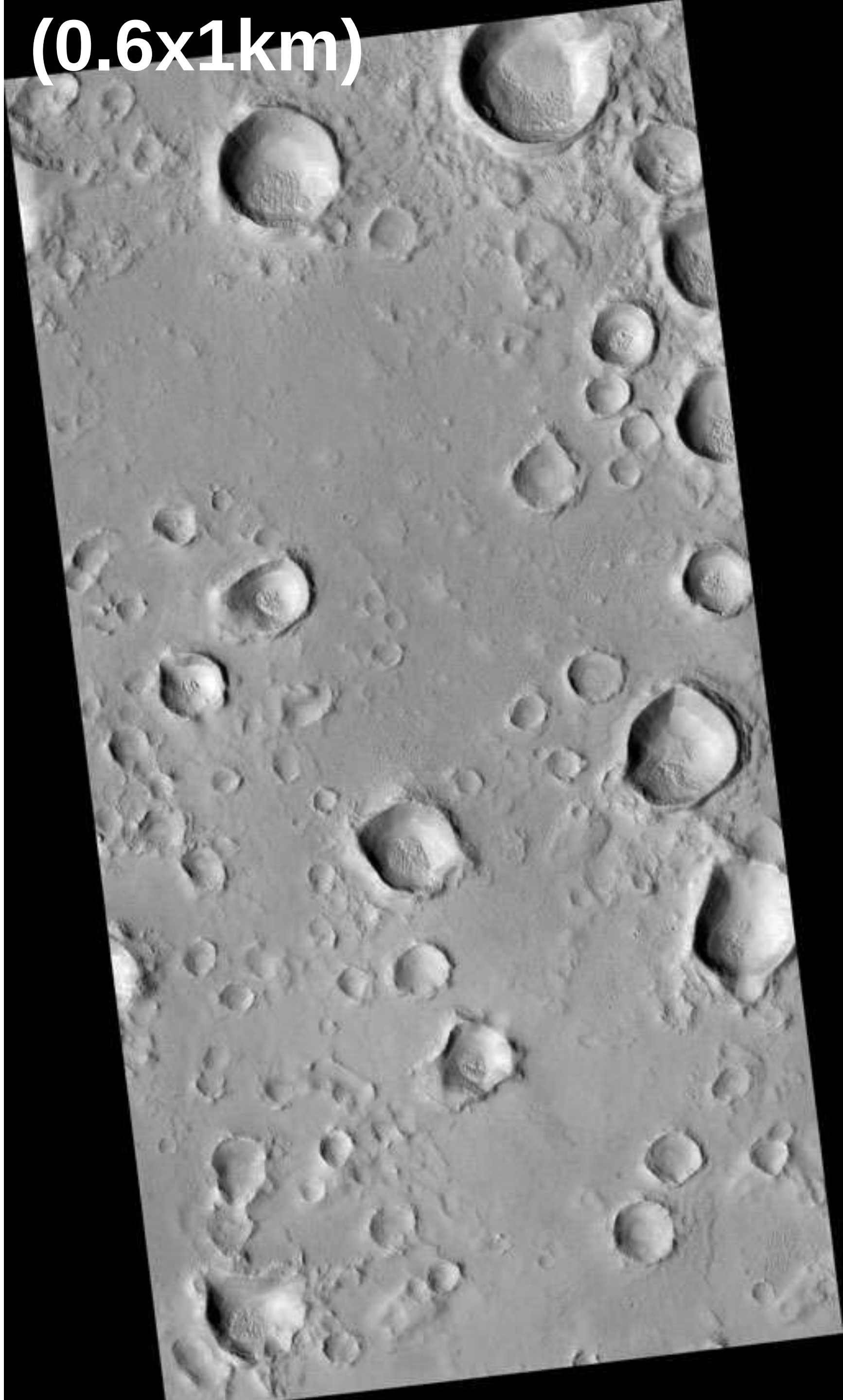
Many secondary craters

Secondary chains

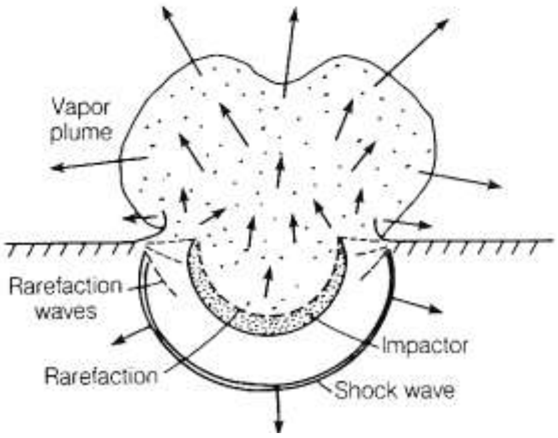
A field of secondary craters in Mars

They are sometimes irregularly shaped because they form at relatively low velocities.

- **Low energy impacts form shallow, less-developed craters.**
- **High energy impacts form deeper, more regular craters.**



- Plume of molten silica expands
- Tektites
  - Drops of impact melt are swept up
  - Freeze during flight – aerodynamic forms
  - Cool quickly – glassy composition

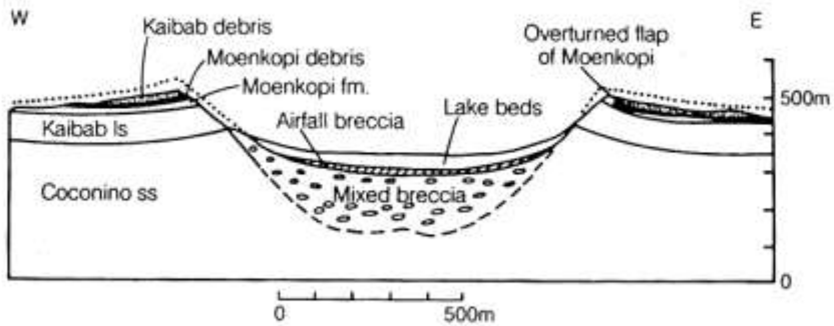


- Minimum size close to 1 nm
- Maximum size depends on how well coupled the gas and particles are
- Tektites rain out over a large area

Crater Morphology

- Simple craters
- Complex craters
- Multiring basins
- Aberrant crater types

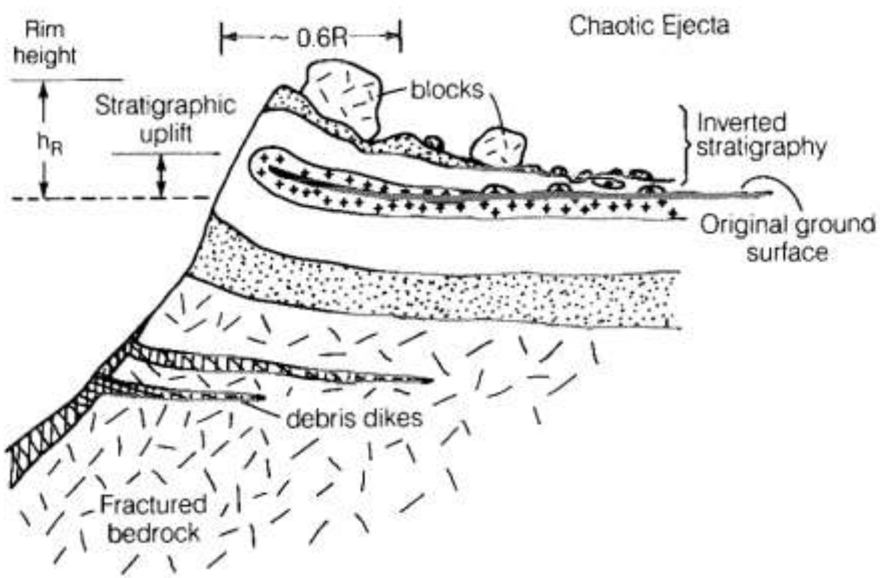
- Planetary craters similar to nuclear test explosions
- Craters are products of point-source explosions
  - Oblique impacts still make round craters



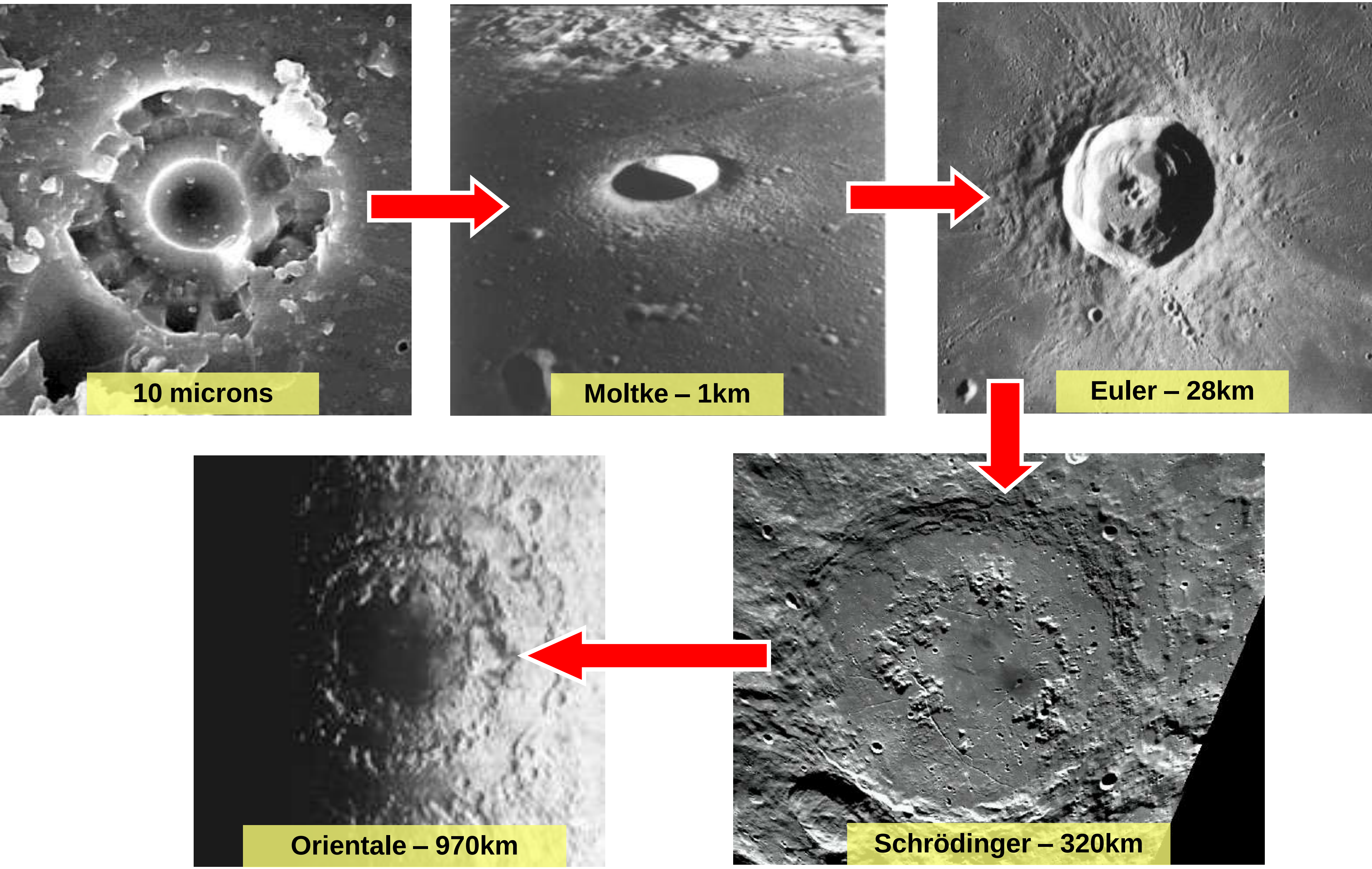
Meteor Crater – 1.2 km

Sedan Crater – 0.3 km

- Overturned flap at edge
  - Gives the crater a raised rim
  - Reverses stratigraphy
- Eject blanket
  - Continuous for ~1 R_c
- Breccia
  - Pulverized rock on crater floor
- Shock metamorphosed minerals
  - Shistovite
  - Coesite
- Tektites
  - Small glassy blobs, widely distributed

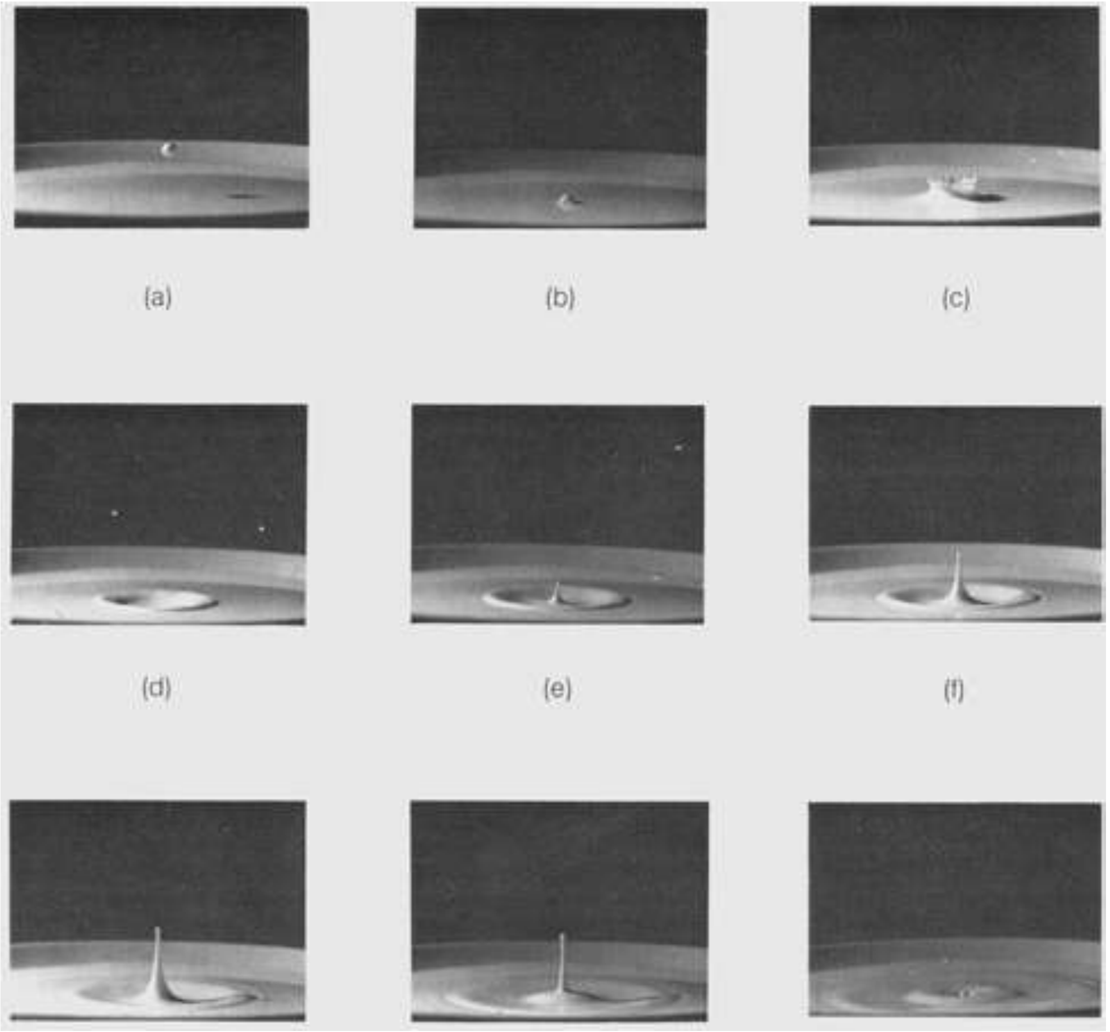


- Morphology changes as craters get bigger
  - Pit → Bowl Shape→ Central Peak → Central Peak Ring → Multi-ring Basin



Hydrodynamical model for the formation of a complex Crater

Analog of the formation of a central peak

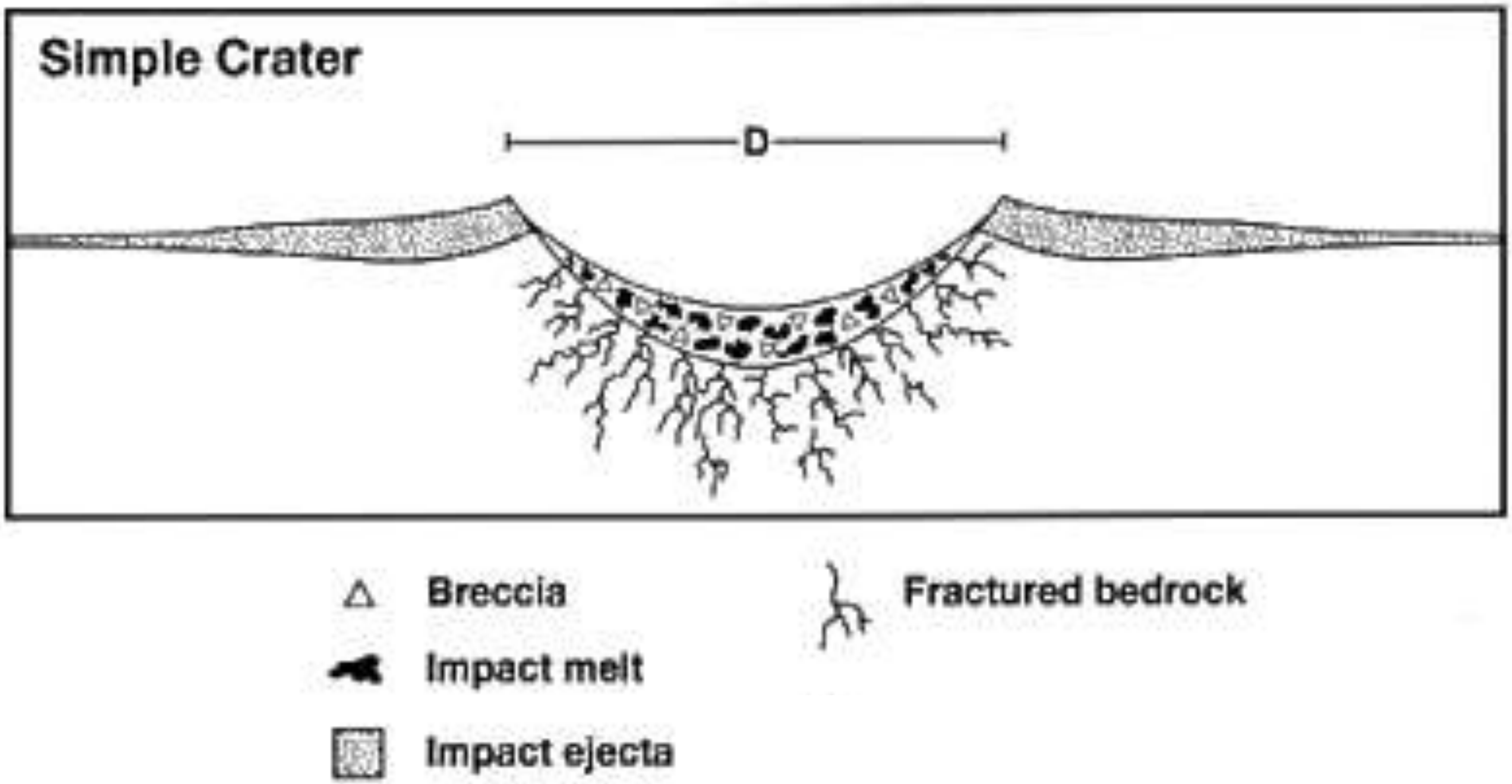


Experiencia del Curso de Ciencias de la Tierra y el Espacio

Simple Crater Facts

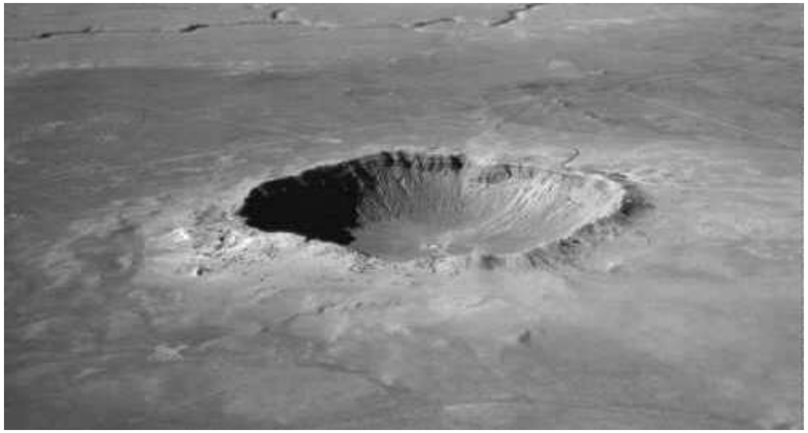
- Common at < 15 km rim-to-rim diameter, D, on moon
- Rim height 4% of D
- Rim-to-floor depth 1/5 of D
- Ejecta blanket extends one D from rim
- Secondary craters and bright ray ejecta
- Floor underlain by breccia
  - Contains shocked quartz i.e. coesite and stishovite
  - Floor typically 1/2 to 1/3 of rim-to-floor depth

Simple Craters Schematic



Simple Craters on Earth

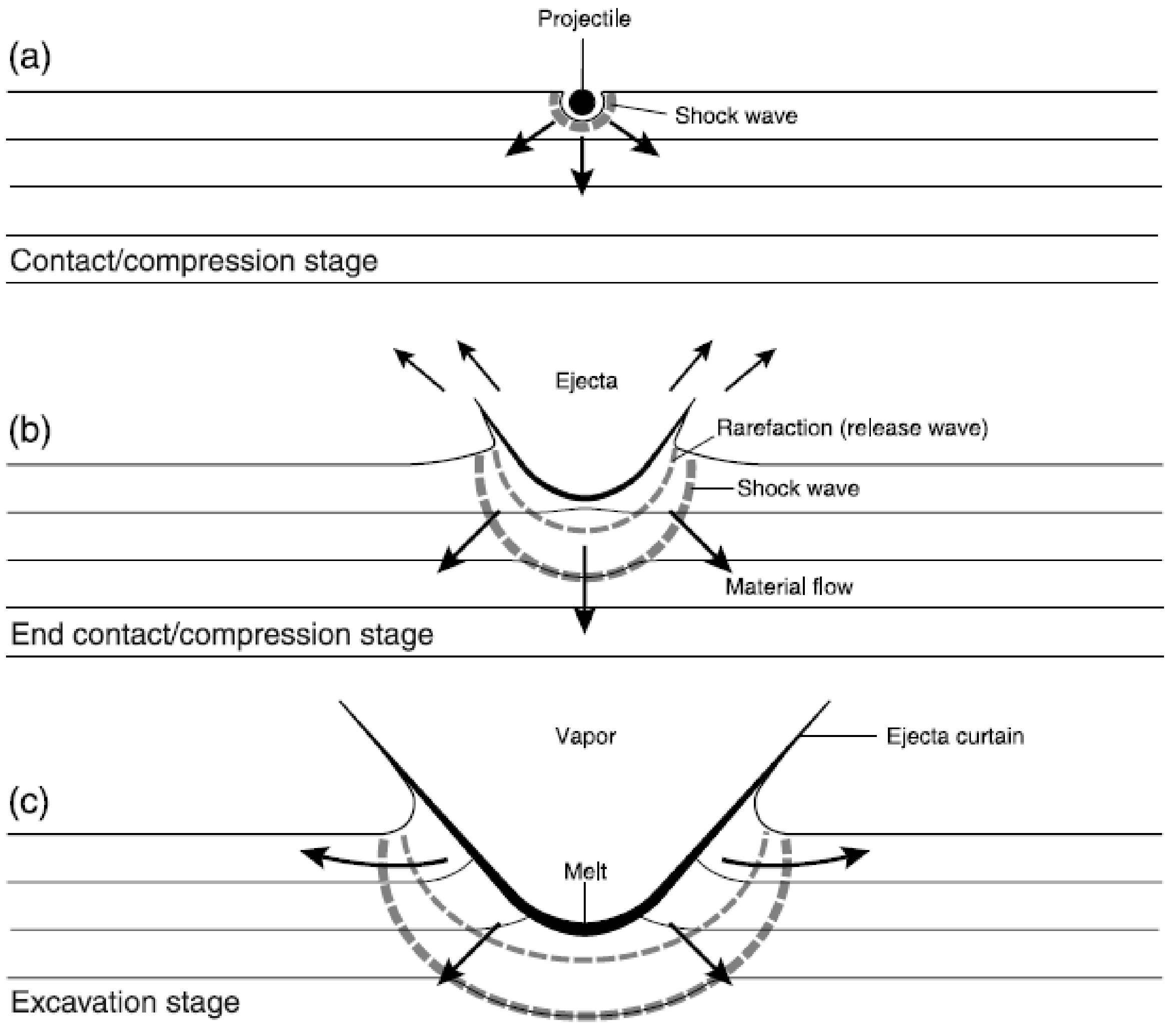
- First to be identified on Earth
- Not always completely circular
  - Faults
- Up to ~3 km diameter



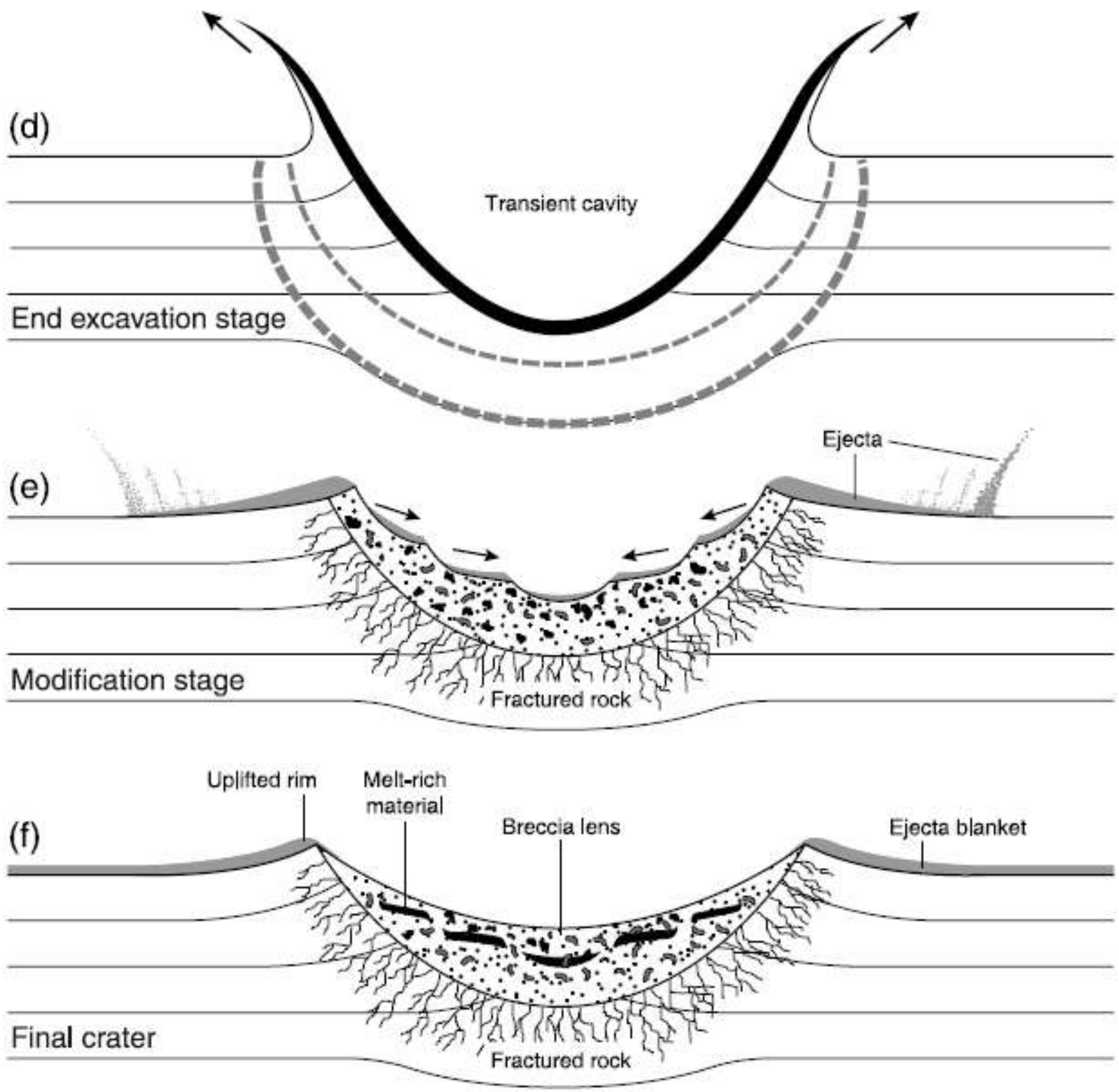
Simple Crater on Moon

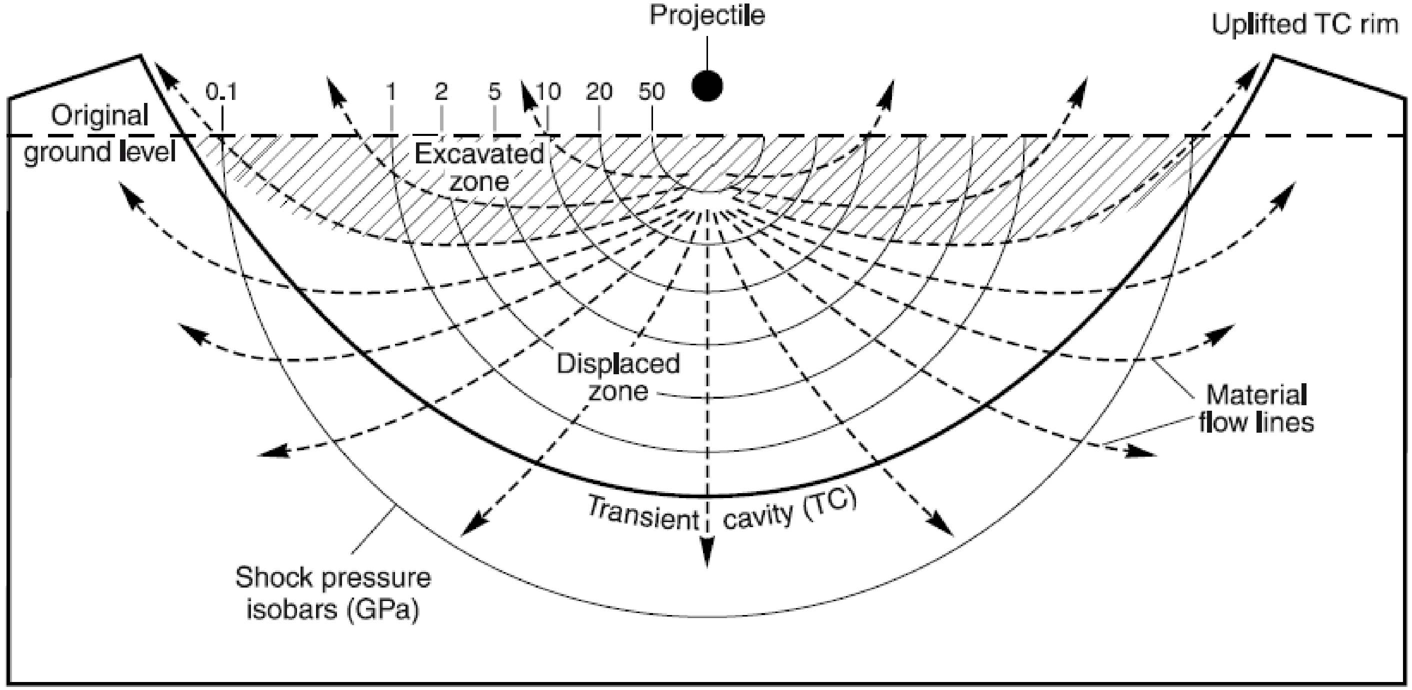
- Moltke crater, a simple crater, was photographed by Apollo 10 astronauts in 1969. The depression, about 7 km (4.3 miles) in diameter.
- Common up to ~18 km diameter

Simple crater formation (I)

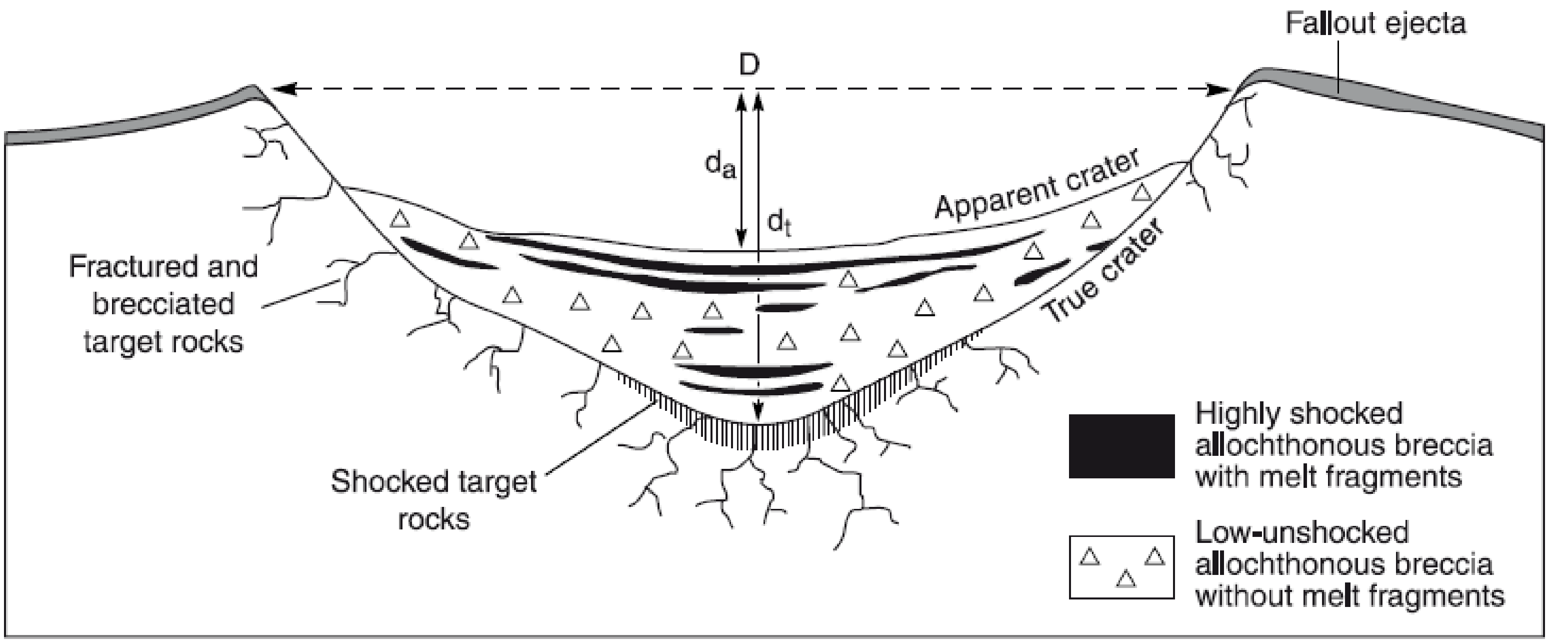


Simple crater formation (II)





Projectile
Uplifted TC rim
0.1
1
2
5
10
20
50
Original ground level
Excavated zone
Displaced zone
Material flow lines
Transient cavity (TC)
Shock pressure isobars (GPa)



Fallout ejecta
D
d_a
d_t
Apparent crater
True crater
Fractured and brecciated target rocks
Shocked target rocks
Highly shocked allochthonous breccia with melt fragments
Low-unshocked allochthonous breccia without melt fragments

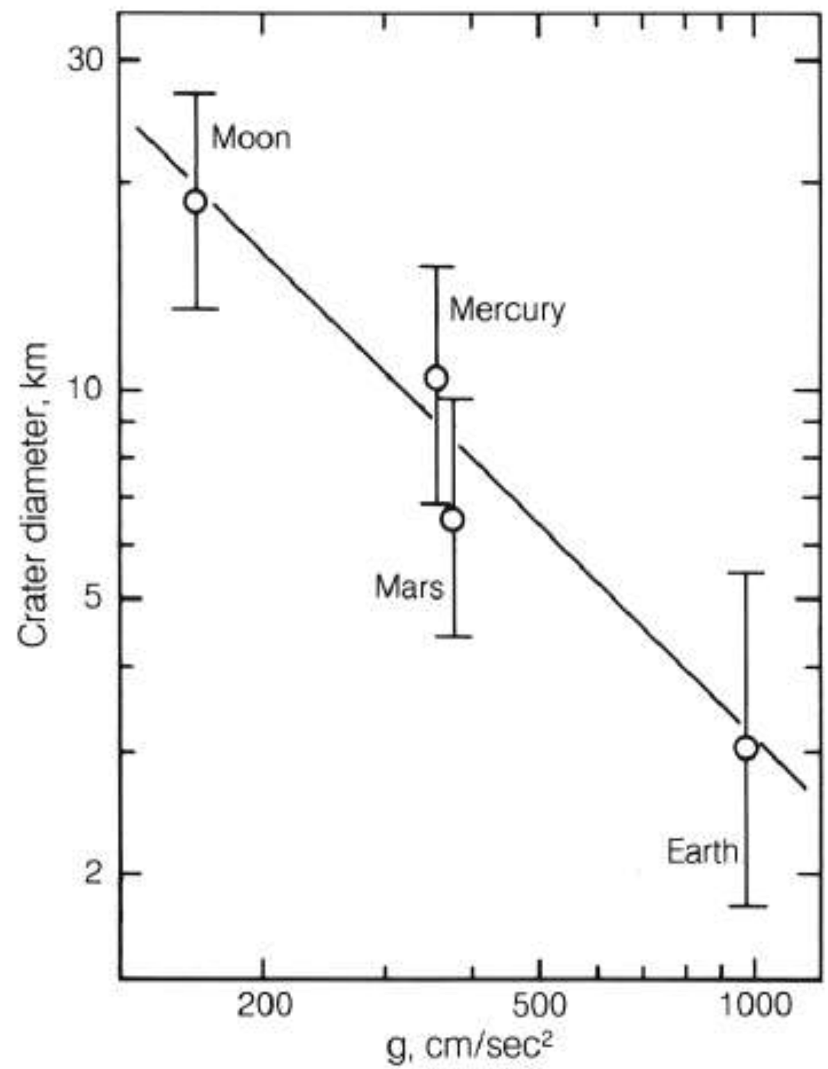
Transition to Complex Craters

- **Transition diameter scales as g^{-1}, where g is the acceleration of gravity at the planet's surface**
- **Because…**

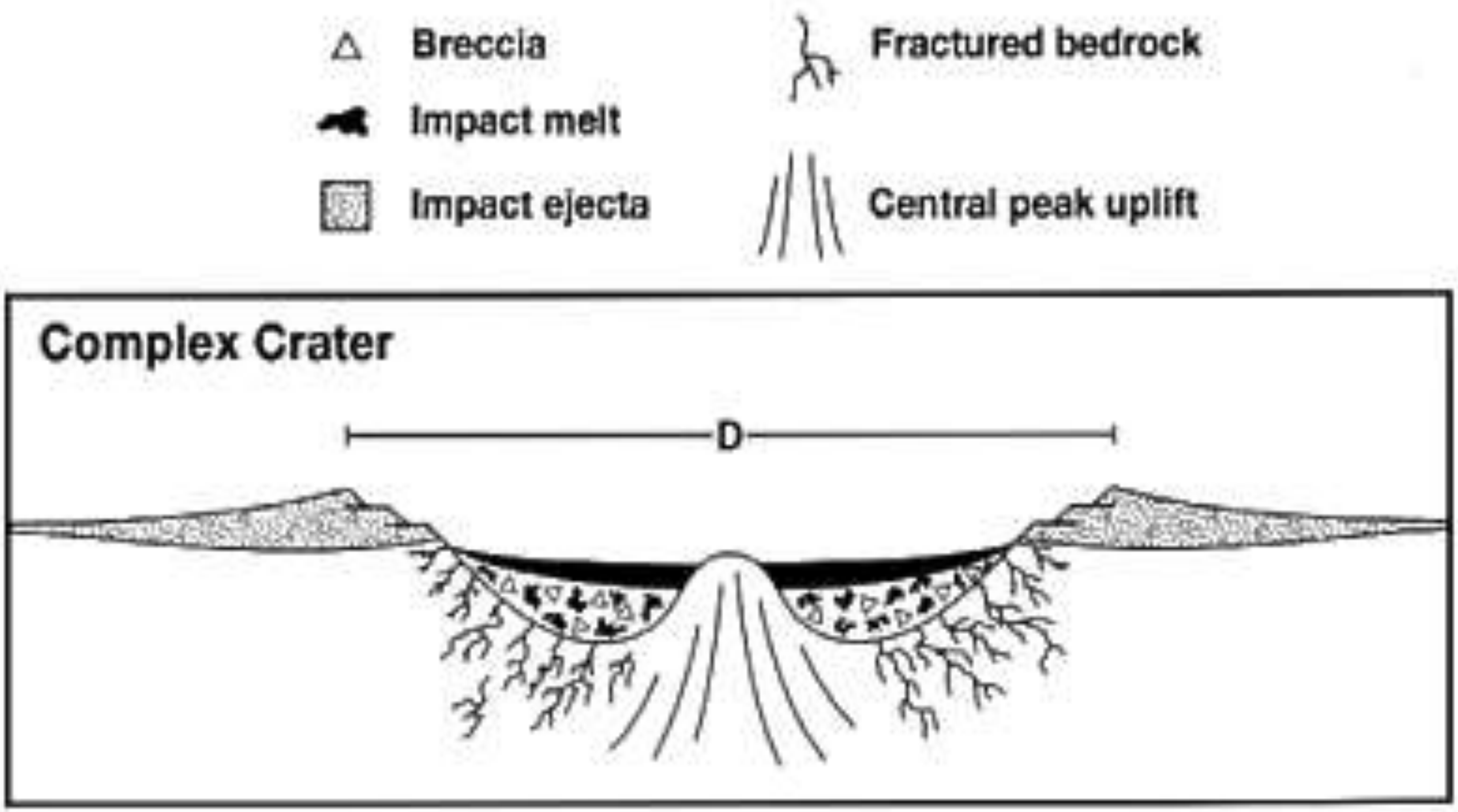
$$D \propto 1/g$$

  - **Earth gravity 9.8 m/s^2**
  - **Moon gravity 1.6 m/s^2**
- **Transition is**
  - **on Moon at ~18 km**
  - **on Earth at ~3km**
- **The transition diameter is higher when**
  - **The material strength is higher**
  - **The density is lower**
  - **The gravity is lower**

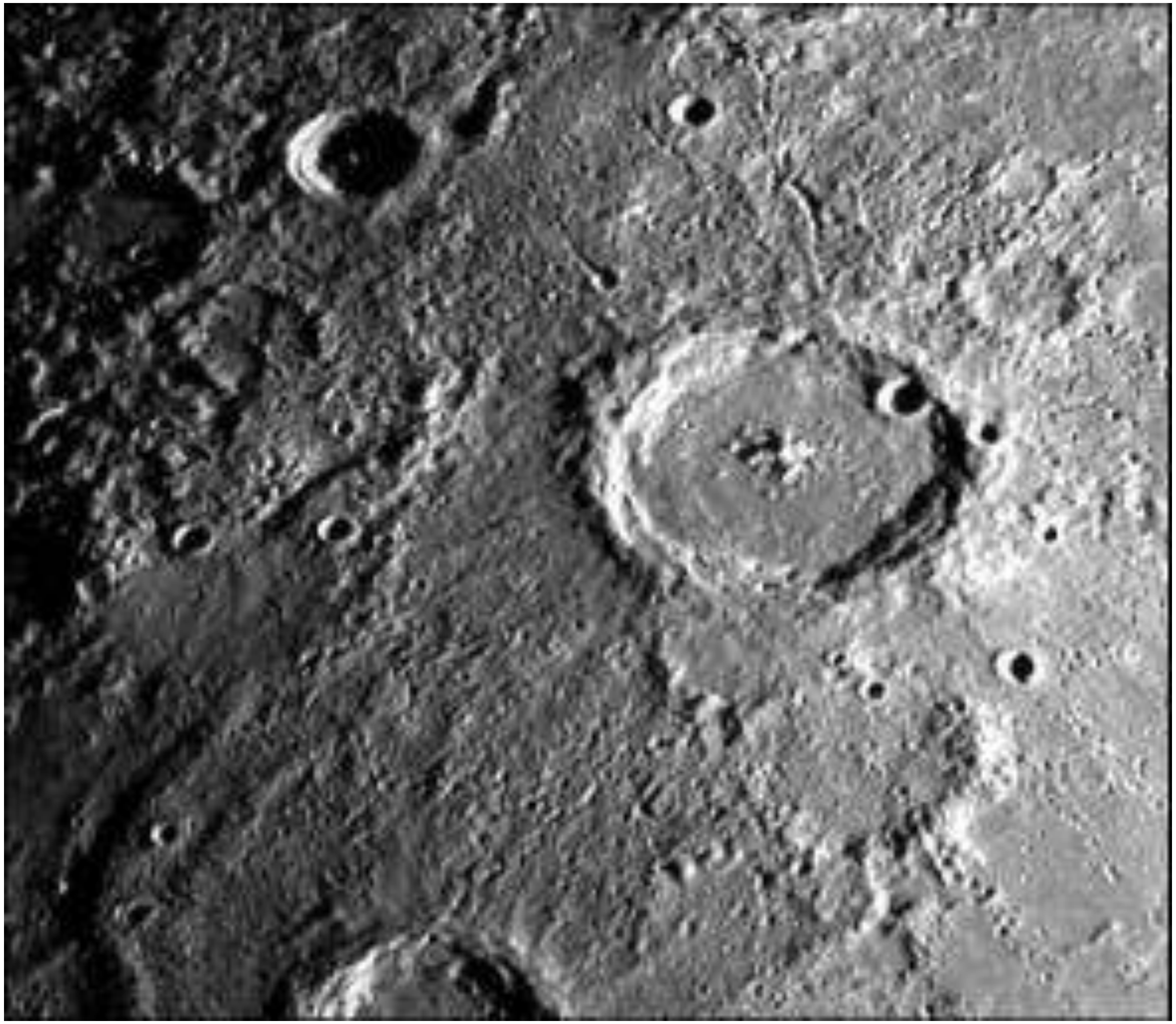
Diameter of crater at the simple/complex transition



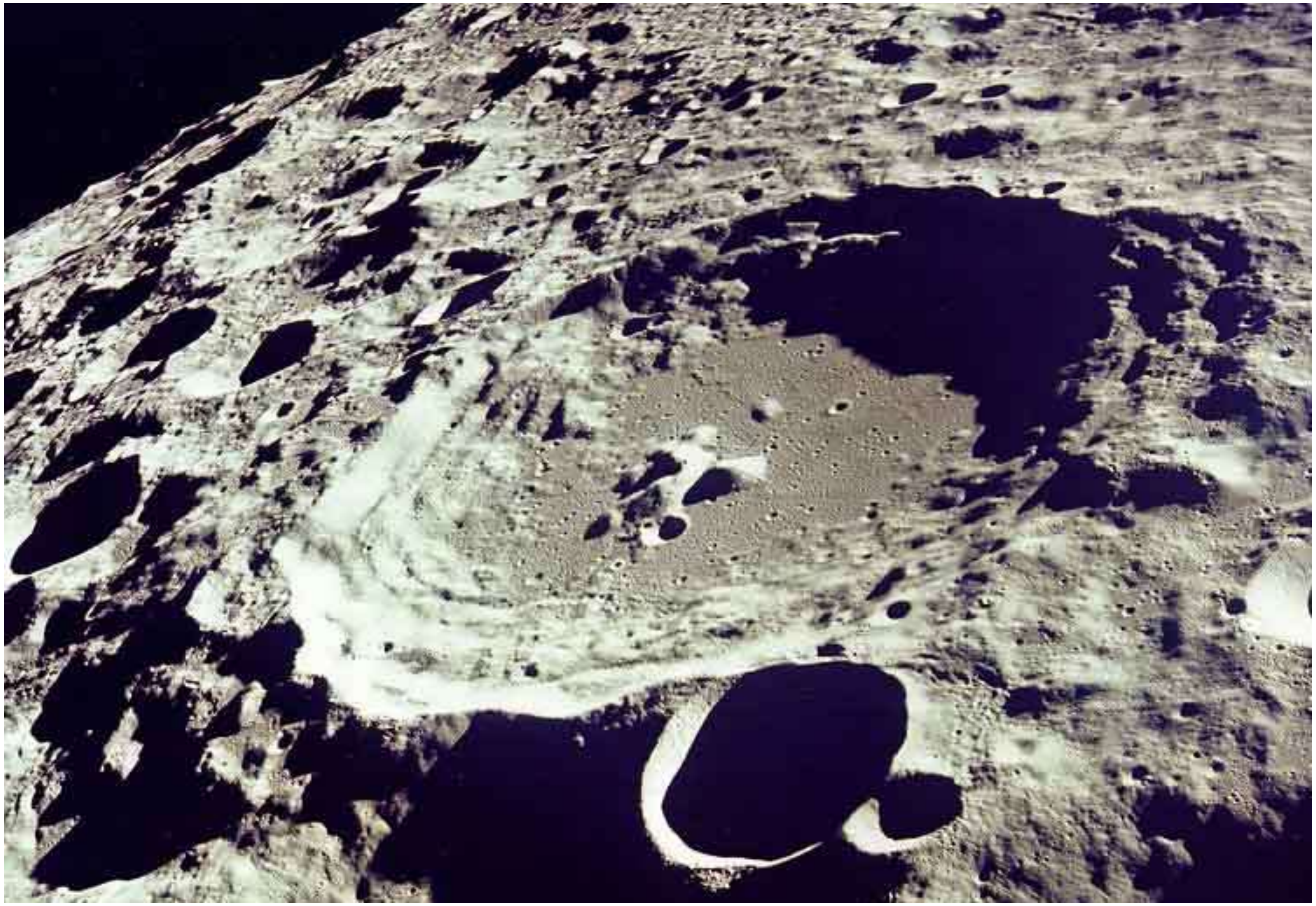
Complex Crater Schematic



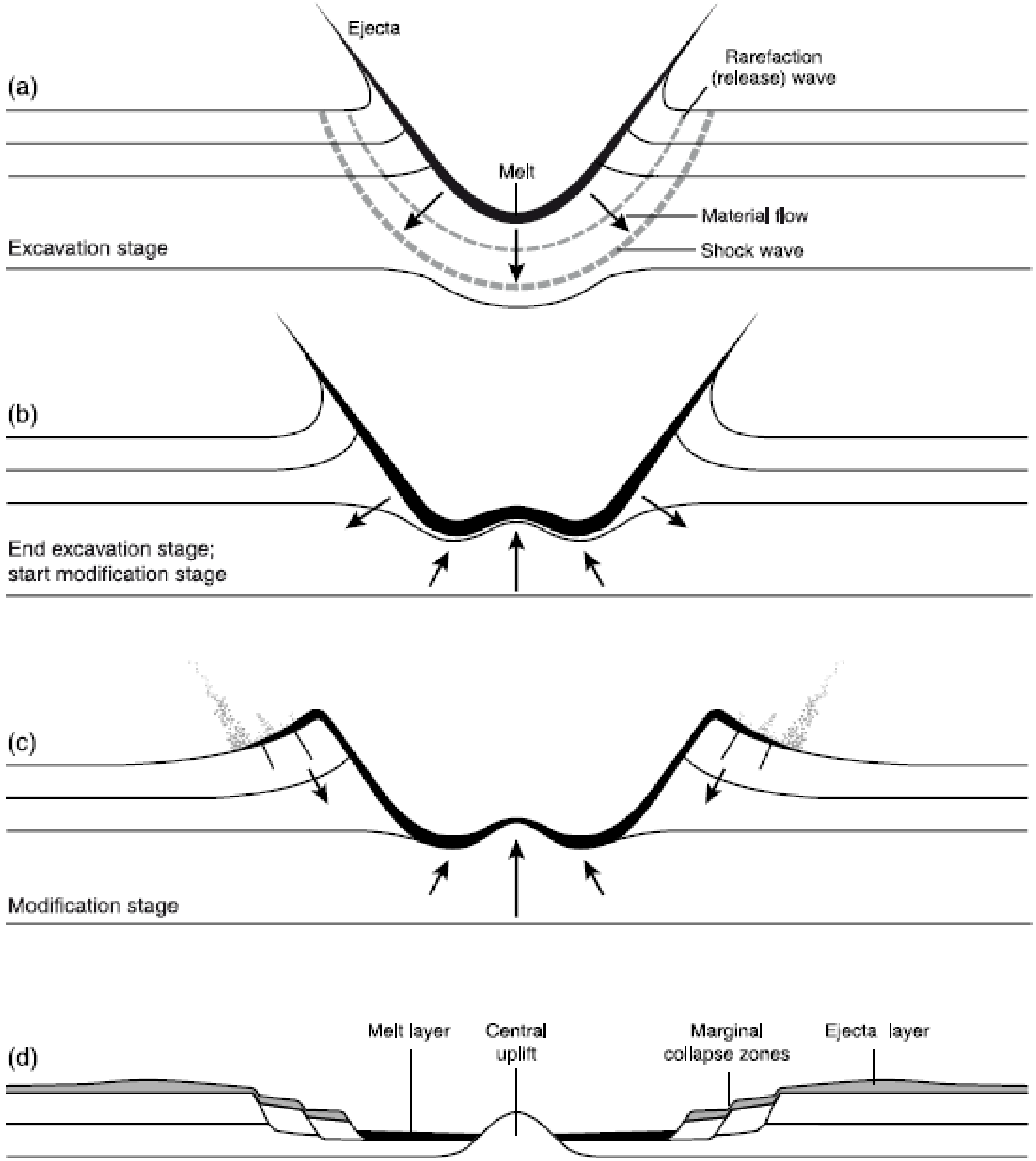
Complex Crater on Mercury



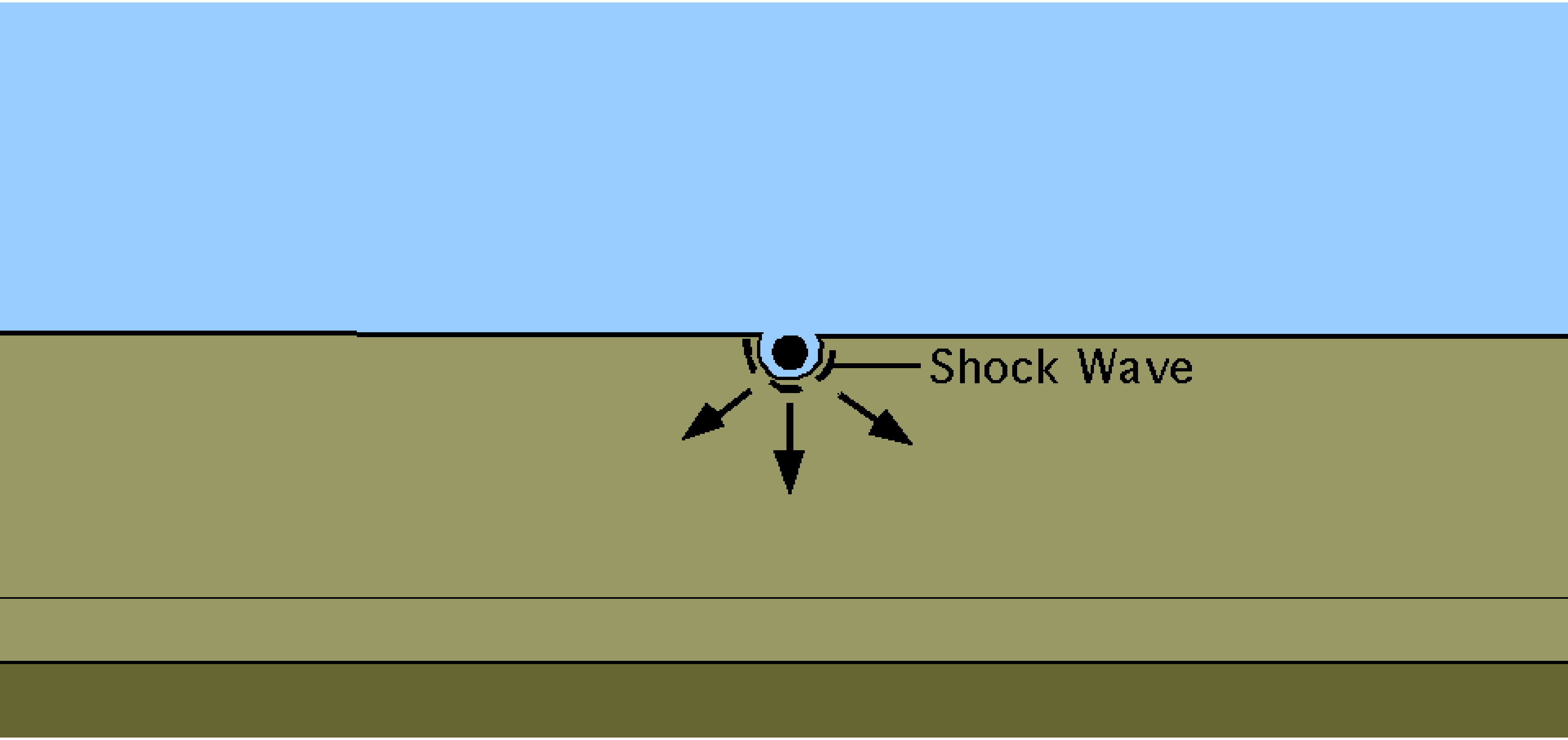
Complex Crater on Moon



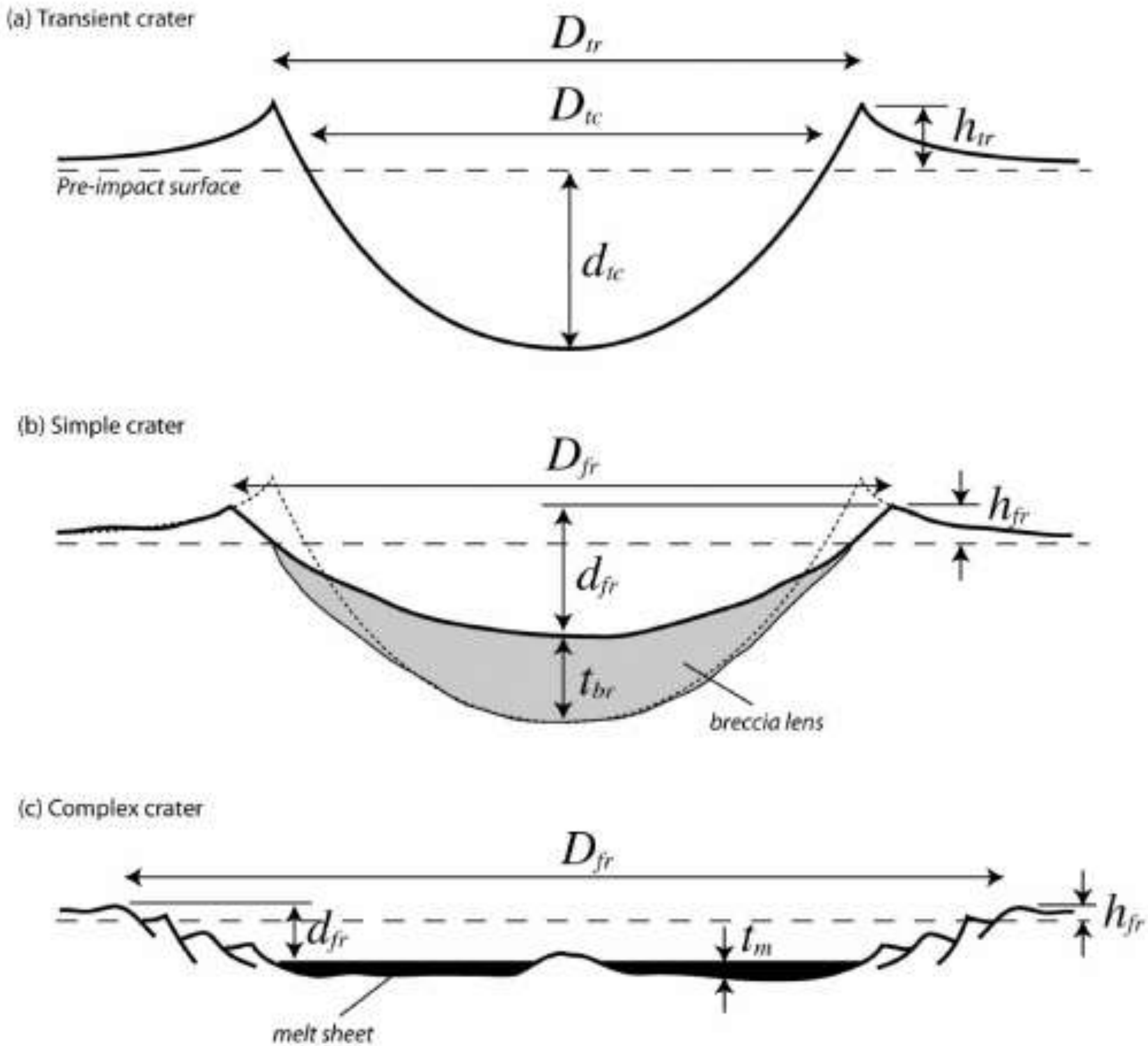
The far side of Earth's Moon. Crater 308. It spans about 30 kilometers (Apollo 11 crew)



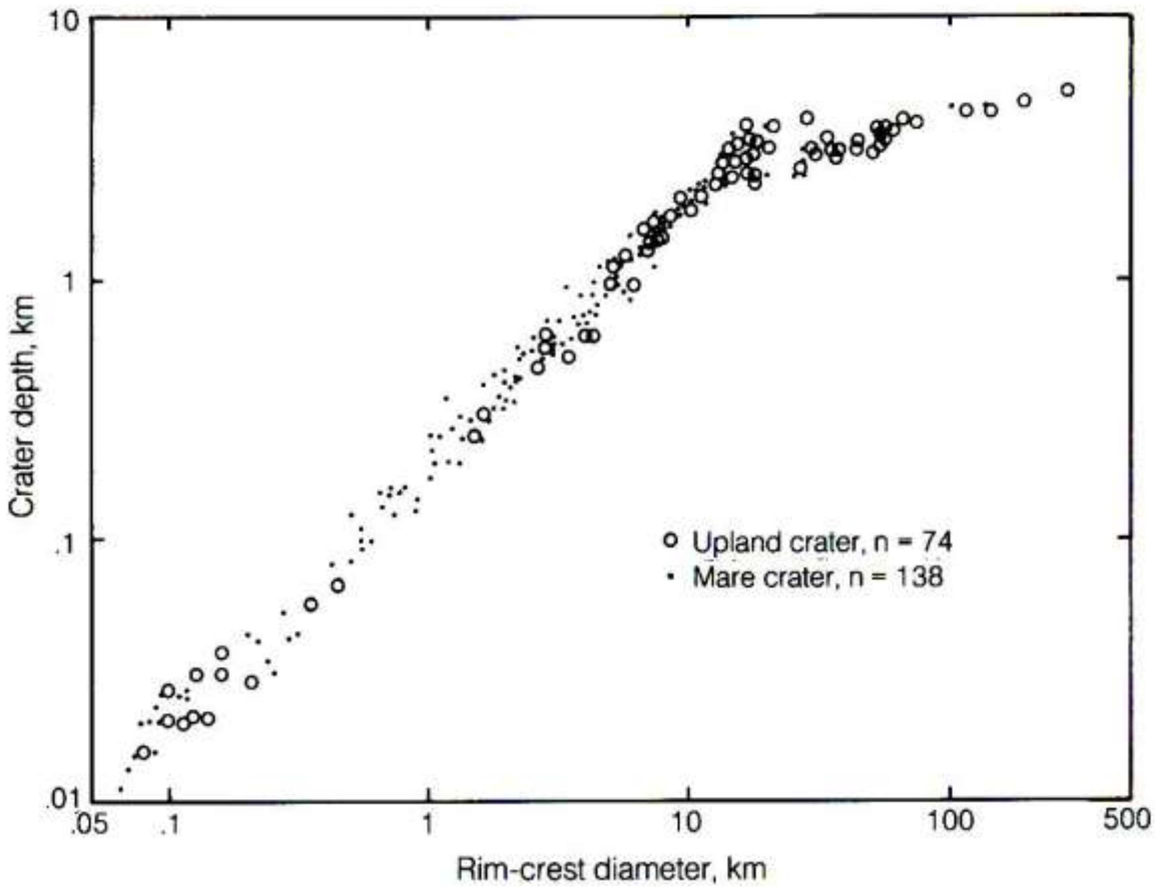
Ejecta
(a)
Rarefaction
(release) wave
Melt
Material flow
Shock wave
Excavation stage
(b)
End excavation stage;
start modification stage
(c)
Modification stage
Melt layer
Central
uplift
Marginal
collapse zones
Ejecta layer
(d)


Shock Wave

All craters start as a transient hemispheric cavity

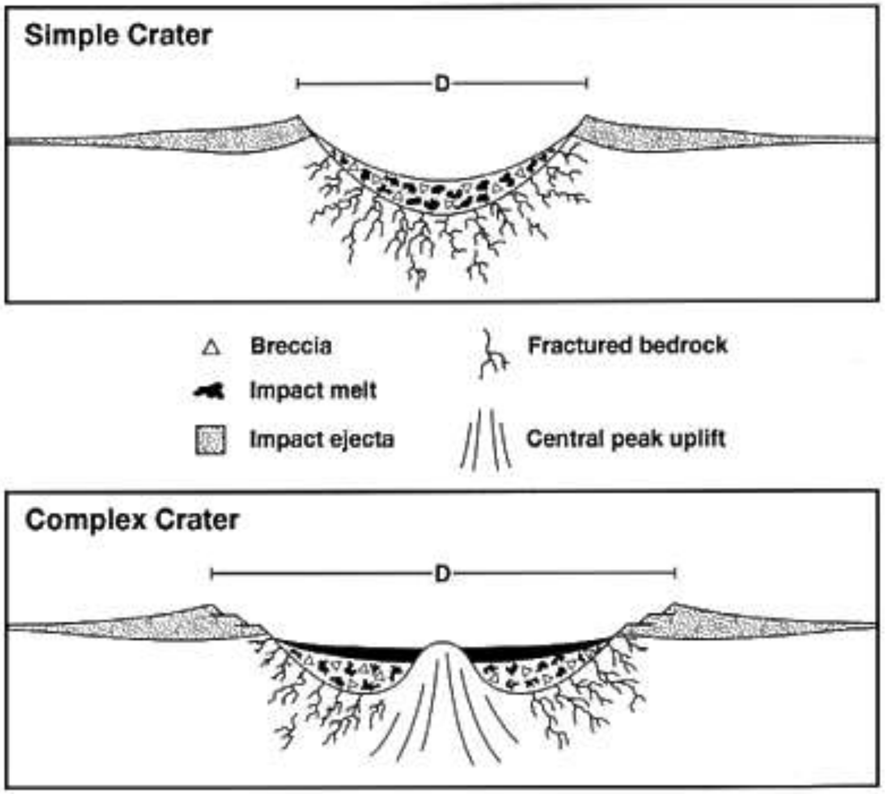


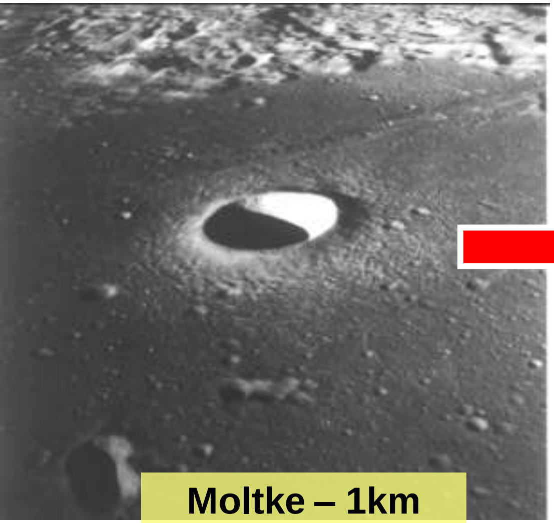
The simple-complex transition is accompanied by a sudden decrease in crater depth

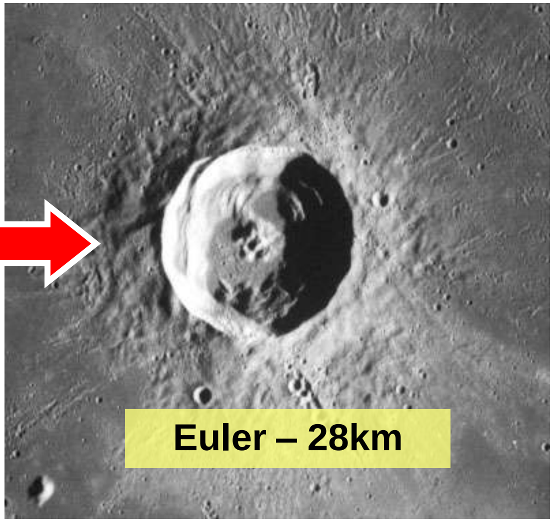


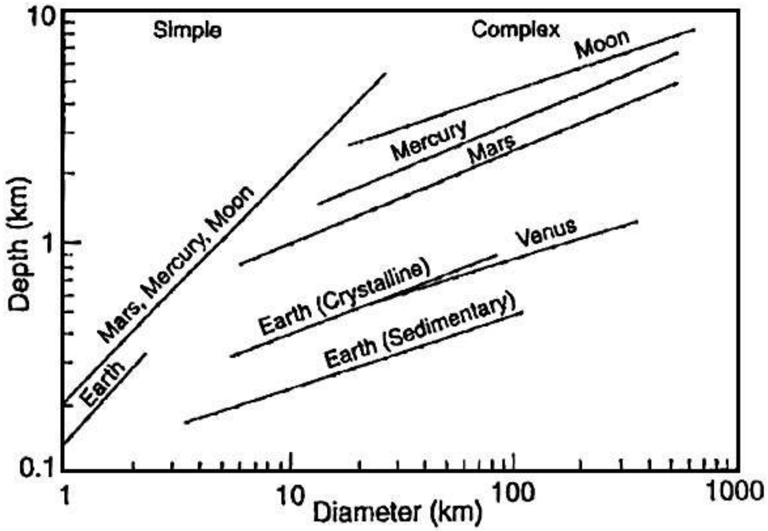
- **Differences in simple and complex morphologies**

Simple	Complex
Bowl shaped	Flat-floored Central peak Wall terraces
Little melt	Some Melt
d/D ~ 0.2	d/D much smaller Diameter dependent
Small sizes	Larger sizes

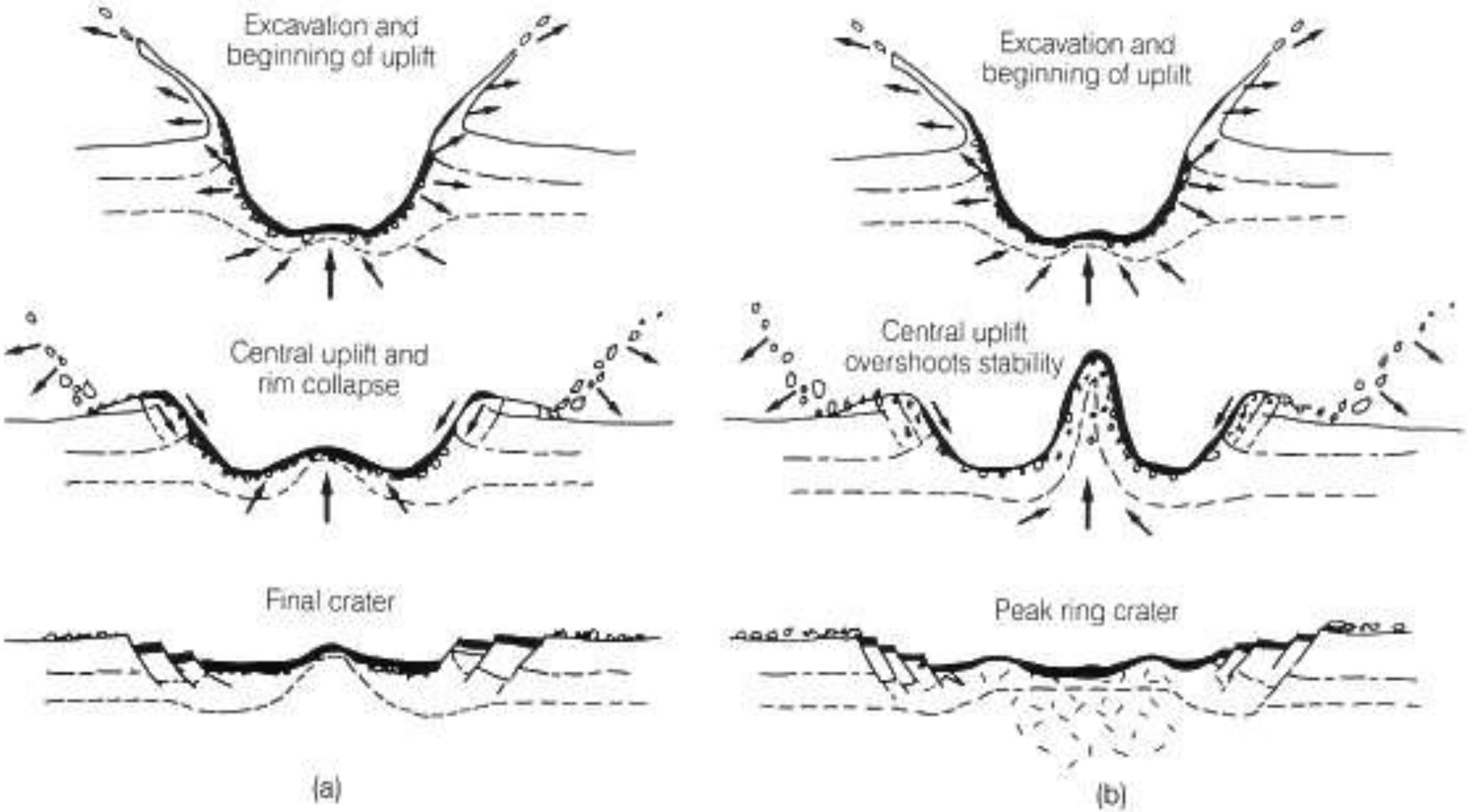








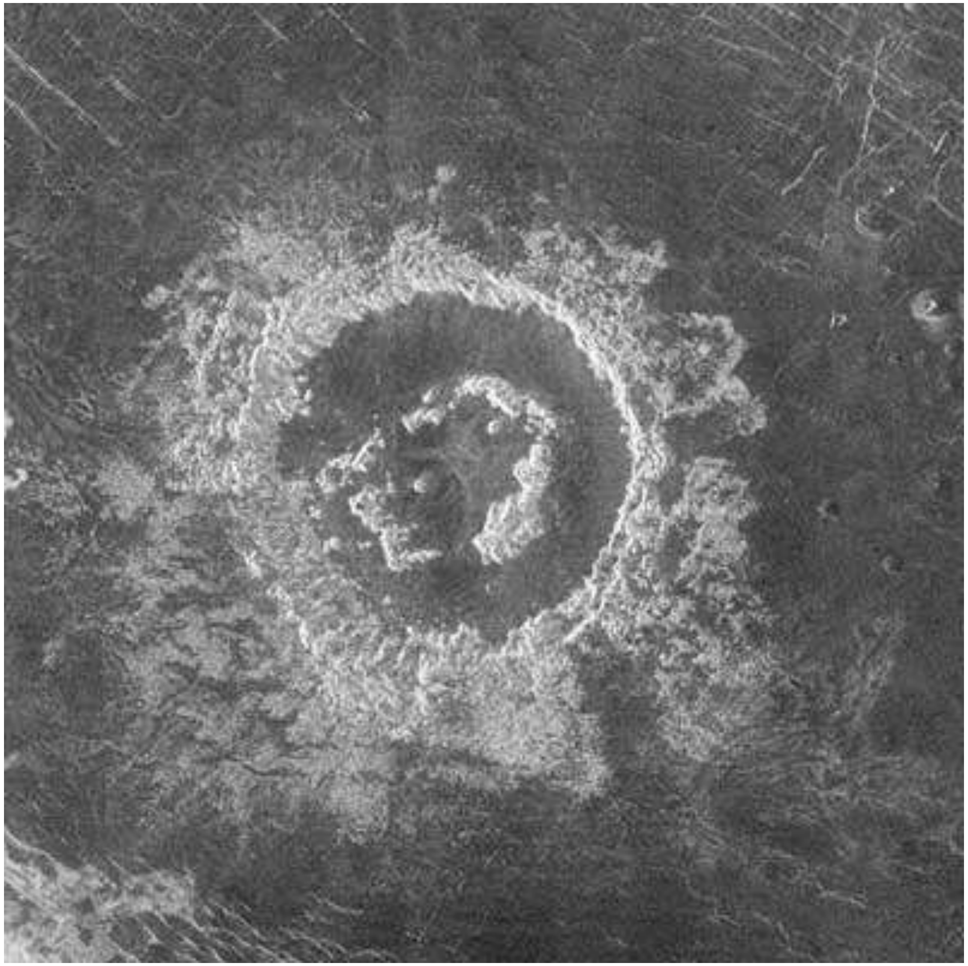
More Complex



More Complex Facts

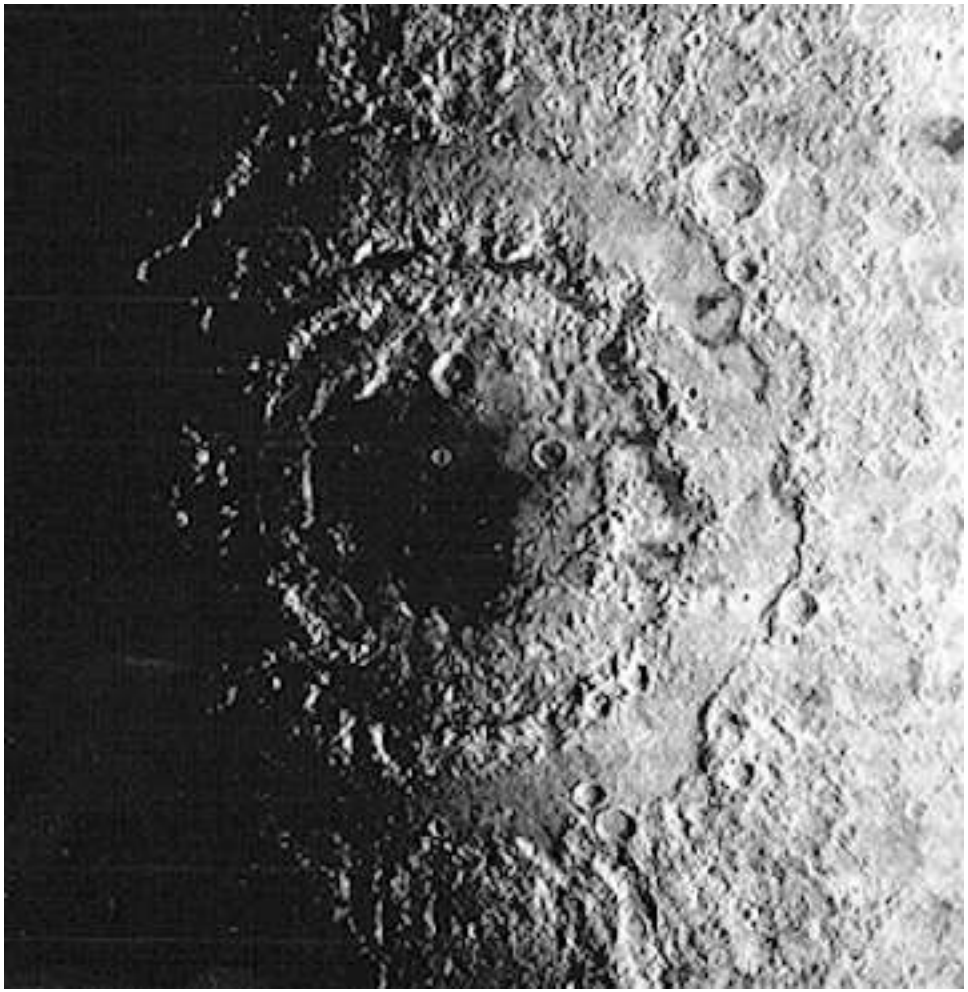
- Transition to central ring at approx 140 km diameter on Moon
- Still follows the g^{-1} rule
- Central ring generally about half of rim-to-rim diameter for terrestrial planets

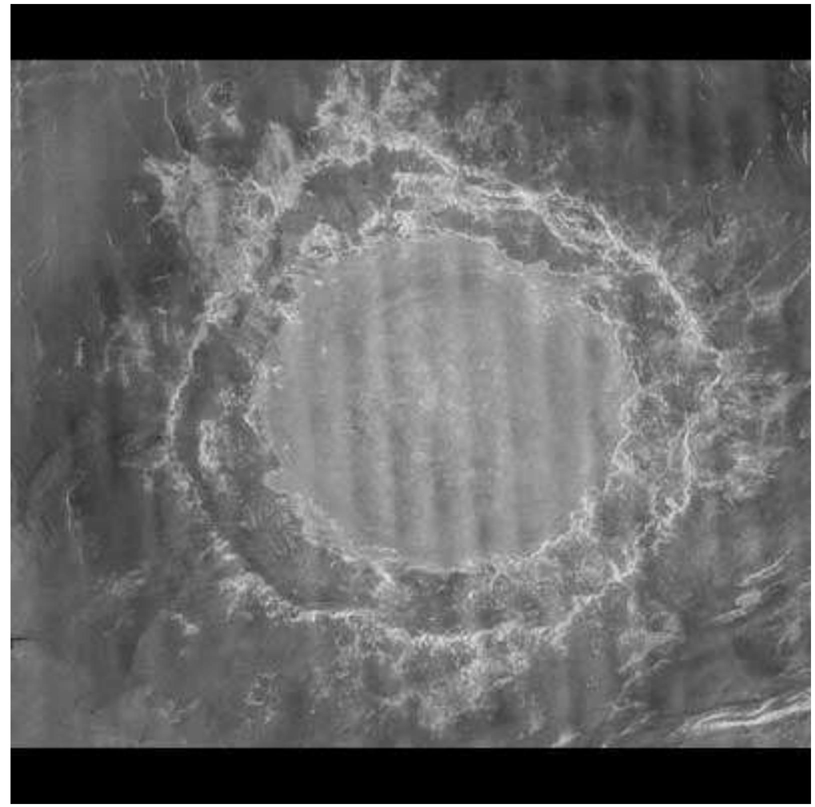
Central Ring Crater



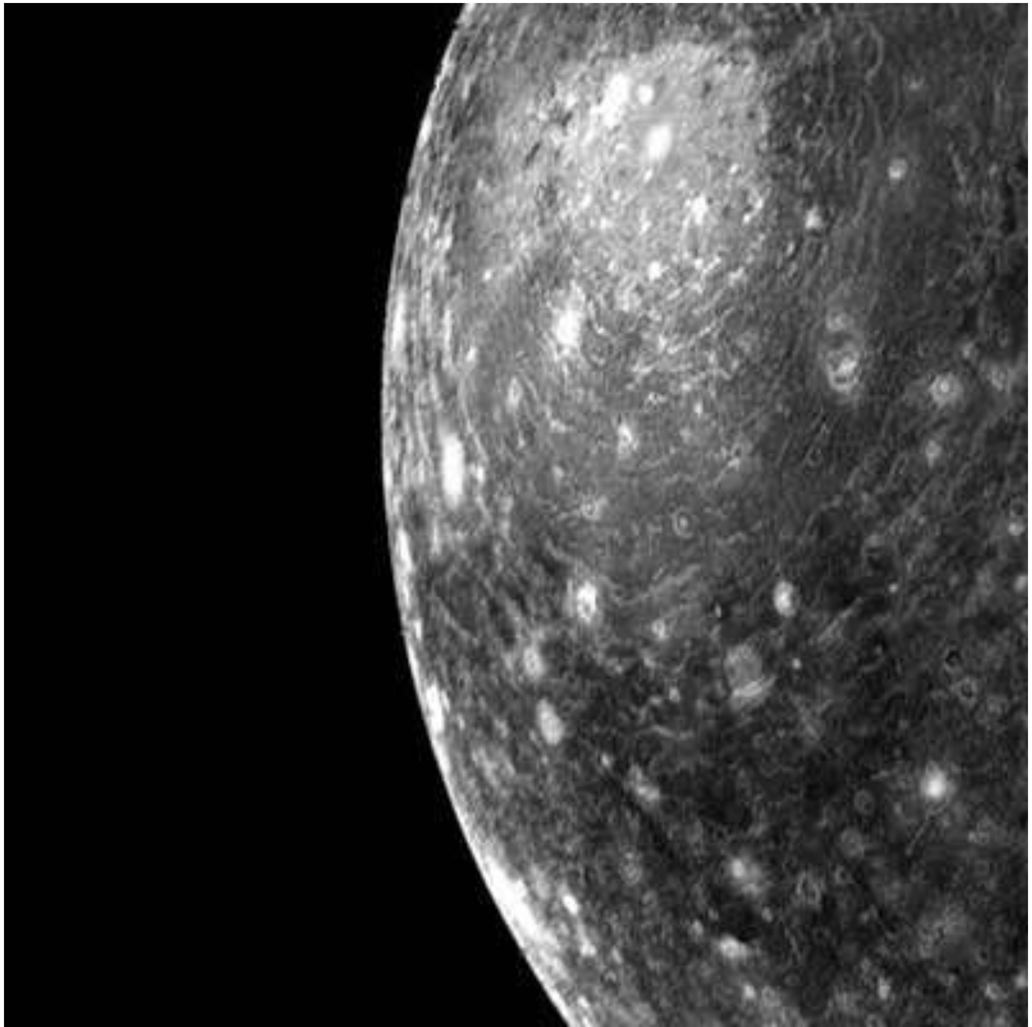
- Barton crater on Venus
- Discontinuous central ring
- Very close to transition diameter
  - 50 km ring

Rings and multirings





Multiring basins



- Valhalla basin on Callisto
- 4000 km
  - Only central bright stop believed to be formed by impact
- Outward facing scarps

Multiring basins

- Orientale basin on Moon
- Youngest and best preserved
- Approx 930 km diameter
- 2 km depth
- Inward facing scarps

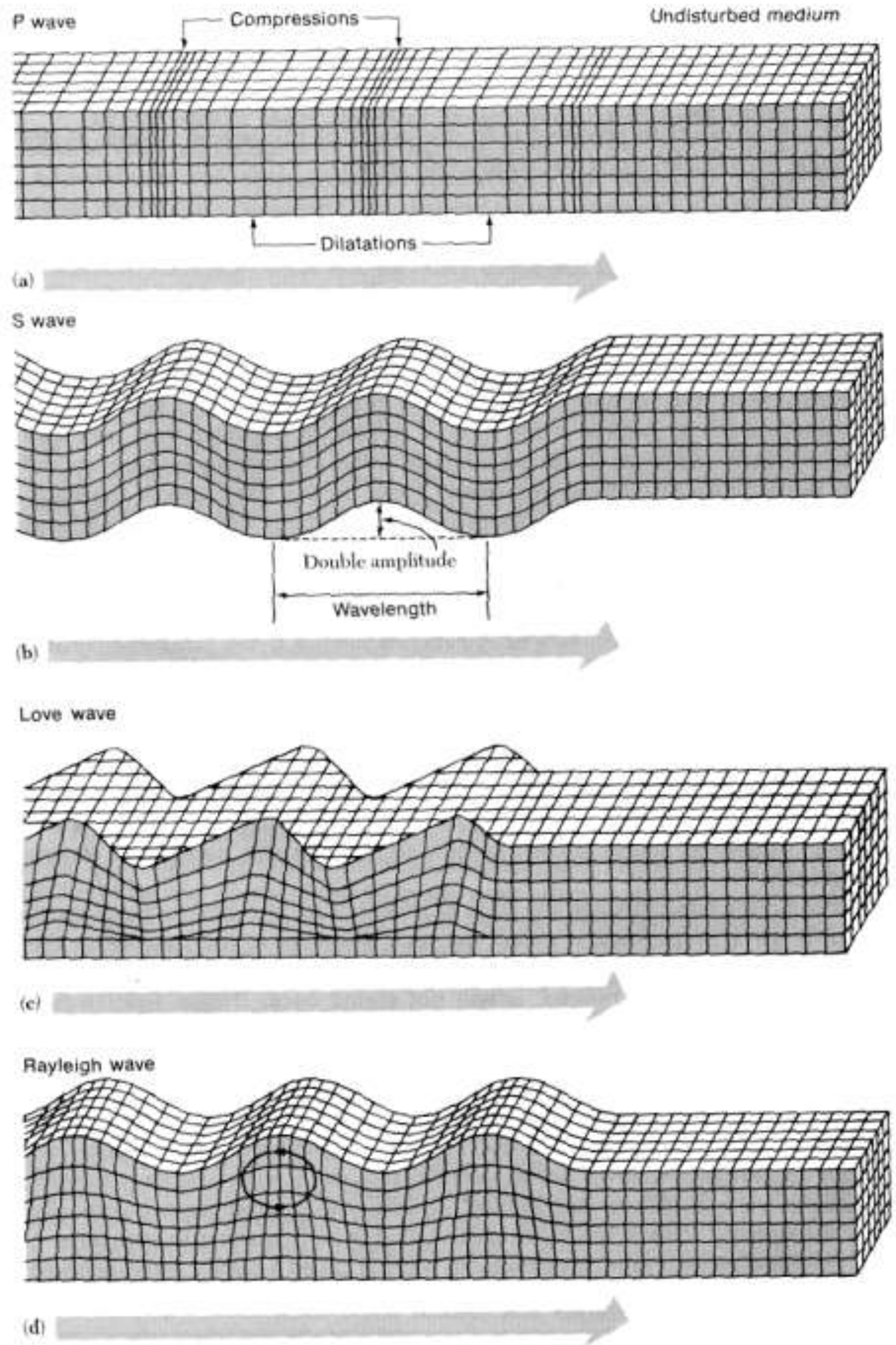
Seismic waves

Ondas sísmicas (I)

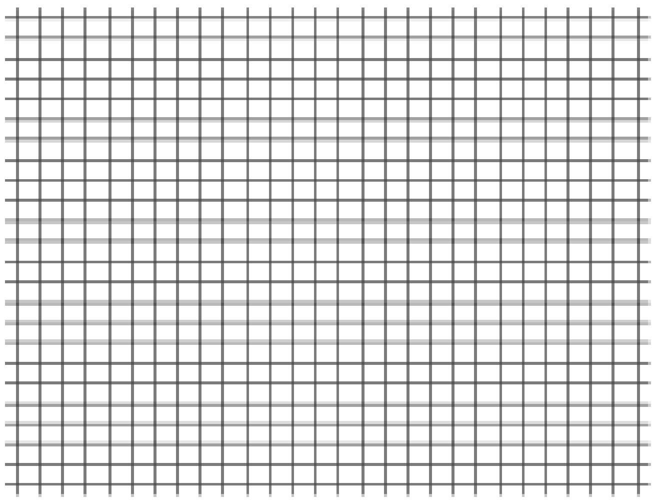
- **Ondas de cuerpo (body waves)**
  - **Las ondas de cuerpo viajan a través del interior de la Tierra. Siguen caminos curvos debido a la variada densidad y composición del interior de la Tierra.**
  - **Ondas P**
    - **Las ondas P (**PRIMARIAS **o *PRIMAE*) son ondas longitudinales o compresionales, lo cual significa que el suelo es alternadamente comprimido y dilatado en la dirección de la propagación.**
  - **Ondas S**
    - **Las ondas S (**SECUNDARIAS **o *SECUNDAE*) son ondas en las cuales el desplazamiento es transversal a la dirección de propagación. Su velocidad es levemente menor que la velocidad de las ondas primarias.**

Ondas sísmicas (II)

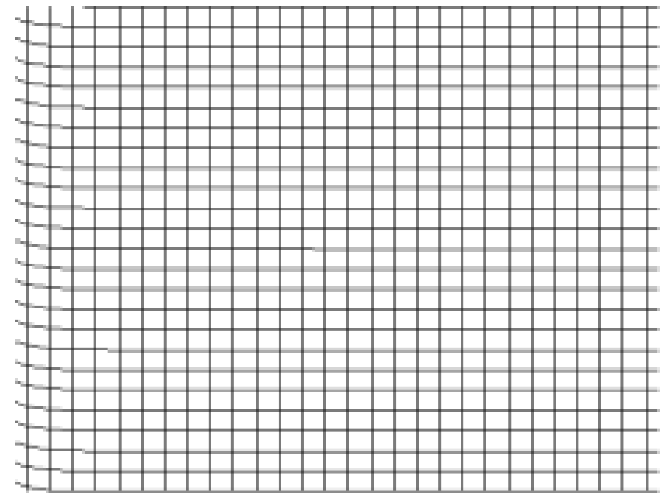
- **Ondas Superficiales**
  - **Cuando las ondas de cuerpo llegan a la superficie, se generan las ondas L (**SUPERFICIALES **o *LONGAE*), que se propagan por la superficie de discontinuidad de la interfase de la superficie terrestre (tierra-aire y tierra-agua). Son las causante de los daños producidos por los sismos en la construcciones.**
  - **Ondas Love**
    - **Las** ondas Love **son ondas superficiales que producen un movimiento horizontal de corte en superficie.**
  - **Ondas Rayleigh**
    - **Las** ondas Rayleigh**, también denominadas *ground roll*, son ondas superficiales que producen un movimiento elíptico retrógrado del suelo.**


P wave
Compressions
Undisturbed medium
Dilatations
(a)
S wave
Double amplitude
Wavelength
(b)
Love wave
(c)
Rayleigh wave
(d)

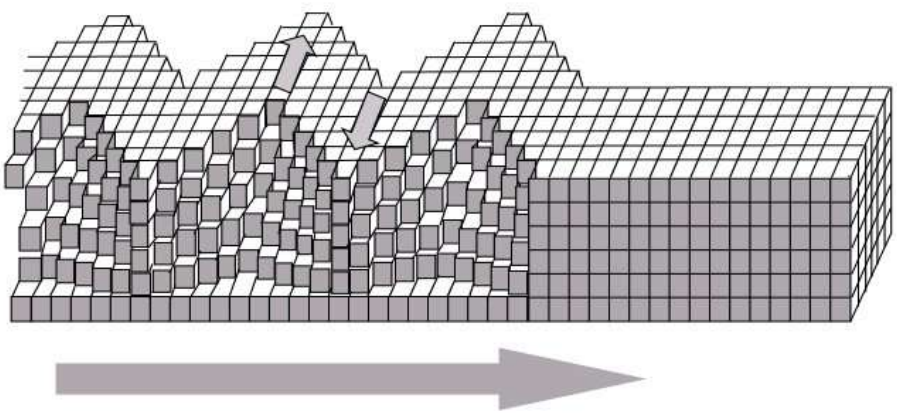
Onda P



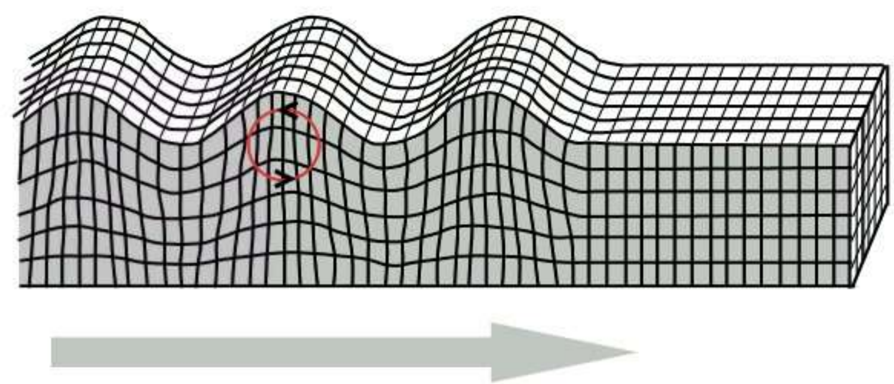
Onda S



Love Wave



Rayleigh Wave



Velocidad de las ondas

K es el módulo de incompresibilidad, *μ* es el módulo de corte o rigidez y *ρ* la densidad del material

Velocidad de ondas primarias

$$v_p = \sqrt{\frac{K + \frac{4}{3}\mu}{\rho}}$$

Velocidad de ondas secundarias

$$v_s = \sqrt{\frac{\mu}{\rho}}$$

$$\boldsymbol{v_p > v_s}$$

Para fluidos v_s=0

Seismic waves at close distance

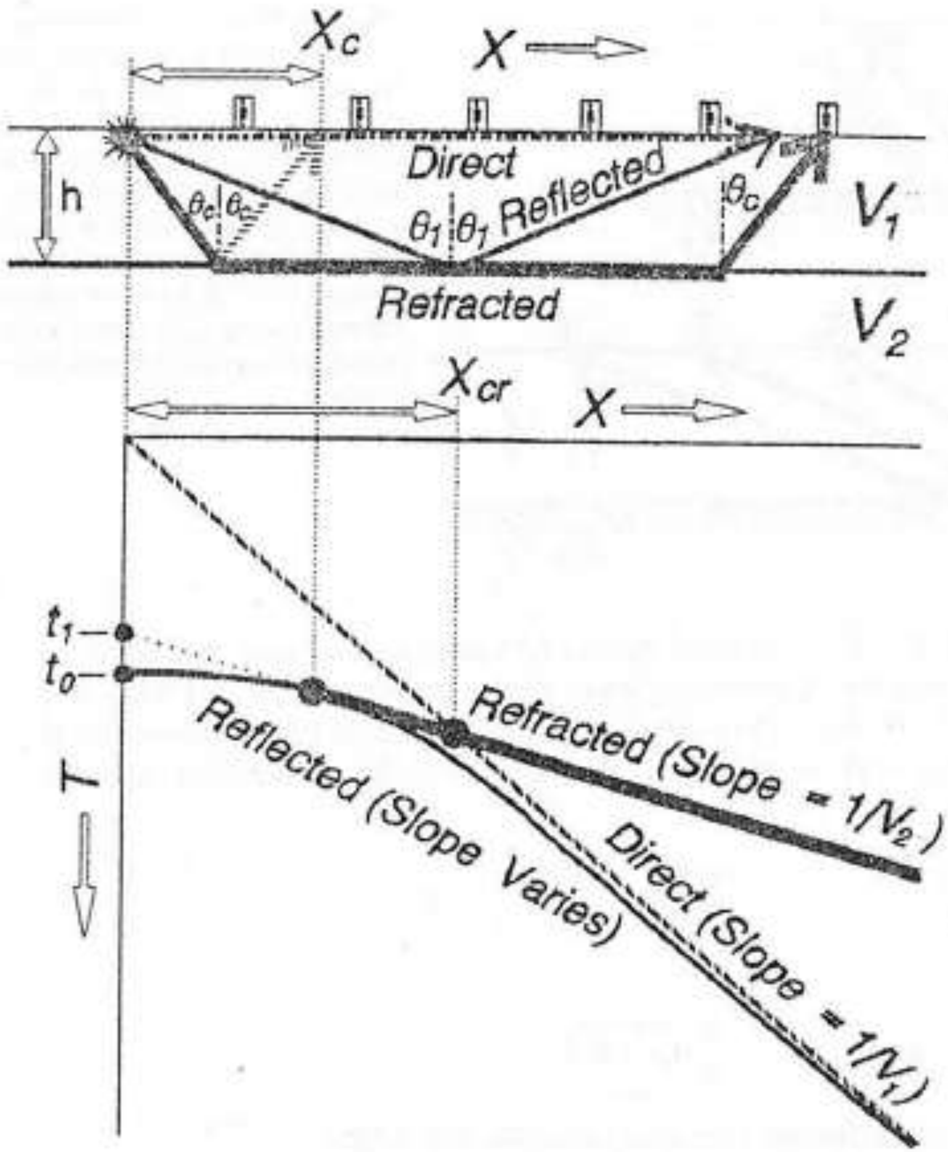
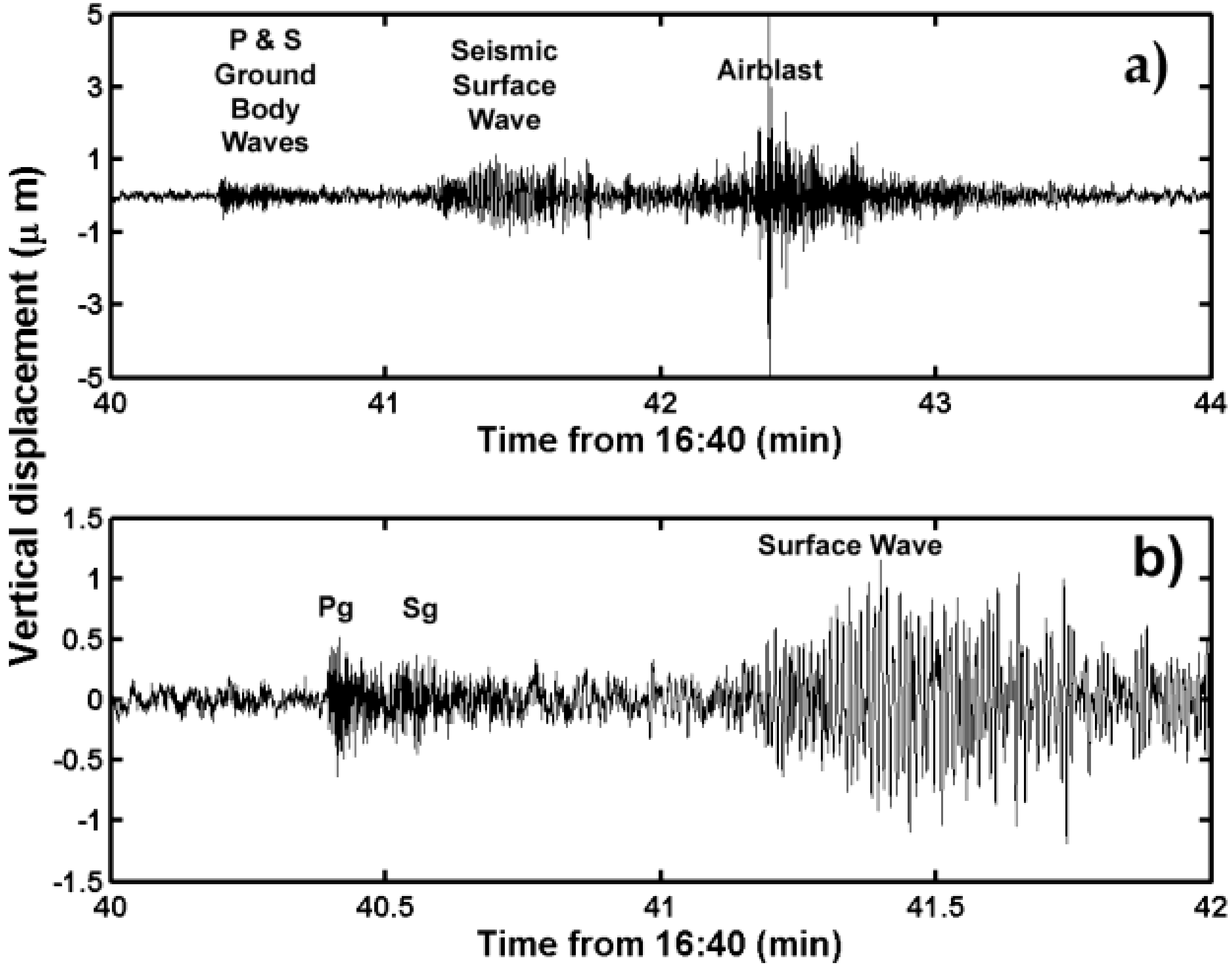


FIGURE 3.31 Selected raypaths and travel-time graph of direct, critically refracted, and reflected waves for a horizontal interface separating a higher velocity (V_2) layer from a lower velocity (V_1) surficial layer. X_c is the *critical distance* (closest distance from the source where the critically refracted wave is observed) and X_{cr} the *crossover distance* (beyond that distance the critically refracted wave arrives before the direct wave).

$$X_c = 2h \frac{v_1}{\sqrt{v_2^2 - v_1^2}}$$

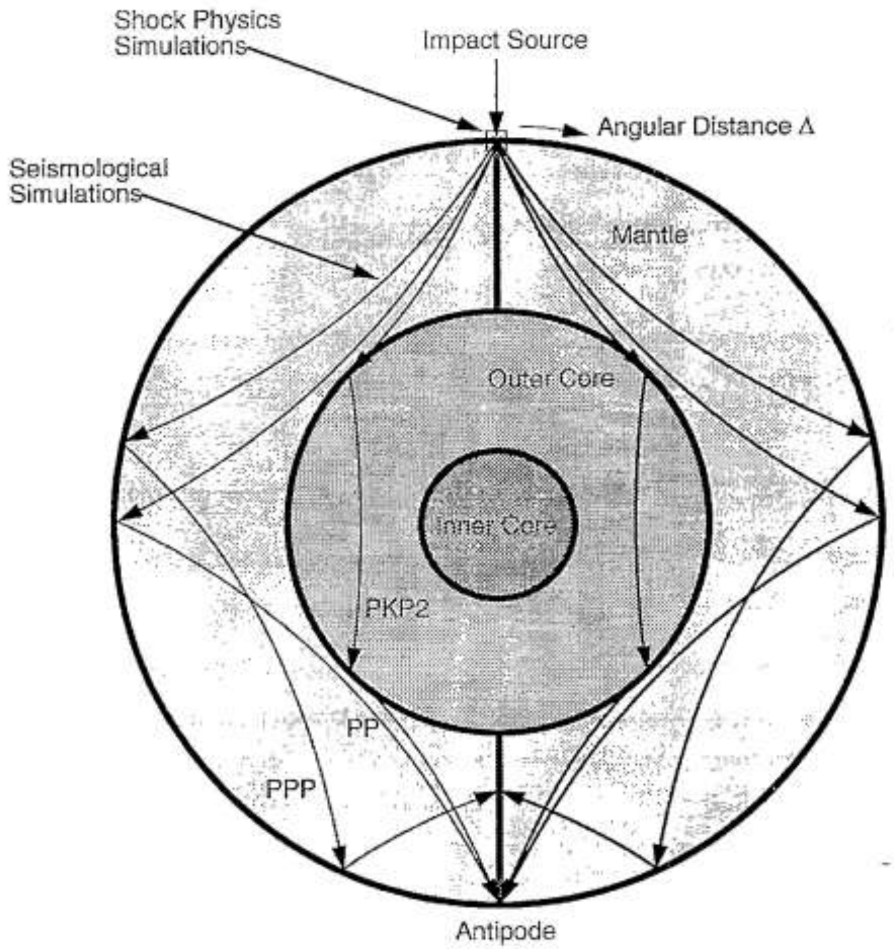
Depending on the depth of the Mohorovic discontinuity (Moho) the critical distance goes from 120-200km

Seismic detections (Tancredi et al. 2009)

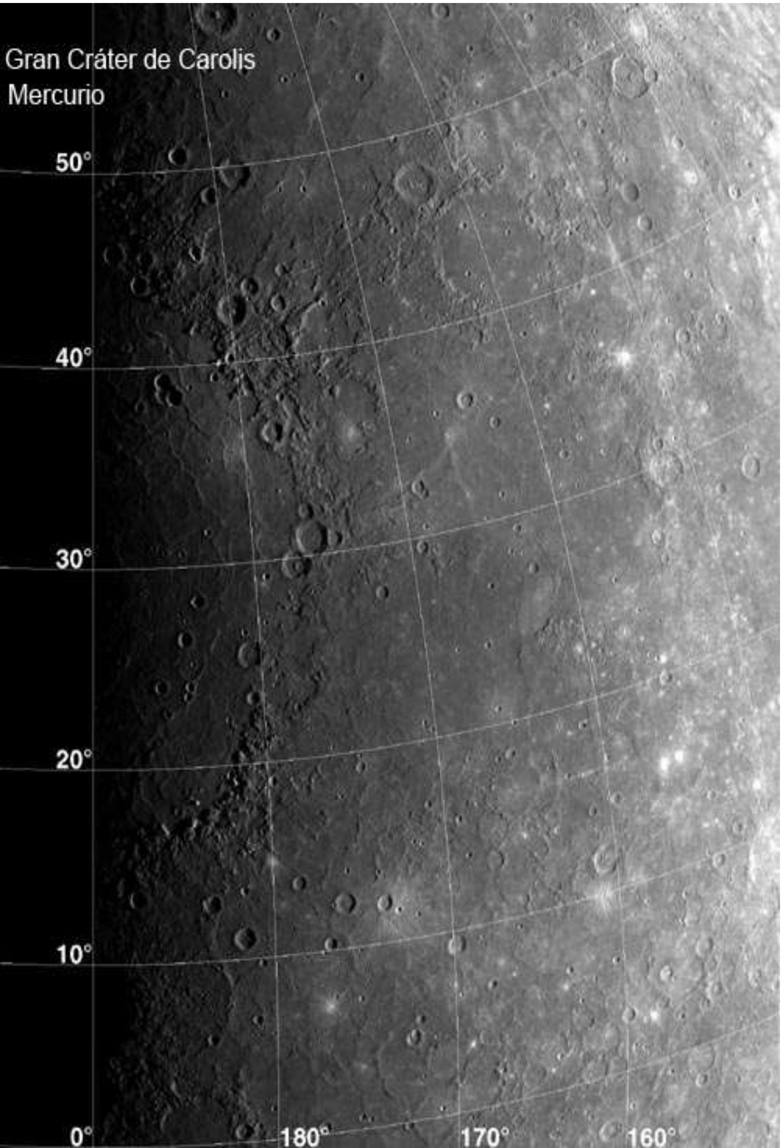


First seismic detection of an extraterrestrial impact on Earth

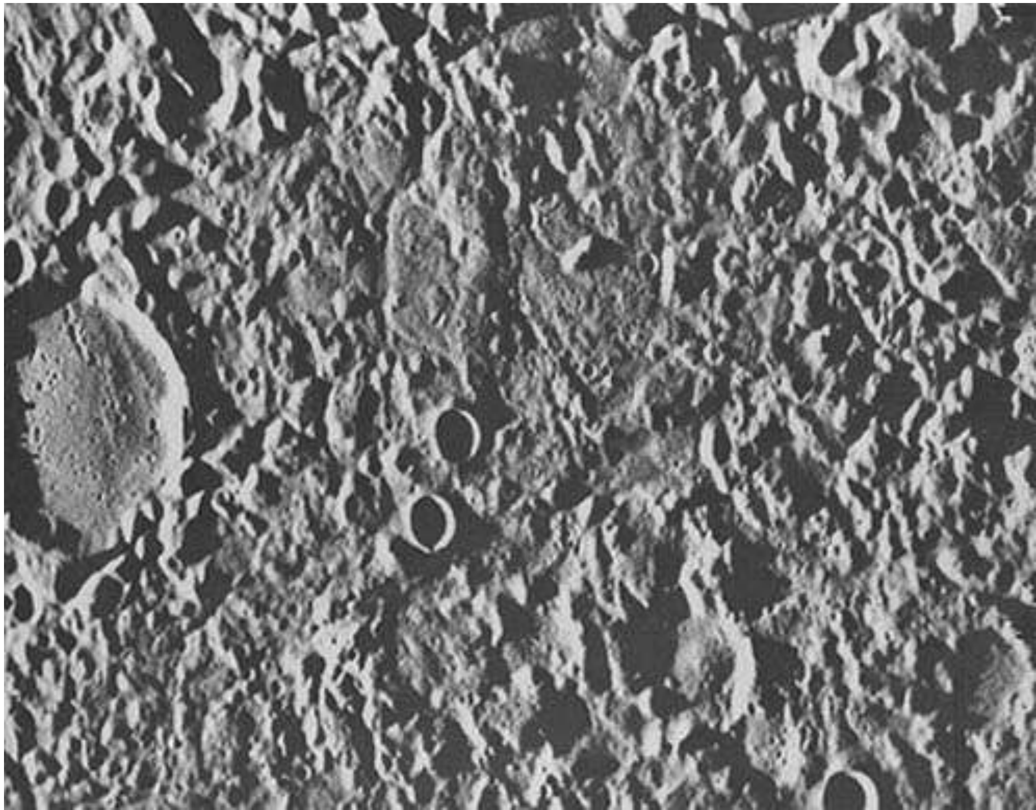
Focusing in the antipode



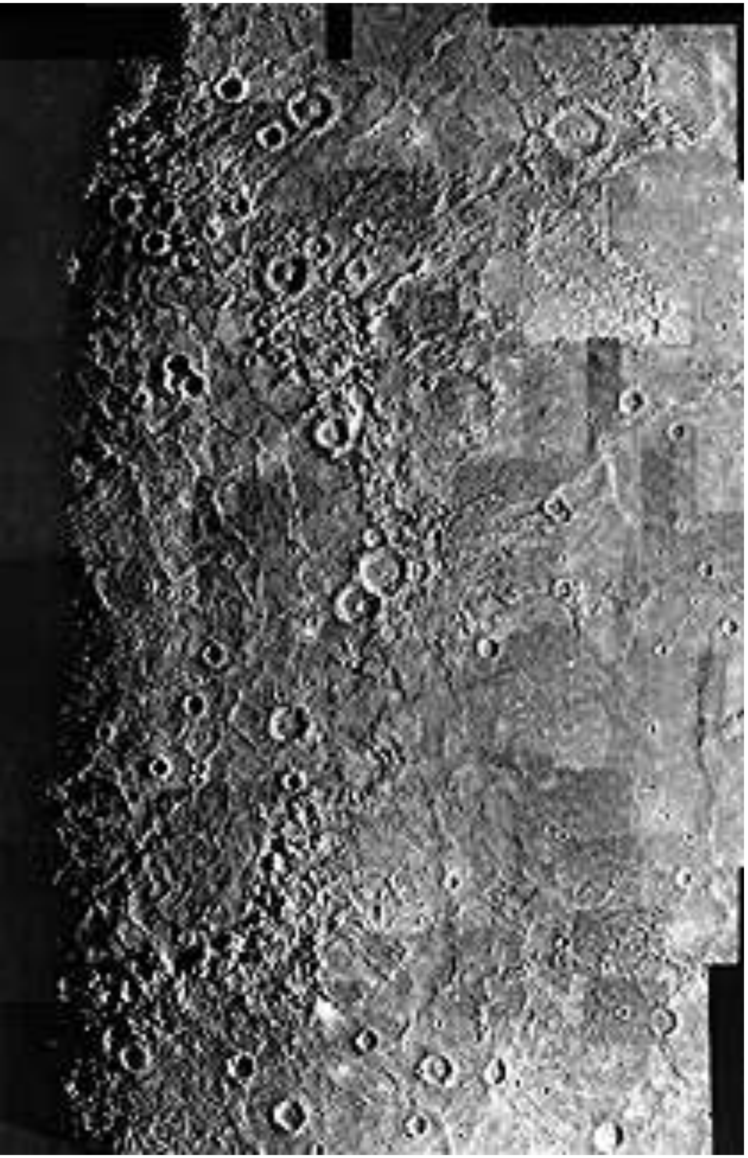
Mercurio – Mariner (1974)



Terreno caótico en las antípodas de Caloris



Focusing in the antipode



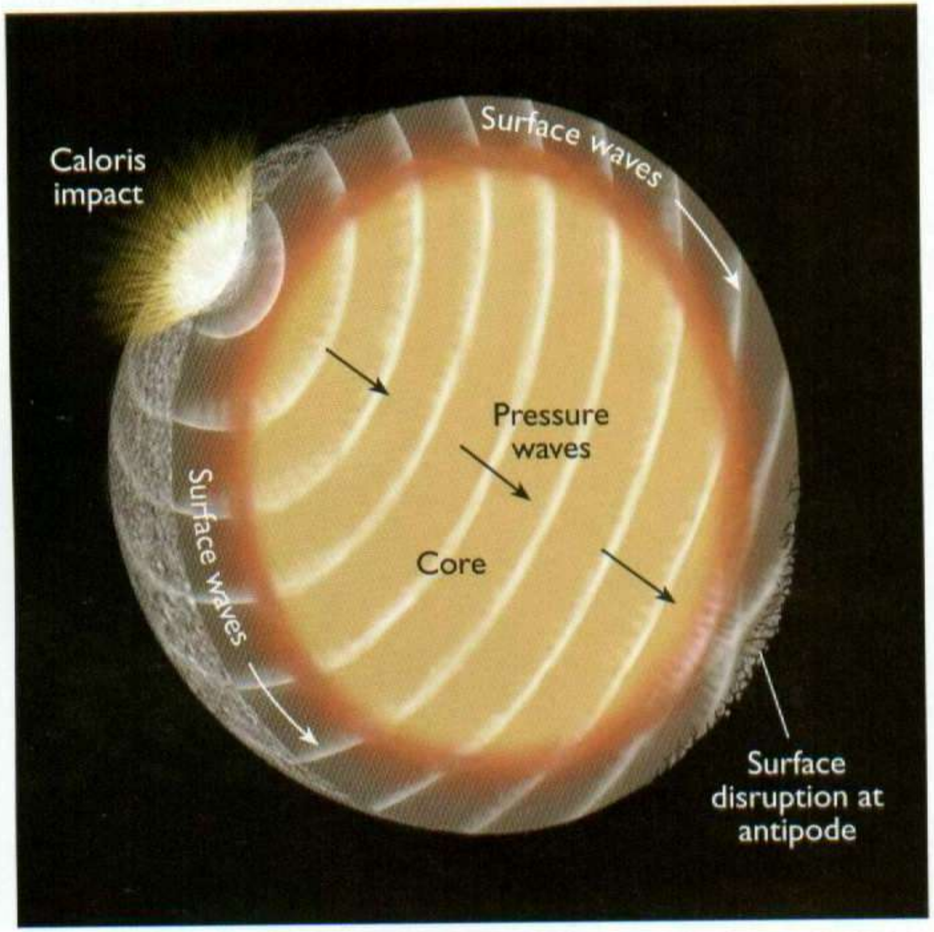
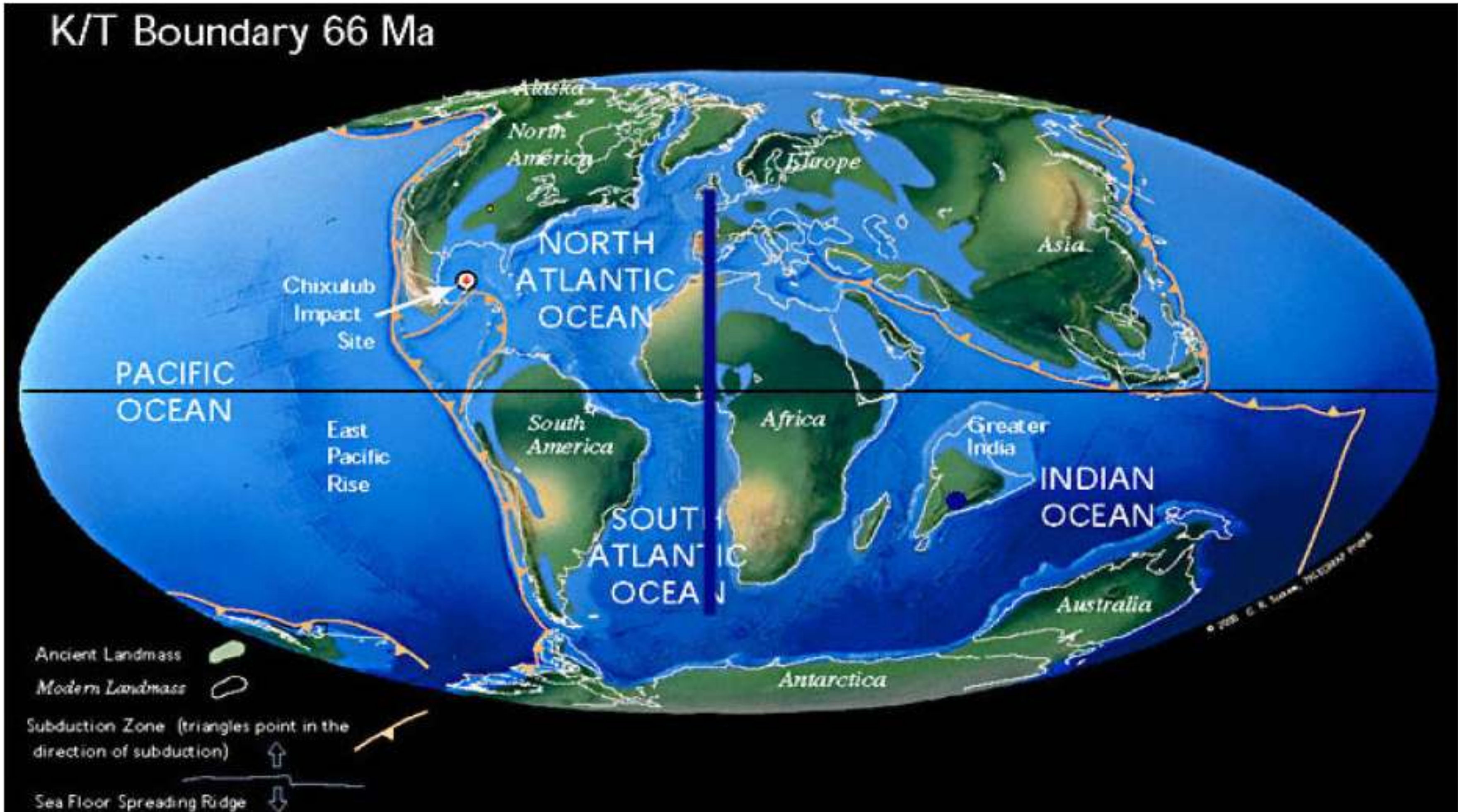
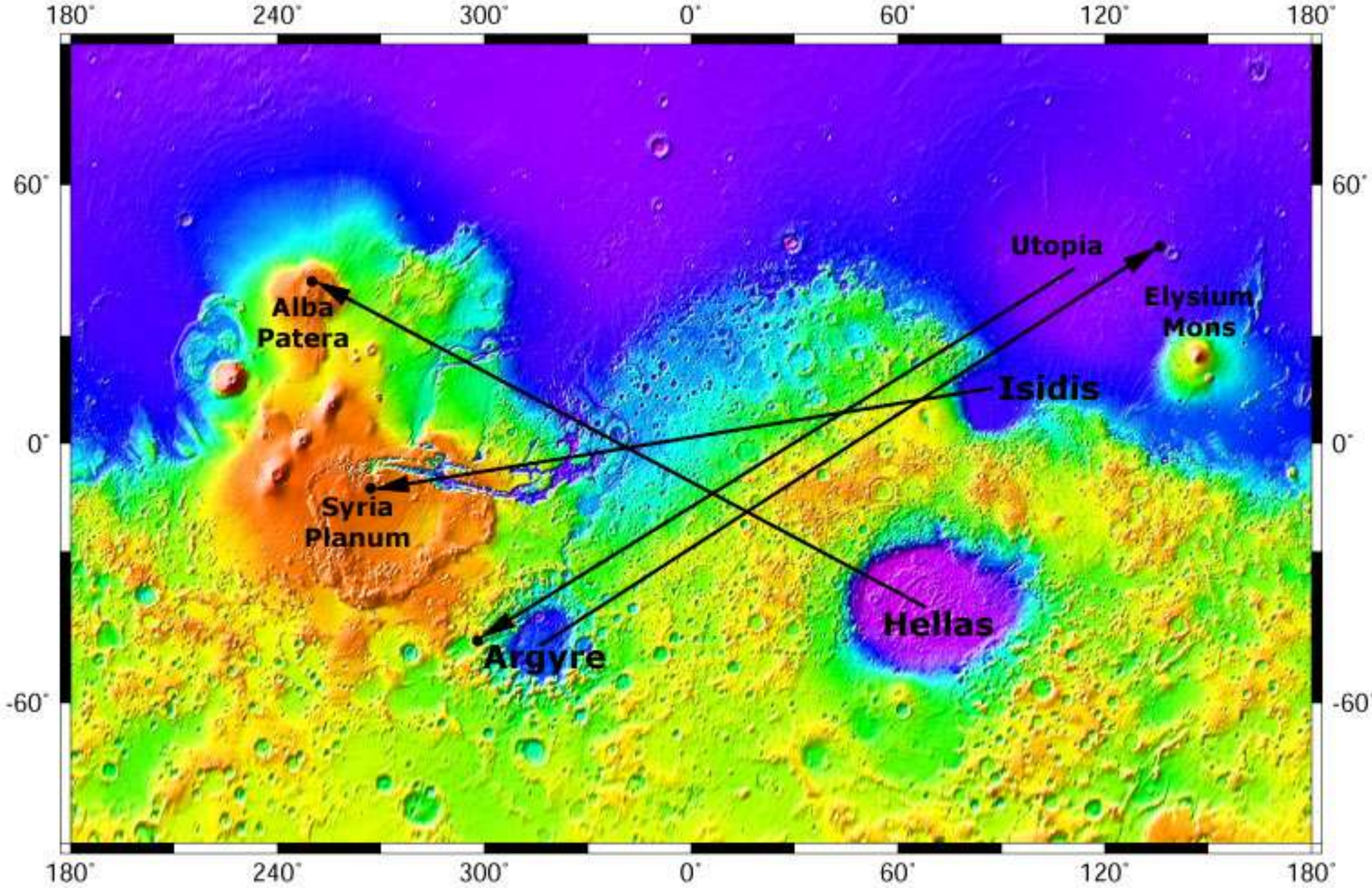


Figure 11. The gigantic impact that created Caloris basin 3.85 billion years ago sent intense seismic waves around and throughout the planet. These came to a focus at the antipodal point, where the ground shook and heaved violently.

The Chixulub crater & the Deccan traps

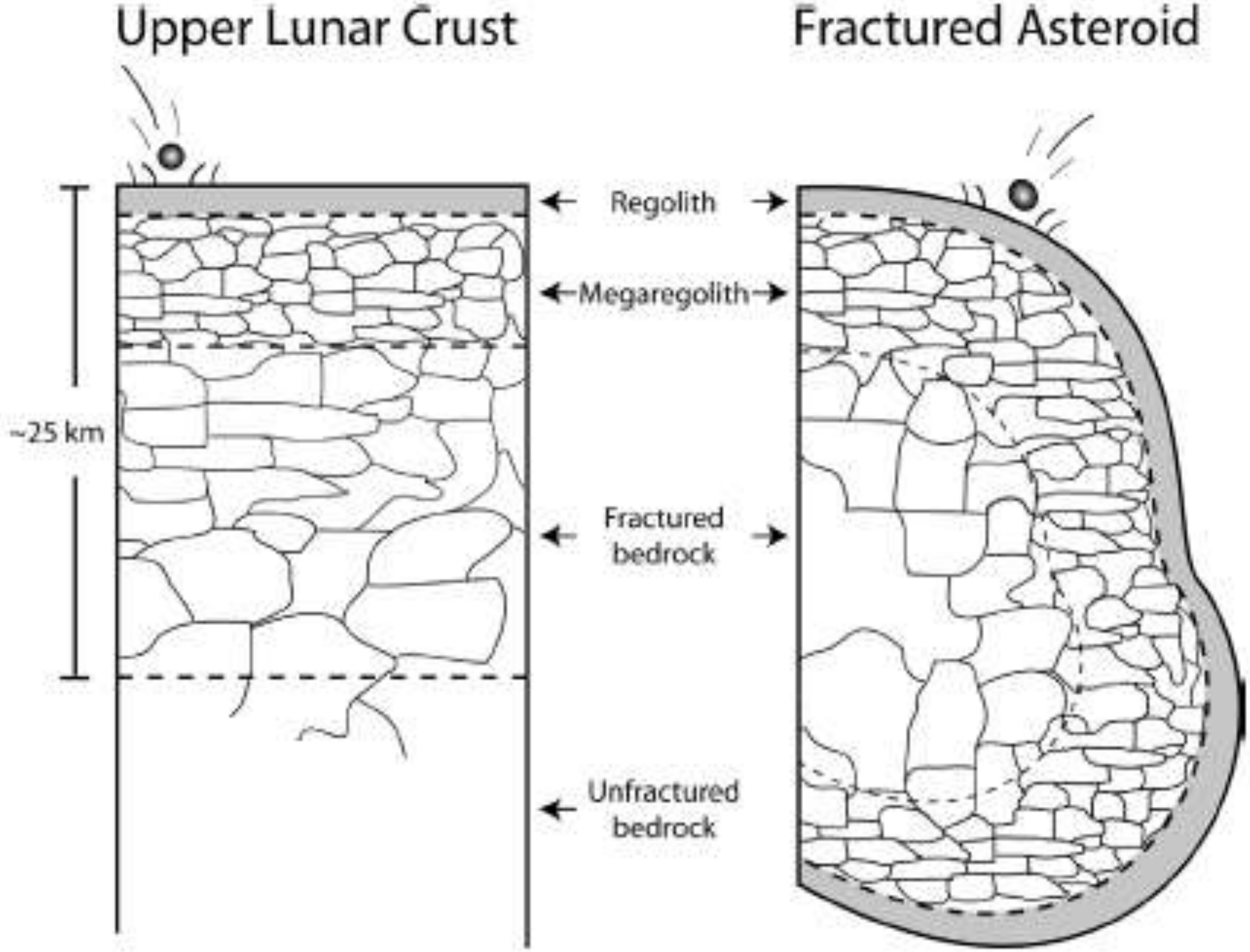


Topographic map of Mars



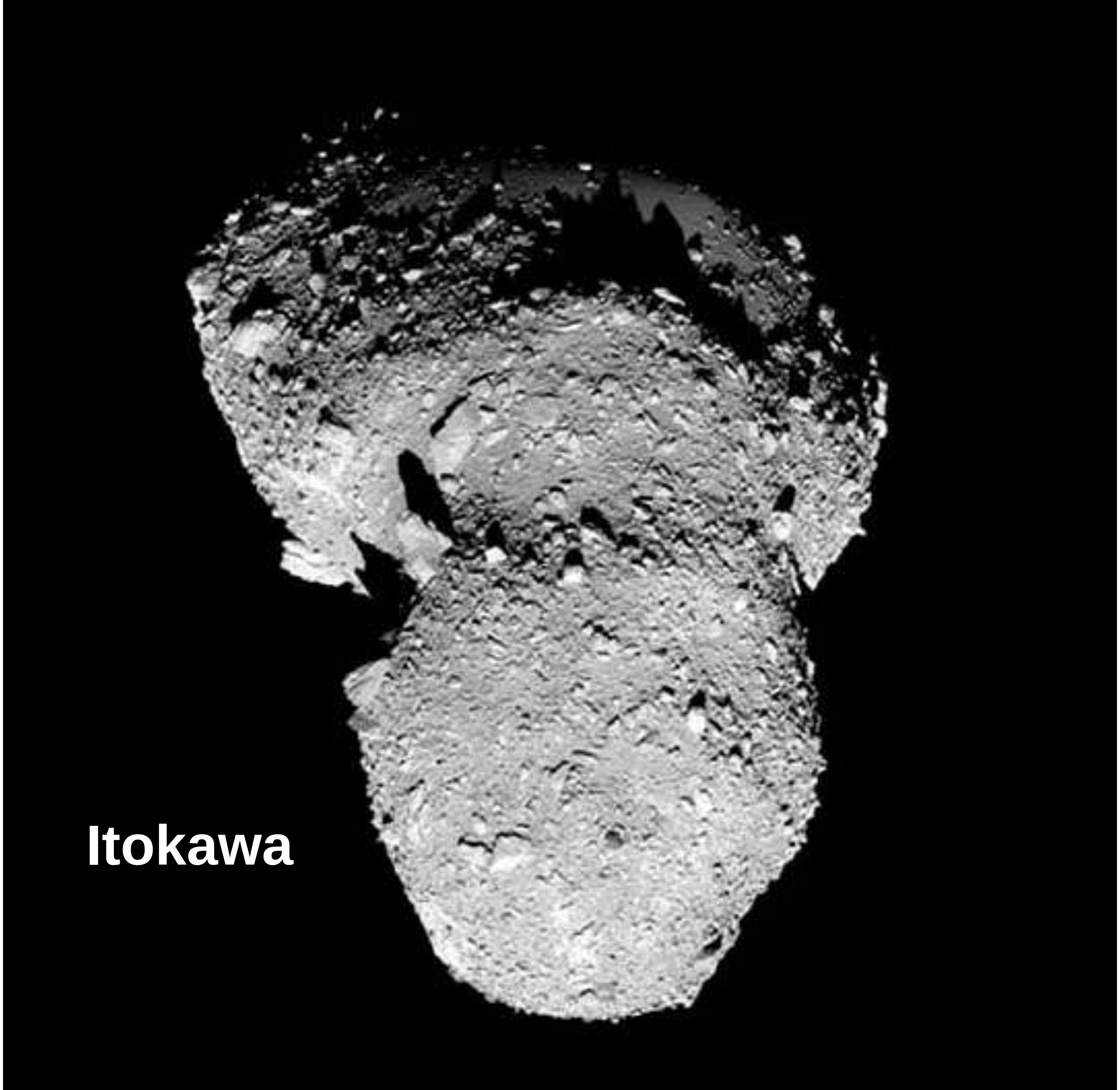
The elevational topography of Mars as recorded by NASA's Mars Orbital Laser Altimeter (MOLA). Elevations are shown in color, with yellow being defined as the mean elevation of Mars.

A little bit of impact seismology



Richardson et al. (2005)

Eros (NEAR - ’00)


Itokawa

Asteroid structures

Cratering laws

Pi-scaling or dimensional analysis

$$\text{Crater size} = f\ [\ \{\text{impactor prop}\},\ \{\text{target prop}\},\ \{\text{env. prop.}\}\ ]$$

$$\boldsymbol{V = f\ [\ \{ a, U, \delta \},\ \{ \rho,\ Y \},\ g\ ]}$$

V – Volume of the crater
a – Radius of the projectile
U – Impact speed
$\boldsymbol{\delta}$ – Projectile density
$\boldsymbol{\rho}$ – Target density
Y – Target strength
g – surface gravity

7 parameters but 3 dimensions (mass, length, time)

→ **There must be a simpler relations among 7-3=4 dimensionless groups**

For example:

$$\frac{\rho V}{m} = \bar{f}\left[\frac{ga}{U^2}, \frac{Y}{\rho U^2}, \frac{\rho}{\delta}\right]$$

where: $$m = \frac{4\pi}{3}\delta a^3$$

$$\pi_V = \frac{\rho V}{m}$$

Crater efficiency
ratio of crater mass to mass of the projectile

$$\pi_2 = \frac{ga}{U^2}$$

Ratio of the lithostatic pressure ρga at a caracteristhic depth equal to one projectile radius to the initial dynamic pressure ρU^2 generated by the impactor

$$\pi_3 = \frac{Y}{\rho U^2}$$

Ratio of the crustal material strength to the initial dynamic pressure

Point-source approximation
(Holsapple 1993)

- The coupling of the impactor energy and momentum into the target material occurs over a region whose size is the same order as the impactor size.
- The final crater size is generally many times larger than the impactor.

- **To a good approximation, the impact occurs as a point source.**
- **Craters similar to underground explosions**

- Theoretical analyses of cratering mechanics show that
  - the rate at which the crater grows
  - its time of formation
  - the velocity of ejected material
  - and other characteristics

  are dependent on a single point-source measure (a “coupling parameter”) :

$$C = a\, U^{\mu}\, \delta^{\nu} \qquad \begin{cases} C = a\, U^{2/3}\, \delta^{1/3} & \text{- energy dominates} \\ C = a\, U^{1/3}\, \delta^{1/3} & \text{- momentum dominates} \end{cases}$$

Simple scaling model

Crater size $= f$ [{impactor prop}, {target prop}, {env. prop.}]

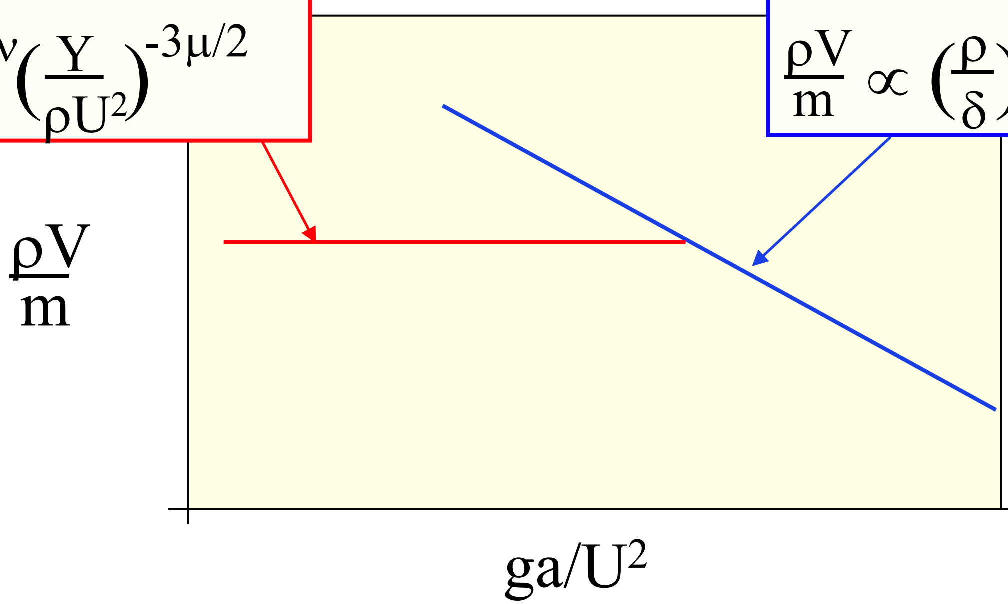
$$V = f\,[\; aU^{\mu}\delta^{\nu}, \quad \rho,\; Y, \quad g \;]$$

Strength-regime:

$$\frac{\rho V}{m} \propto \left(\frac{\rho}{\delta}\right)^{1-3\nu}\left(\frac{Y}{\rho U^2}\right)^{-3\mu/2}$$

Gravity-regime:

$$\frac{\rho V}{m} \propto \left(\frac{\rho}{\delta}\right)^{\frac{2+\mu-6\nu}{2+\mu}}\left(\frac{ga}{U^2}\right)^{-3\mu/(2+\mu)}$$



(from Housen 2003)

Pi-scaling or dimensional analysis

Strength Regime

$$\frac{\rho V}{m} = \bar{f}\left[\frac{Y}{\rho U^2}\right].$$

Gravity Regime

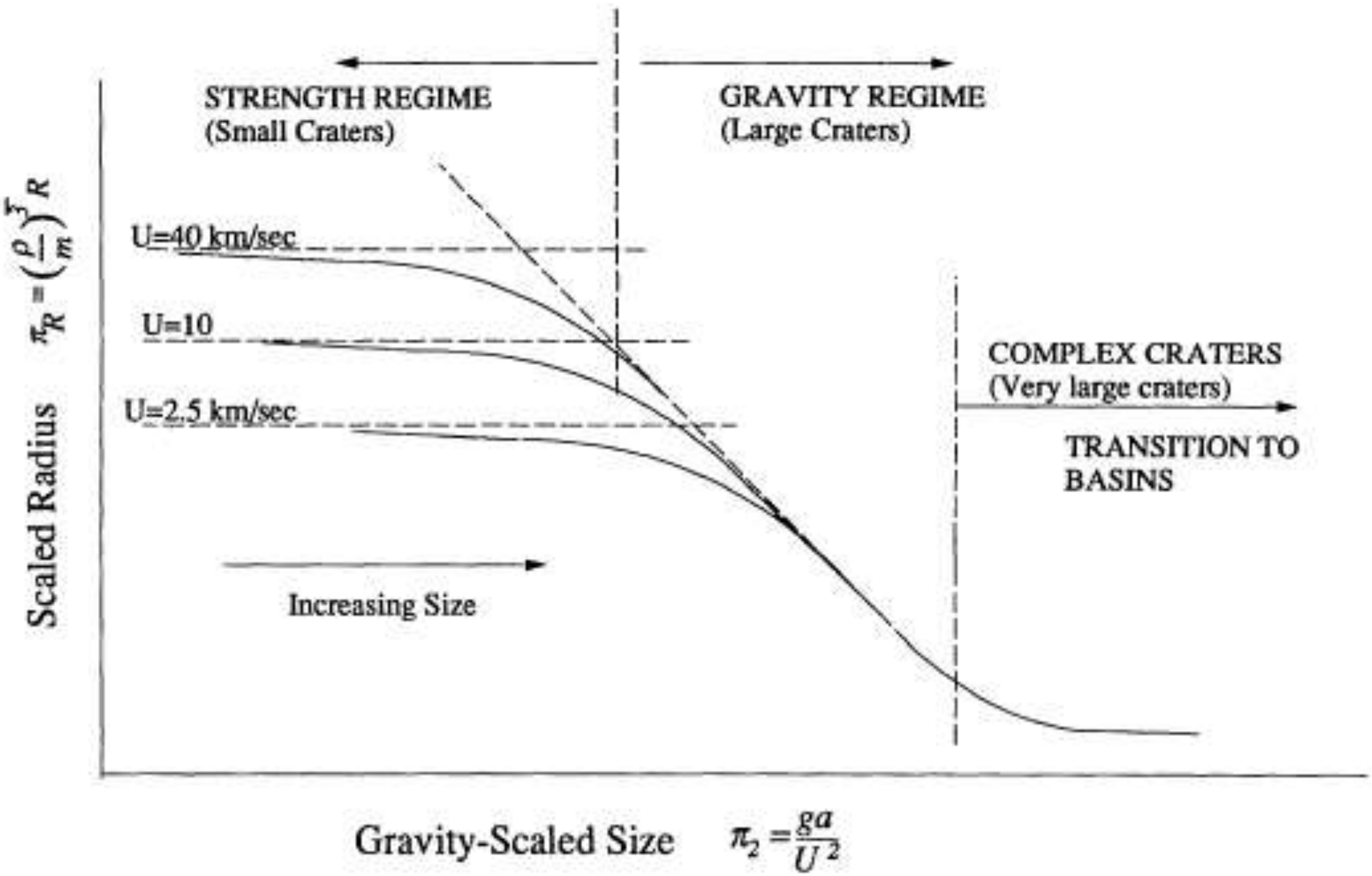
$$\frac{\rho V}{m} = \bar{f}\left[\frac{ga}{U^2}\right].$$

Cratering law

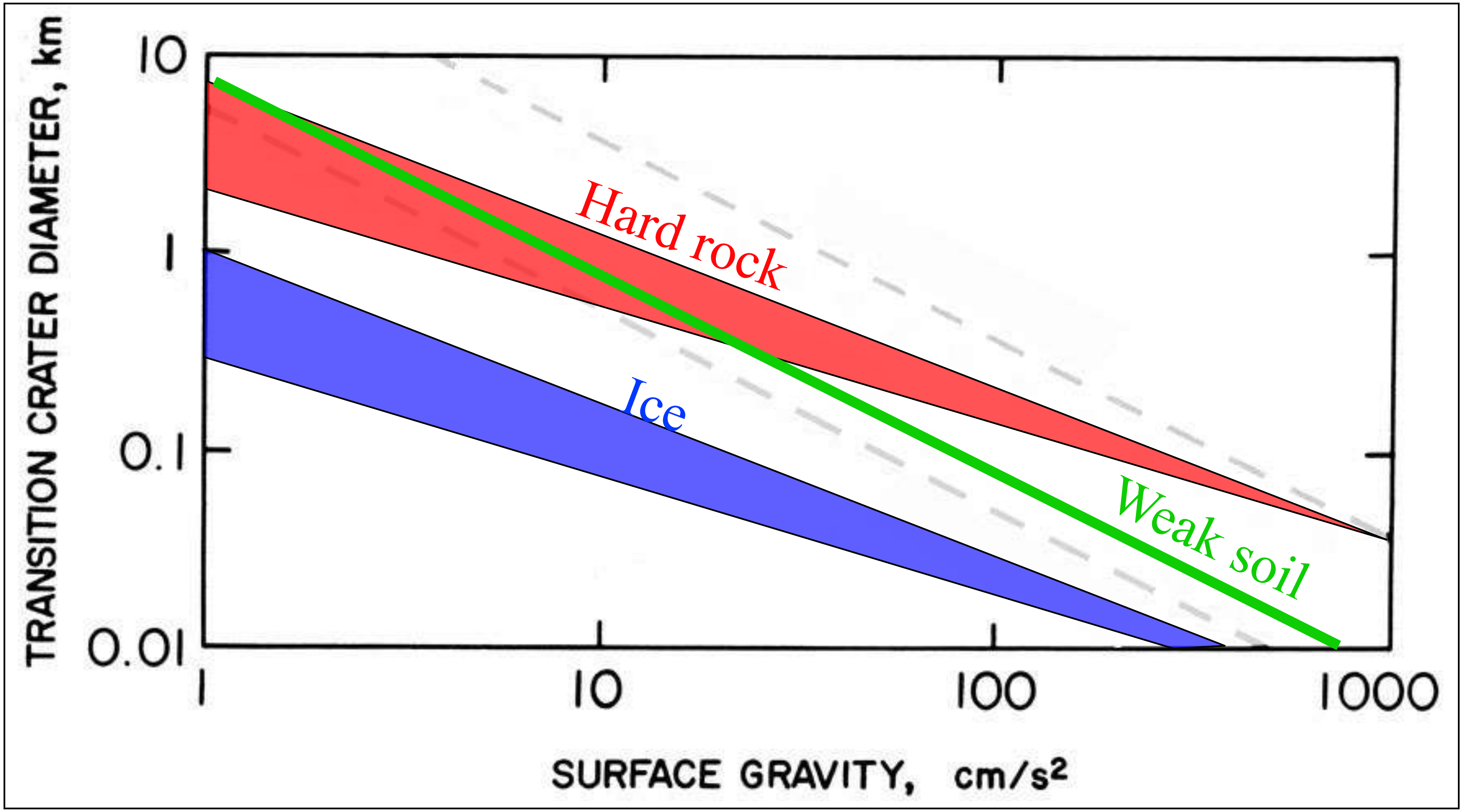
$$\pi_V = K_1 \left\{ \pi_2 \left(\frac{\rho}{\delta}\right)^{\frac{6\nu-2-\mu}{3\mu}} + K_2 \left[\pi_3 \left(\frac{\rho}{\delta}\right)^{\frac{6\nu-2}{3\mu}} \right]^{\frac{2+\mu}{2}} \right\}^{-\frac{3\mu}{2+\mu}}$$

$$\pi_V = \frac{\rho V}{m}, \quad \pi_2 = \frac{ga}{U^2}, \quad \pi_3 = \frac{Y}{\rho U^2}$$

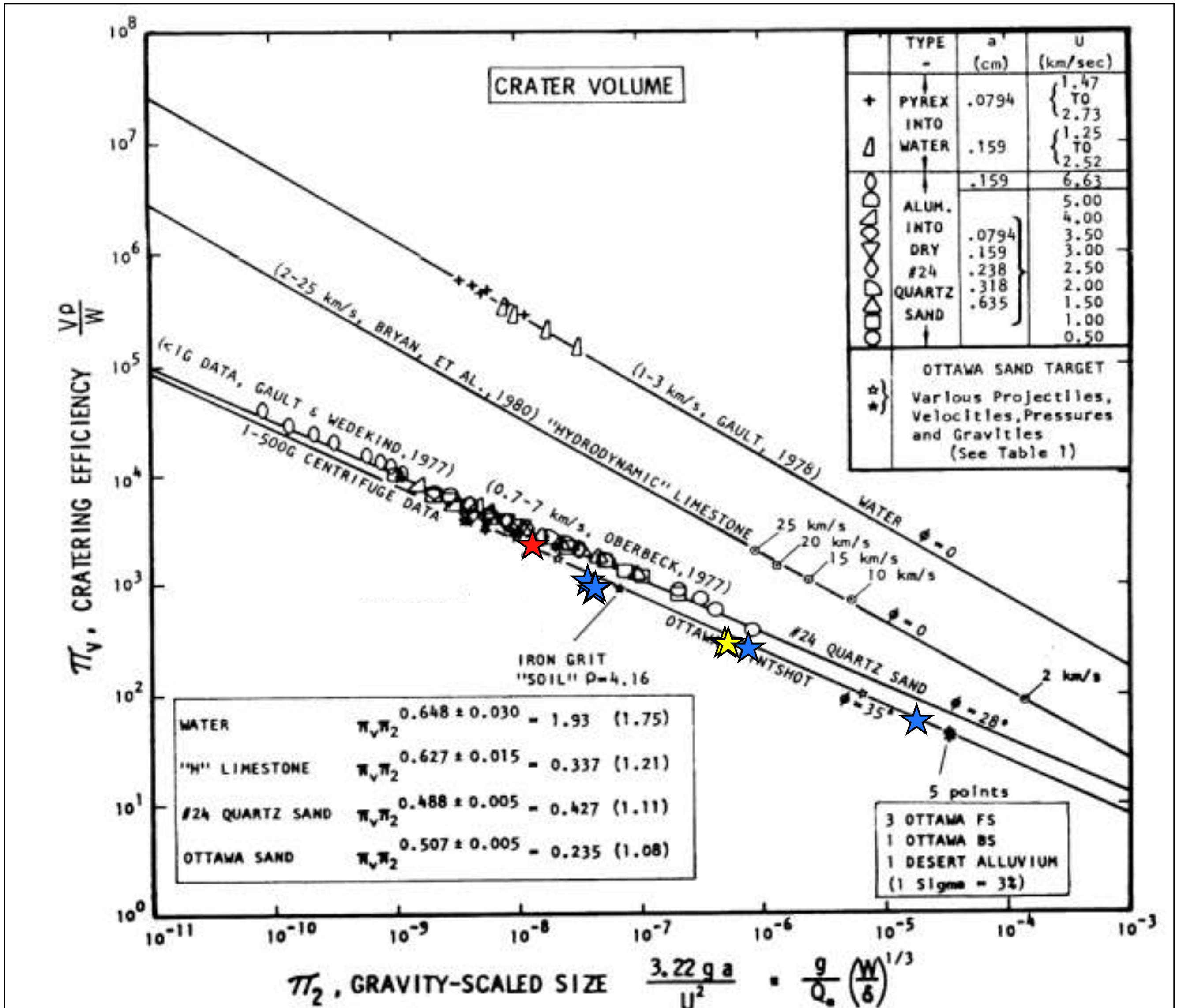
Impact Regimes



Strength-gravity transition



Impacts experiments (Schmidt, 1980)



- Al --> "Hevi-sand"
- Lead --> sand
- Tungsten Carb.

Material	**K₁**	**K₂**	μ	ν	Y (dynes/cm^2)	ρ (gm/cm^3)
Water	0.98	0	0.55	.33	0	1
Dry Sand	0.132	0	0.41	.33	0	1.7
Dry Soil	0.132	0.26	0.41	.33	2E6	1.7
Wet Soil	0.095	0.35	0.55	.33	5E6	2.1
Soft Rock (Hard Soil)	0.095	0.215	0.55	.33	1E7	2.1
Hard Rock	0.095	0.257	0.55	.33	1E8	3.2
Lunar Regolith	0.132	0.26	0.41	.33	1E5	1.5
Cold Ice	0.095	0.351	0.55	.33	1.5E5	0.93

Impactor type	**Mass density** δ
Aluminum	2.7
Plastic	0.95
Steel	7.8
C-Type	1.8
S-Type	3.0
Comet	0.8

Crater size R (Holsapple & Housen 2007)

General form with point source impactor measure $aU^{\mu}\delta^{\nu}$	$\frac{R}{a} = K_1\left[\frac{ga}{U^2}\left(\frac{\rho}{\delta}\right)^{\frac{2\nu}{\mu}} + \left(\frac{\bar{Y}}{\rho U^2}\right)^{\frac{2+\mu}{2}}\left(\frac{\rho}{\delta}\right)^{\frac{\nu(2+\mu)}{\mu}}\right]^{-\frac{\mu}{2+\mu}}$
Sand or cohesive soil, $\mu = 0.41$, $\nu = 0.4$ (gravity or strength)	$\frac{R}{a} = 1.03\left(\frac{ga}{U^2}\right)^{-0.170}\left(\frac{\delta}{\rho}\right)^{0.332}$ (gravity) $\frac{R}{a} = 1.03\left(\frac{\bar{Y}}{\rho U^2}\right)^{-0.205}\left(\frac{\delta}{\rho}\right)^{0.40}$ (strength)
Wet soils and rock, $\mu = 0.55$, $\nu = 0.4$ (strength)	$\frac{R}{a} = 0.93\left(\frac{\bar{Y}}{\rho U^2}\right)^{-0.275}\left(\frac{\delta}{\rho}\right)^{0.40}$ (strength)
Water, $\mu = 0.55$, $\nu = 0.4$ (gravity)	$\frac{R}{a} = 1.17\left(\frac{ga}{U^2}\right)^{-0.22}\left(\frac{\delta}{\rho}\right)^{0.31}$ (gravity)
Highly porous scaling, $\mu = 0.40$, $\nu = 0.4$ (strength)	$\frac{R}{a} = 0.725\left(\frac{\bar{Y}}{\rho U^2}\right)^{-0.20}\left(\frac{\delta}{\rho}\right)^{0.40}$ ($\bar{Y} = 1$ kPa)

Radius of transient crater

$$R = K_r V^{1/3}$$

depth

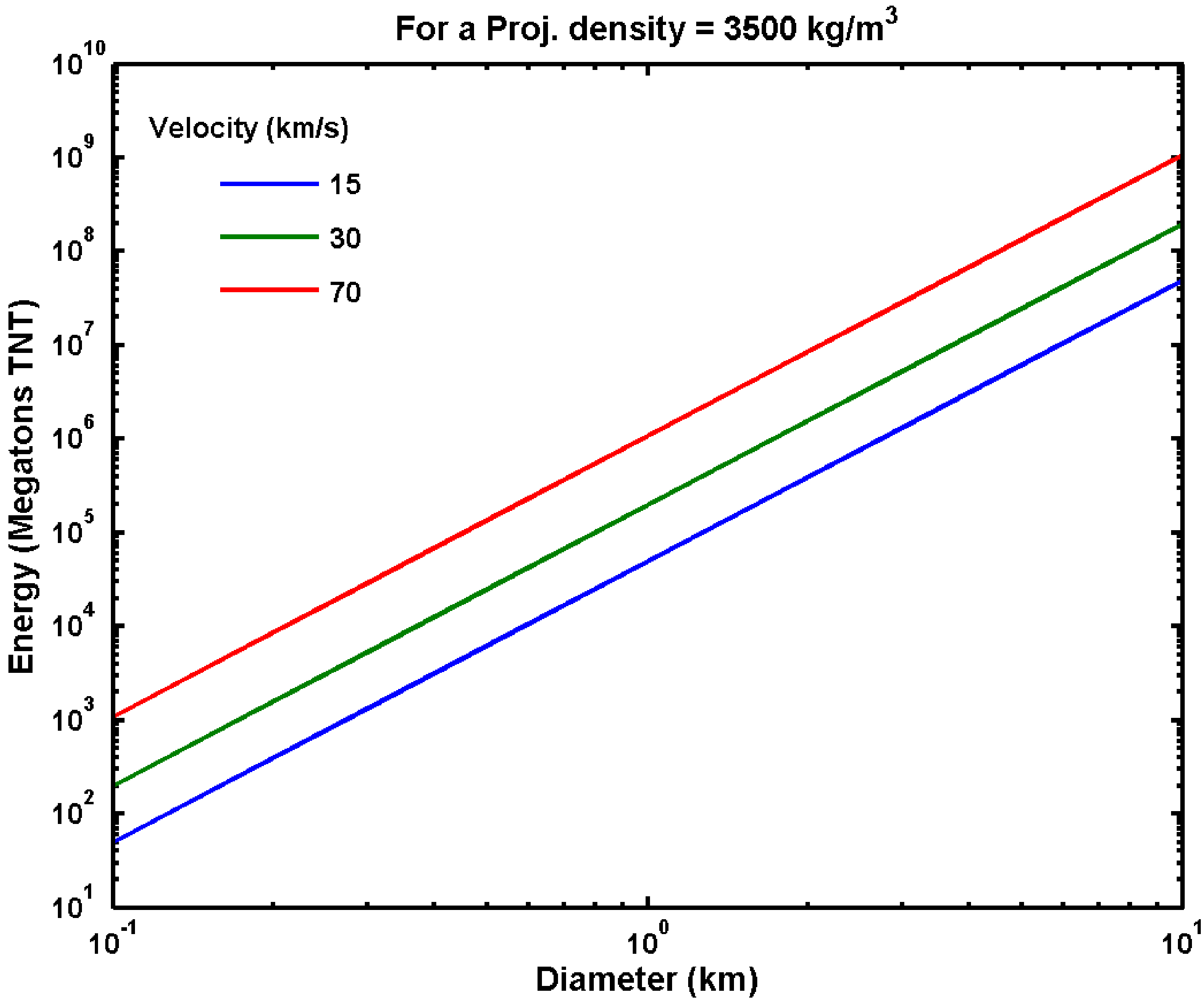
$$d = \text{depth} = K_d V^{1/3}$$

Material	K_r	K_d
Water	0.8	0.75
Dry Sand	1.4	0.35
Dry Soils (some cohesion)	1.1	0.6
Soft Rock	1.1	0.6
Cold Ice	1.1	0.6

$$R_{final} = 1.3\ R$$

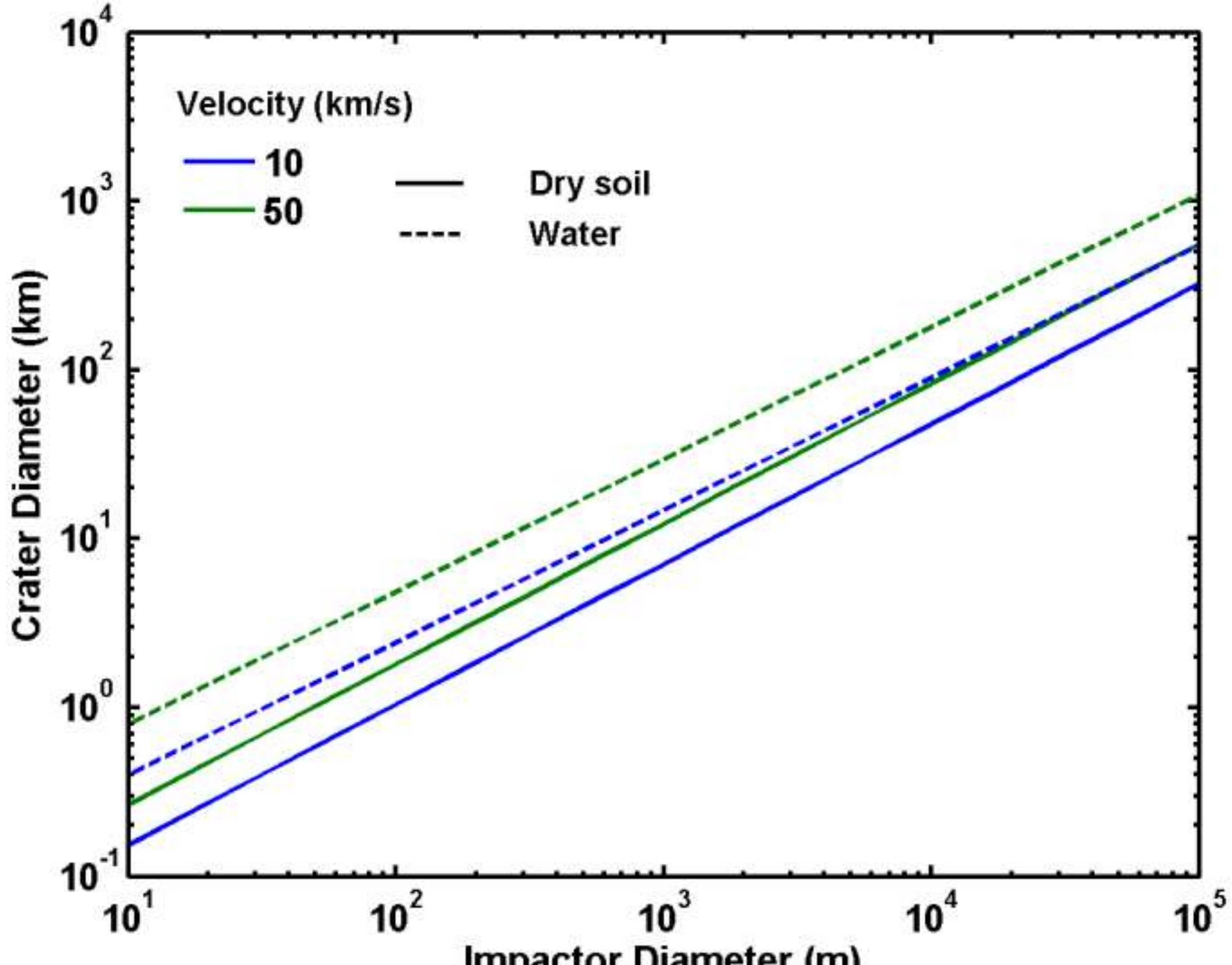
$$d/D_{final} \sim 0.2 \quad \text{for simple craters}$$

Impact Energy

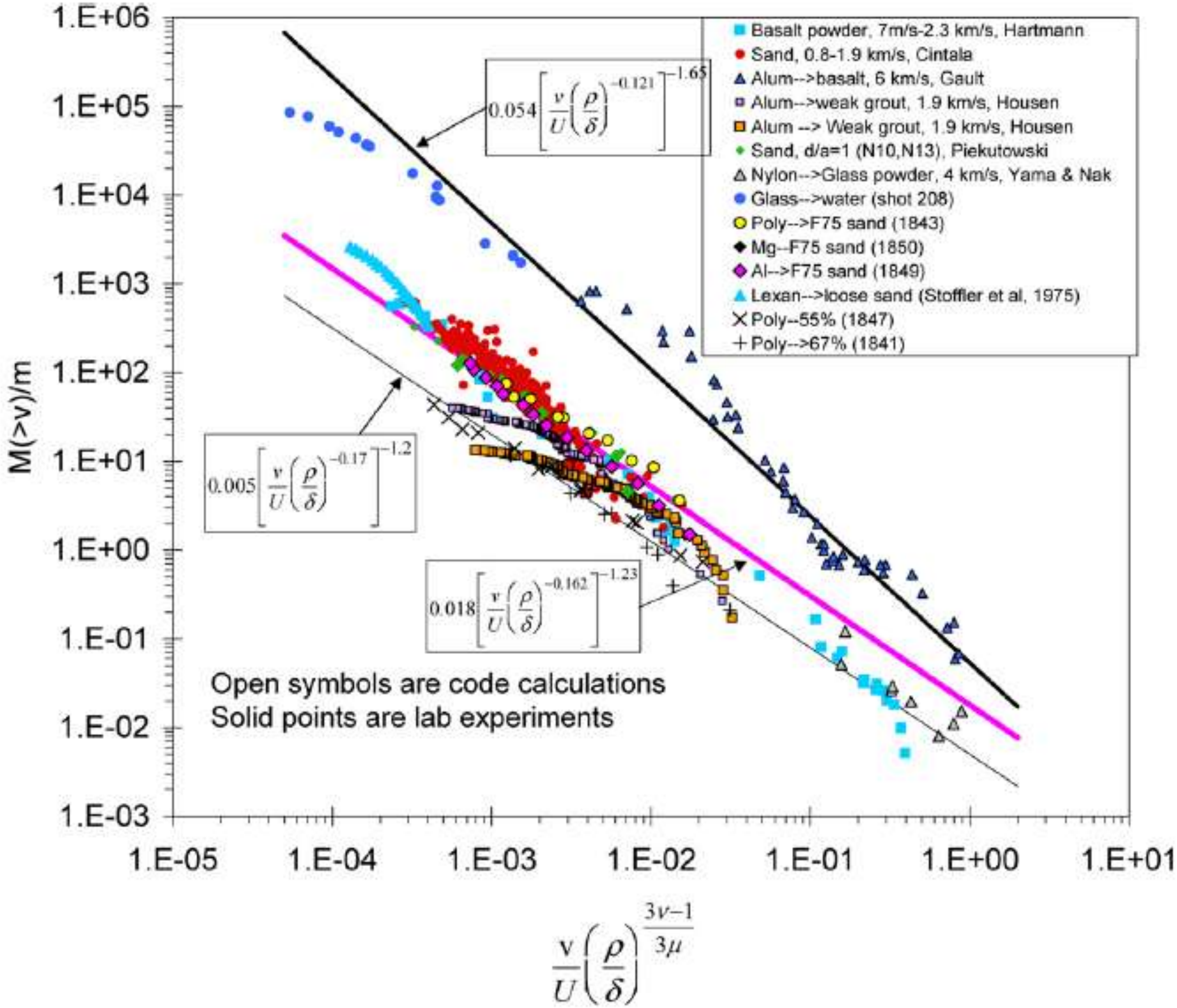


Crater diameter

Impact on Earth for a projectile density of 3500 kg/m³



Ejection velocities



Mass of material ejected at velocities greater than *V* (Holsappple & Housen 2007)

Fragmentation and Disruption by impact

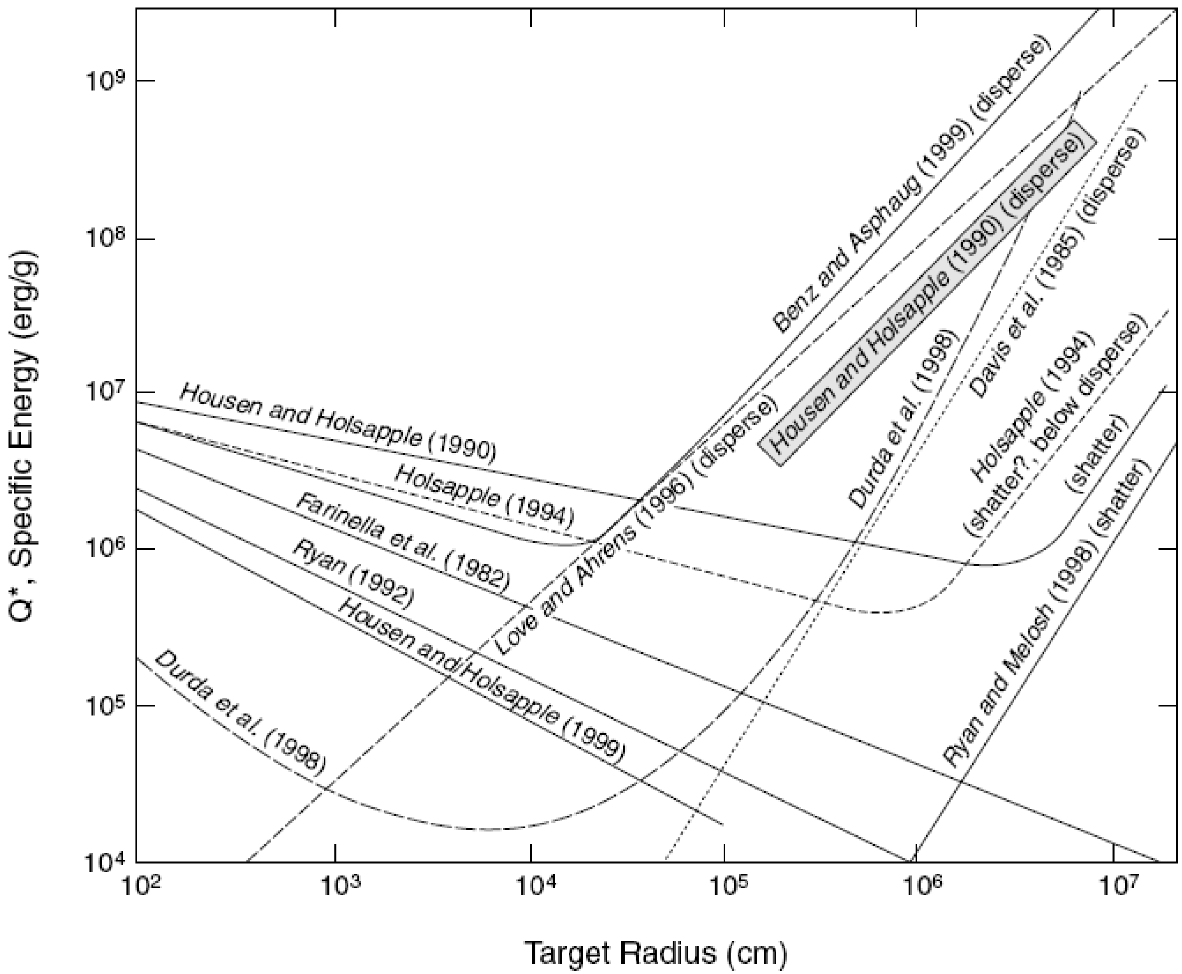
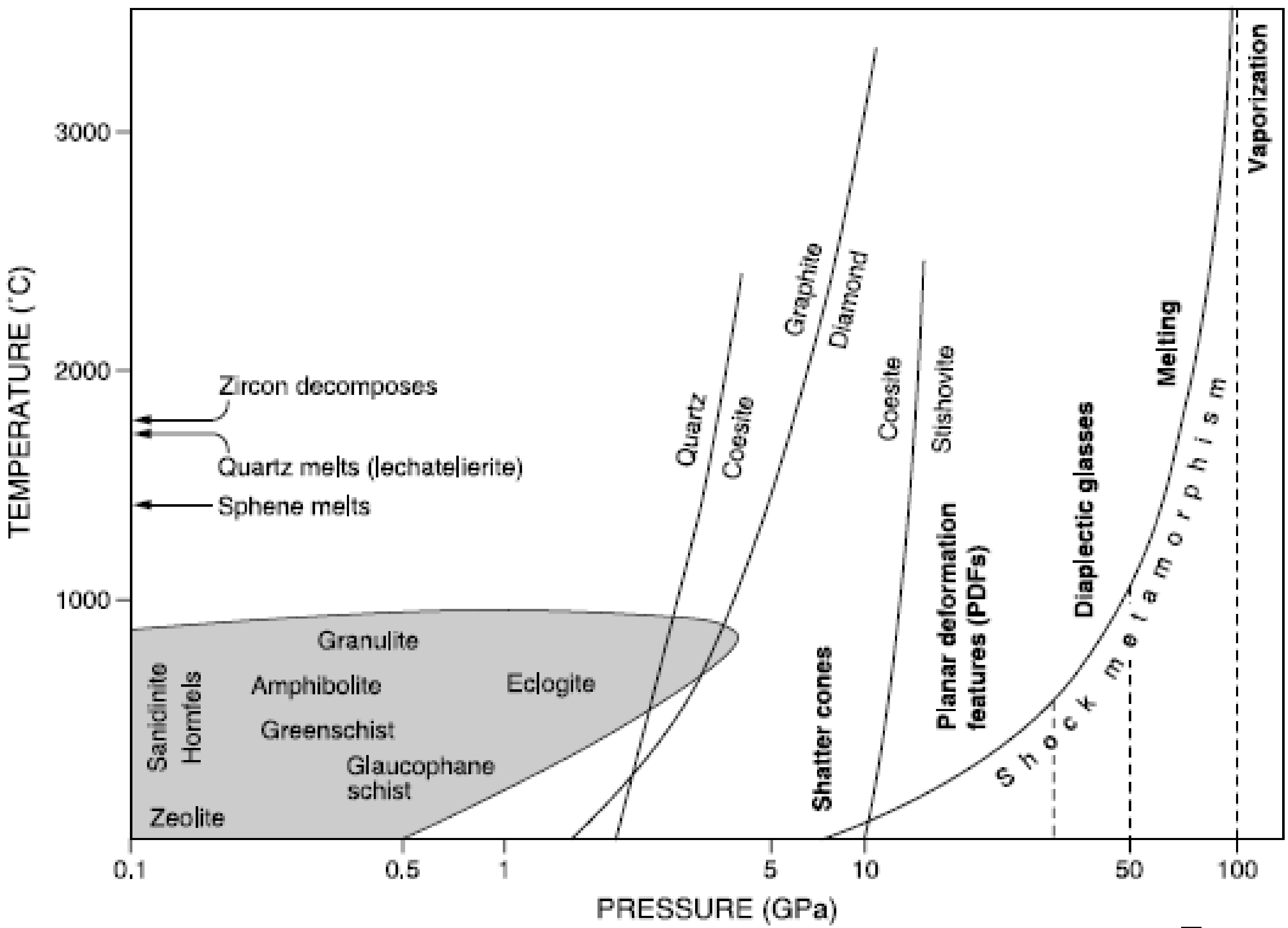


Fig. 6. Specific energy thresholds, some for shattering and some for dispersion, as presented by various authors. For small asteroids (on the left) the specific energy decreases with increasing target size because of a decreasing asteroid effective strength with size. For large asteroids (on the right), the energy increases with increasing target size because of the increasing role of self-gravitation. Note that these results are for rocky bodies only, and not for porous bodies.

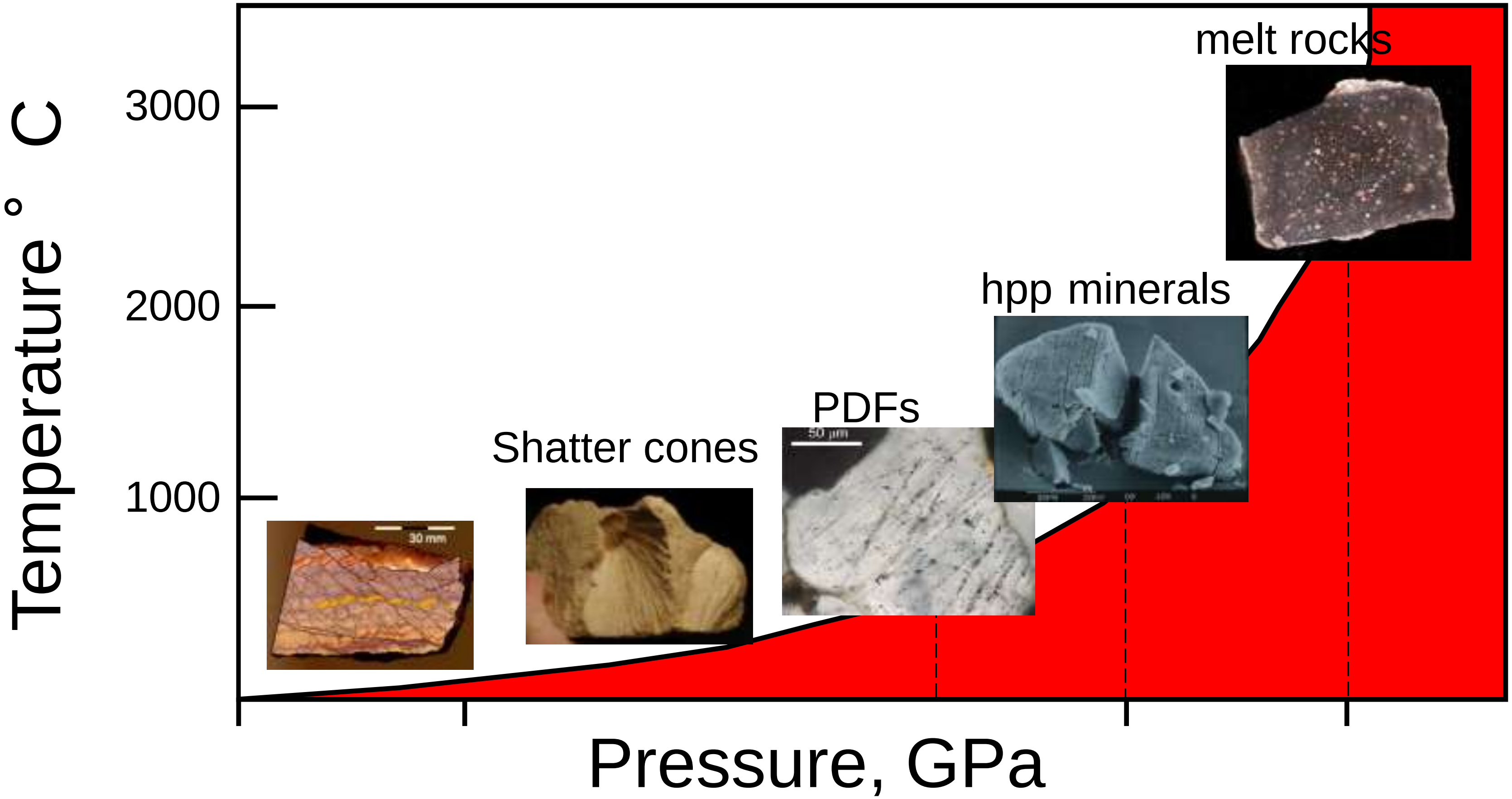
Shock metamorphism

Impact metamorphism



French (1998)

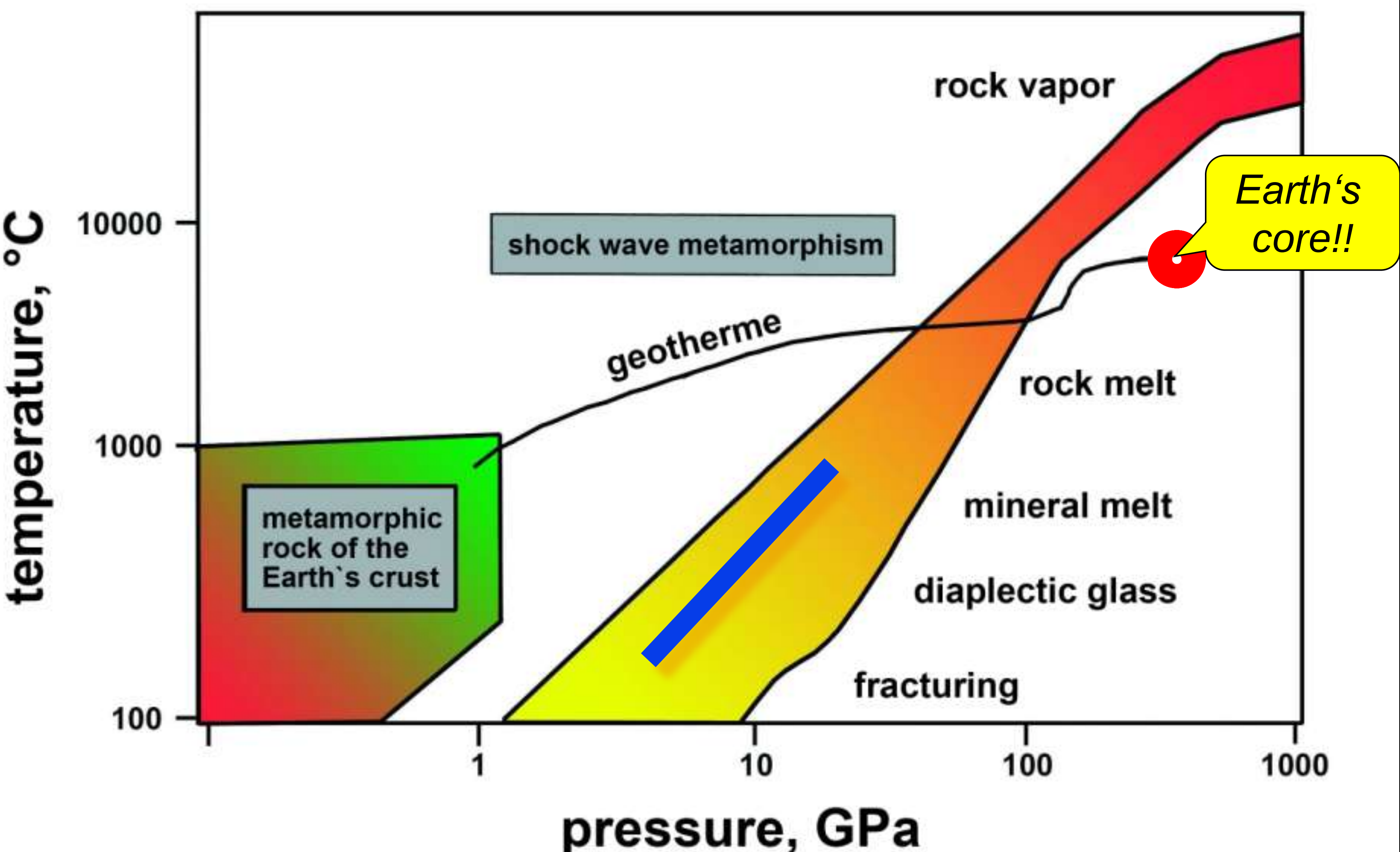
Shock barometry is well calibrated in experimental studies



Shock features in minerals/rocks tell us something about the thermodynamic conditions the material was exposed to

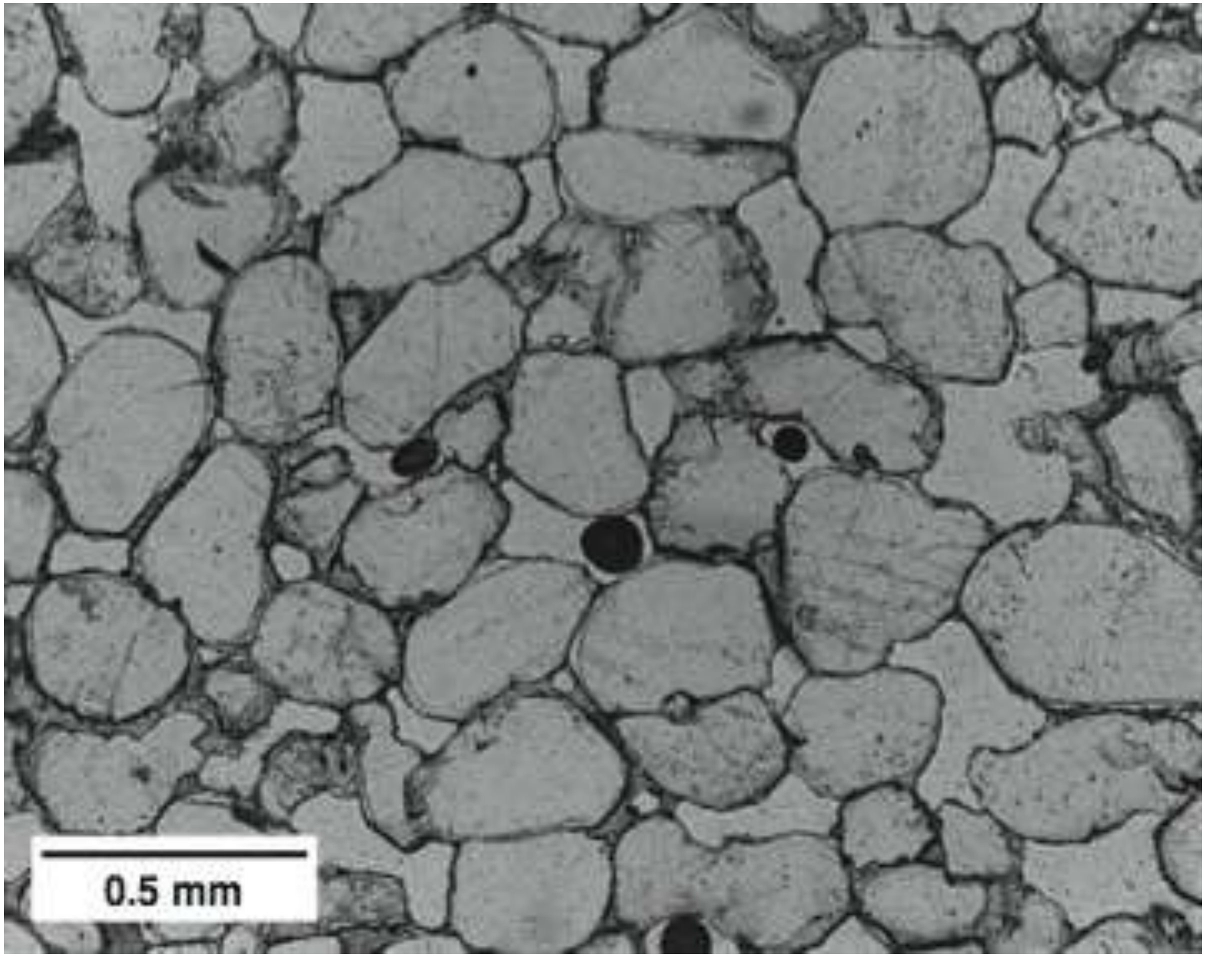
Shocks from impact cratering

Cover a field that goes beyond the reach of experiments

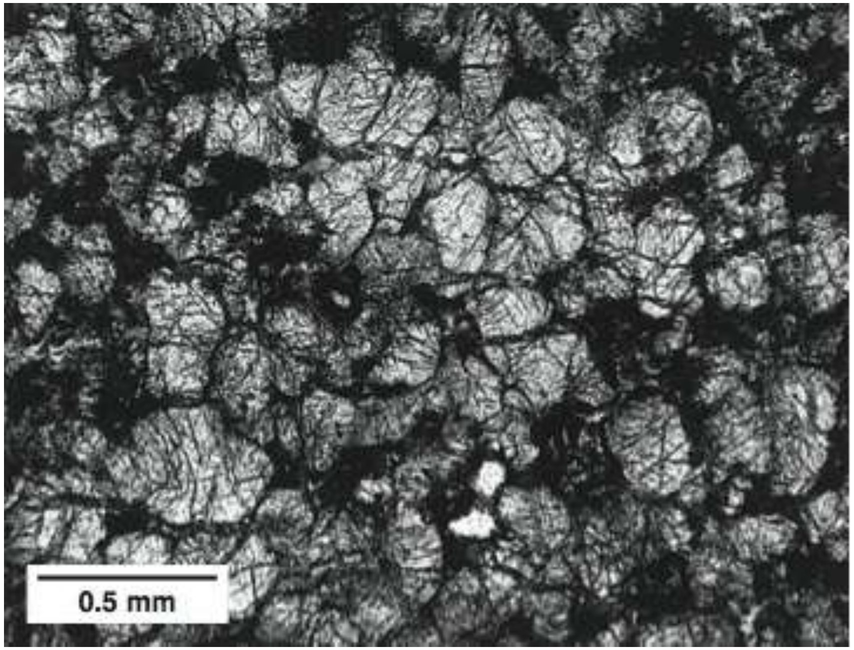


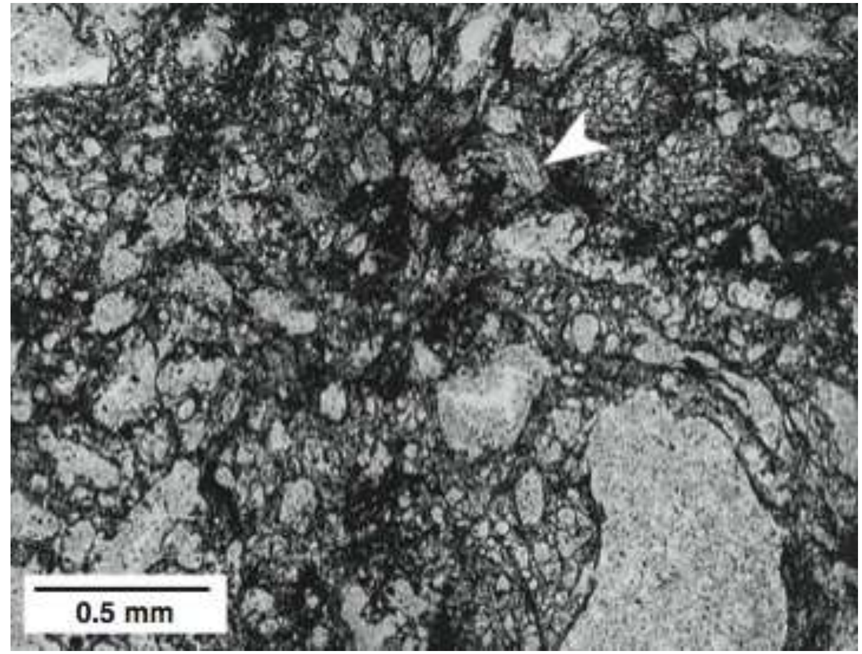
Shatter cones

Thanks to Bevan French, here is a sequence of changes that occurs in a quartz sandstone (Coconino from Meteor Crater) at progressively higher shock levels



Unshocked Coconino Sandstone





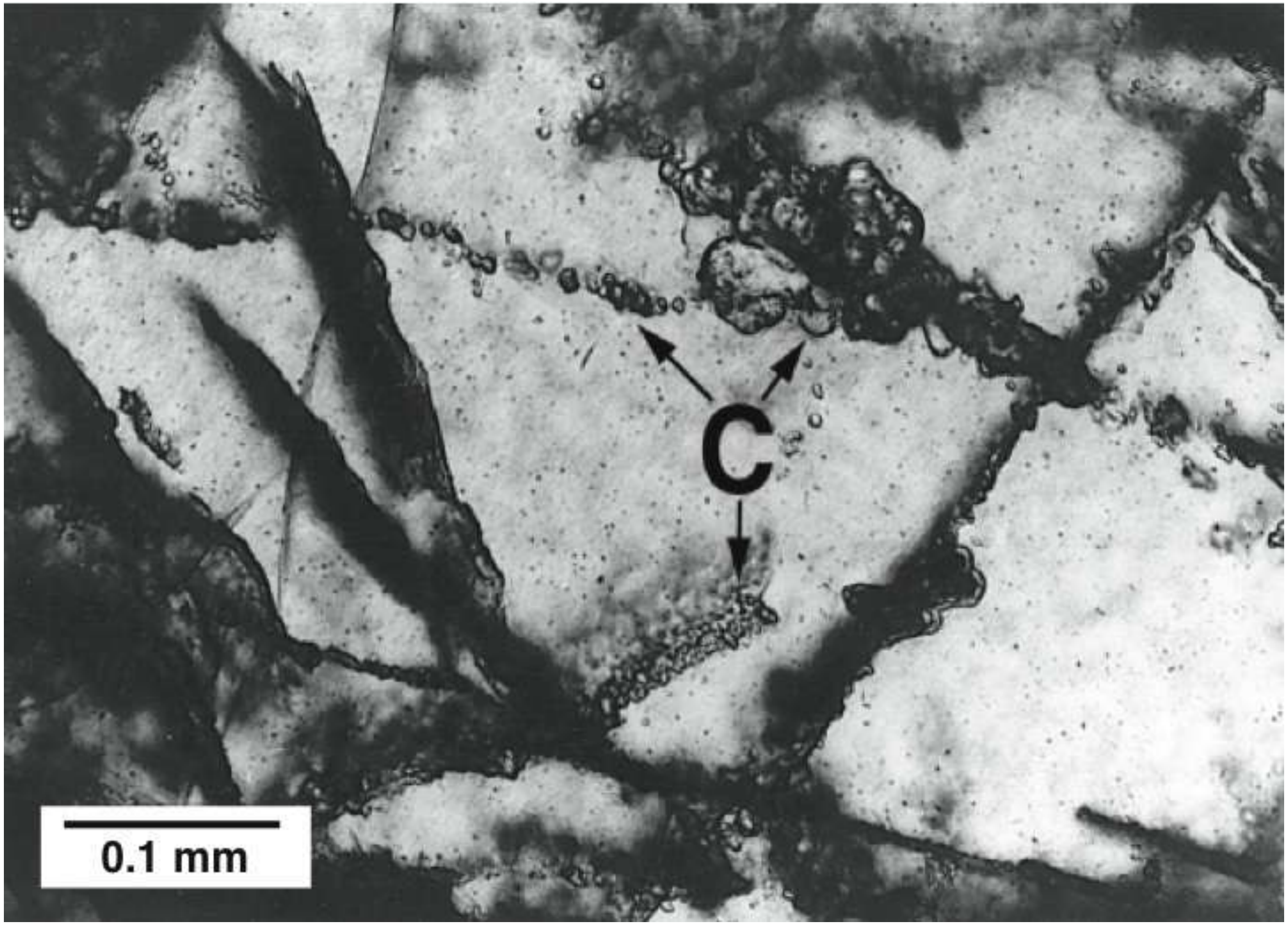
Moderately Shocked:

Pore space collapsed, heavily fractured, glassy blebs contain coesite

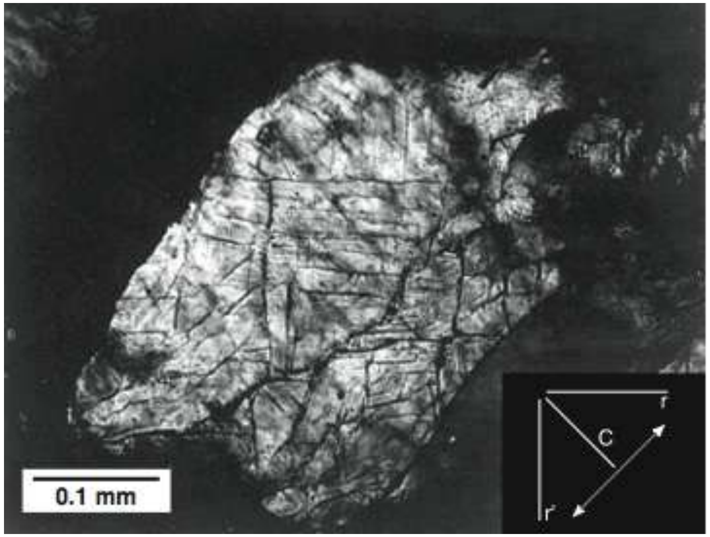
Highly Shocked:

Converted to a light, frothy glass (Lechatelierite) with few relict grains of quartz

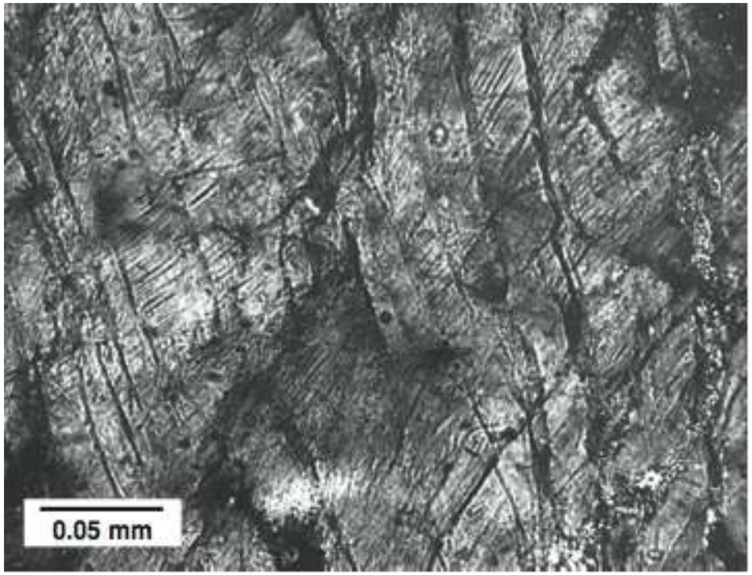
Quartz can form diaplectic glass which may contain small blebs of Coesite



In addition to phase transformations, Quartz especially shows a wide range of fracture features

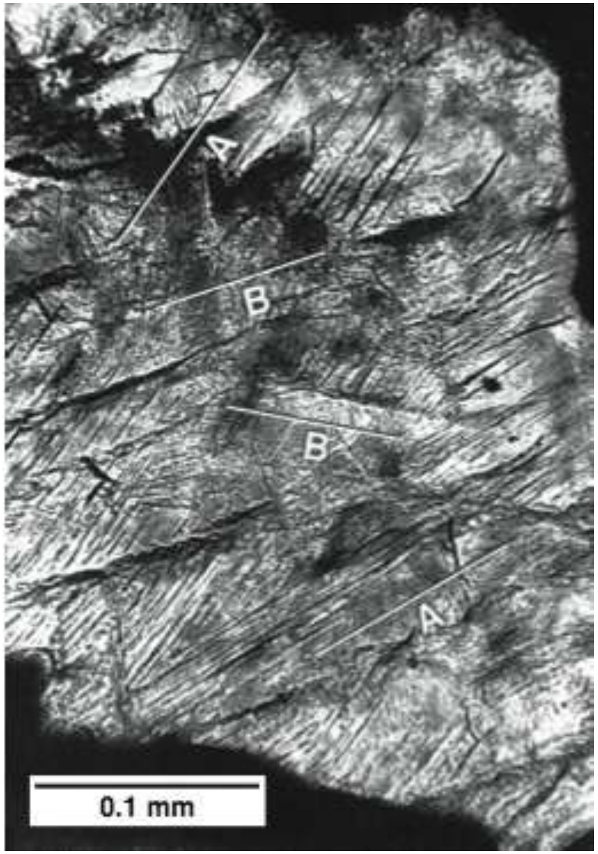


Cleavage in moderately shocked grain, Coconino SS

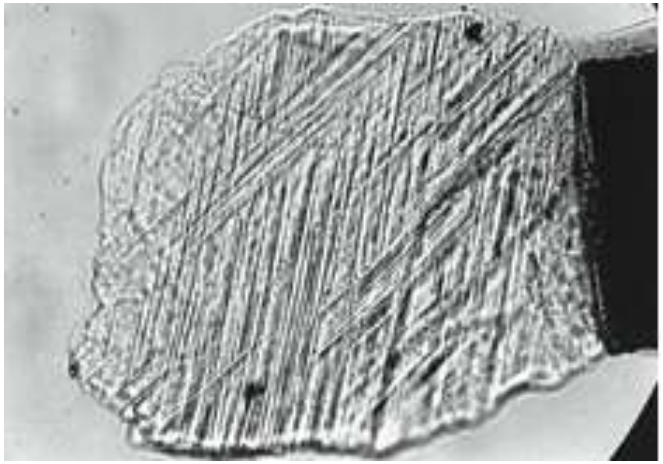


Cleavage plus Planar Deformation Features (PDFs) in more highly shocked Coconino SS

Classic sets of Multiple Planar Deformation Features in quartz. These are fresh, undecorated PDFs



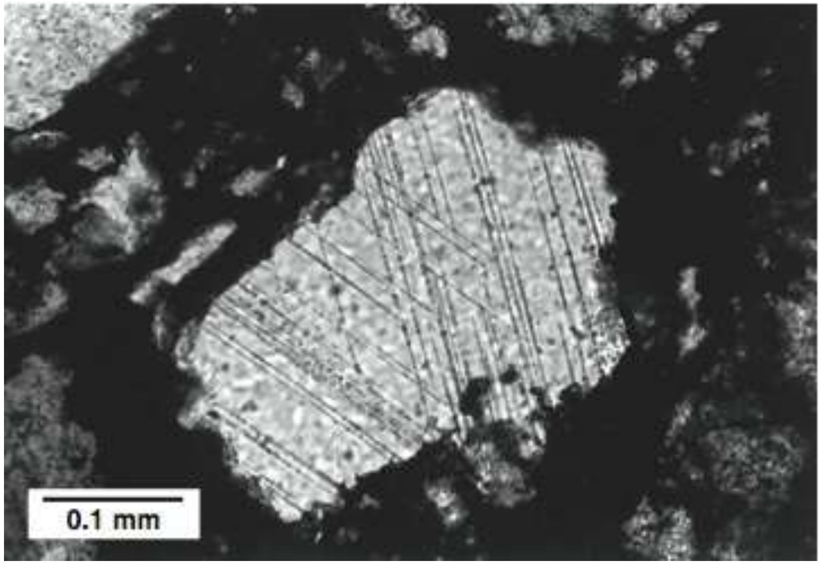
Ries Crater, Germany



K/T Chicxulub ejecta, Starkville South, Colorado.

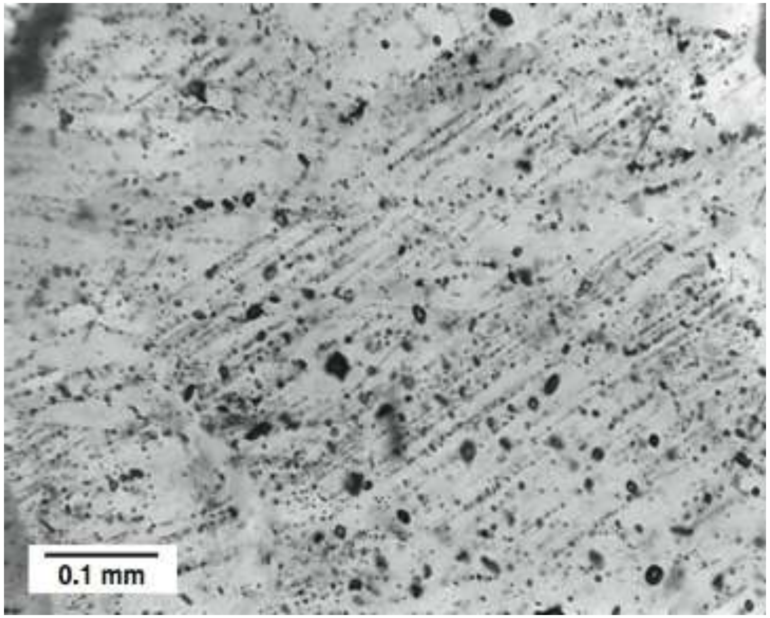
0.20 mm long

In more altered rocks, the PDFs may be replaced by lines of tiny fluid inclusions "decorating" the original fracture planes



Gardnos Crater, Norway

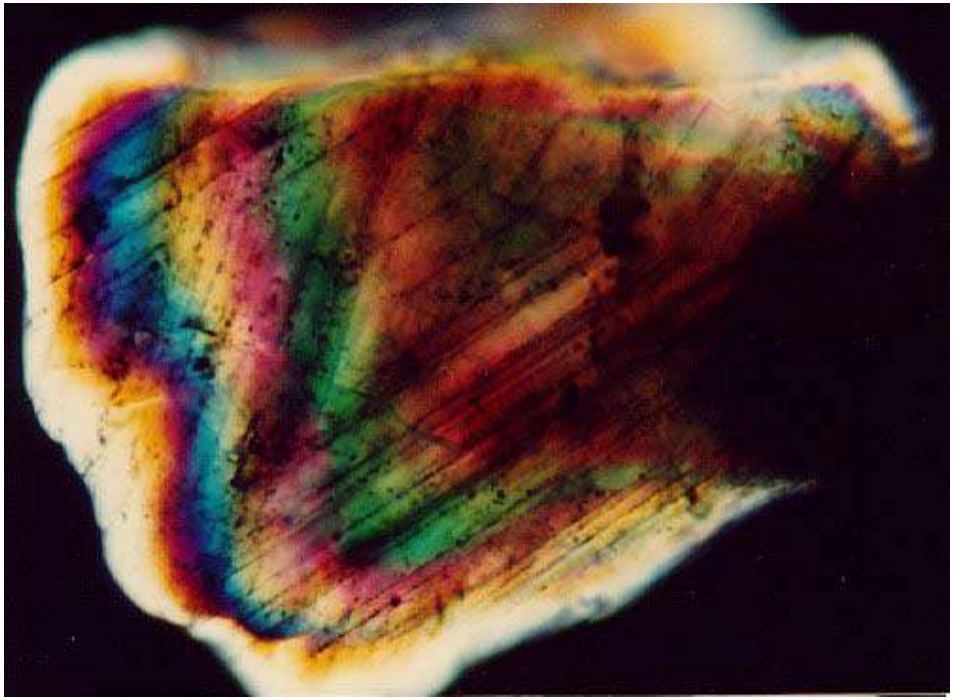
About 700 Myr old



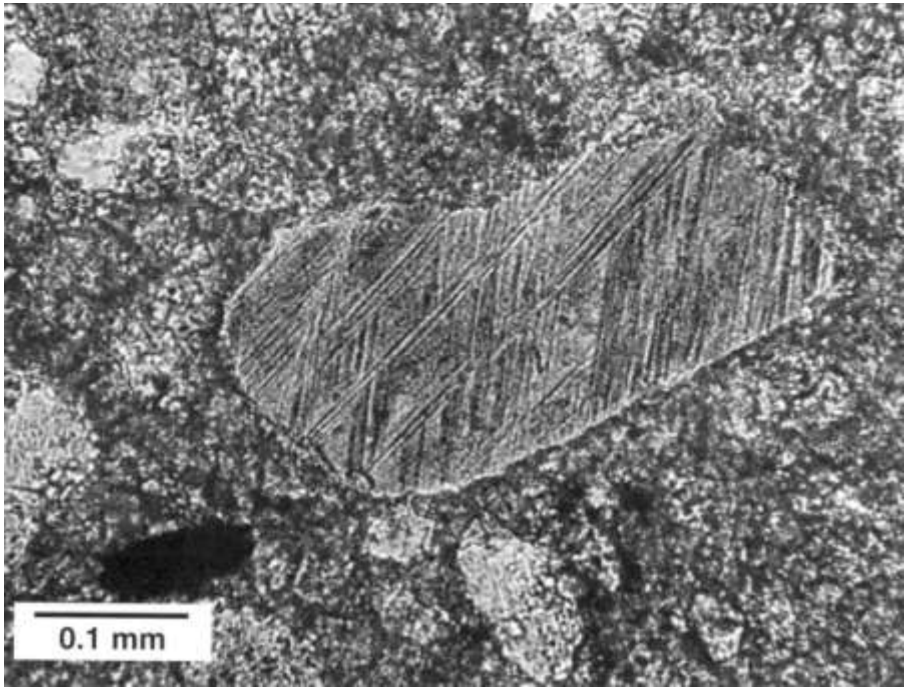
Onaping Formation,
Sudbury, Canada.

1.8 Gyr old

Planar Deformation Features (PDFs)



Quartz grain with PDFs
(Polarized-analyzed light)



PDFs also appear in minerals other than Quartz

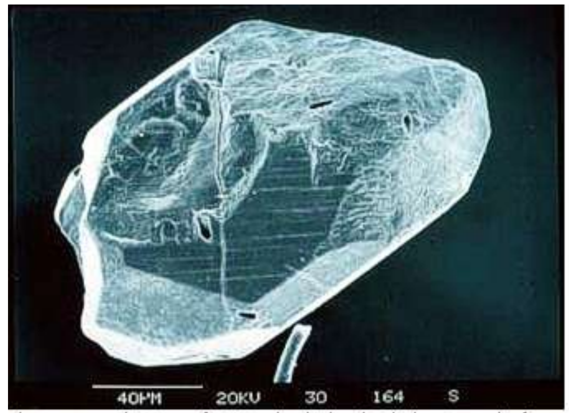


Fig. 7. SEM image of an etched shocked zircon grain from the Berwind Canyon (Raton Basin, Colorado, USA) K-T boundary section; the whole grain shows the typical crystal habit of zircon and displays PDFs in two different orientations (courtesy B. Bohor, U.S. Geological Survey).

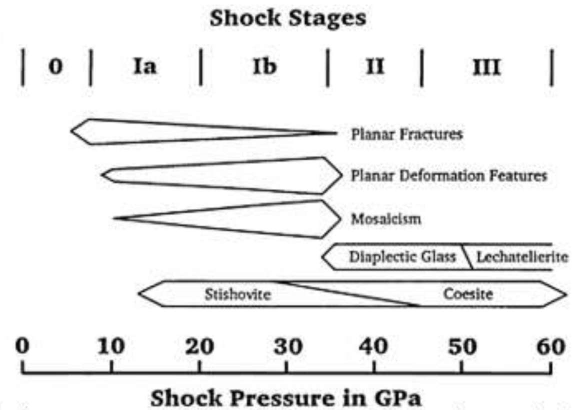
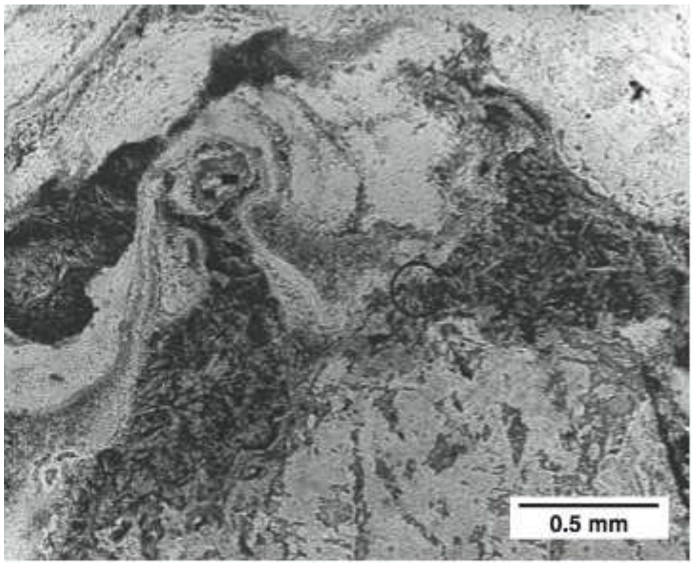


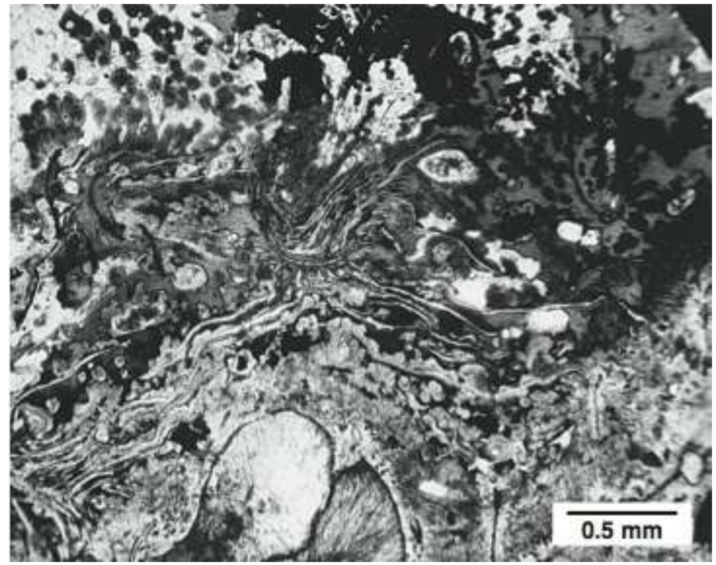
Fig. 8. Pressure dependency of various characteristic shock indicators in quartz, and relation to shock stages. (After Stöffler and Langenhorst, 1994).

- **PDFs and diaplectic glass from Ries Crater, Germany**

PDFs in Zircon, Chicxulub Ejecta, Colorado

As shock pressure increases, melting and extreme deformation become more common



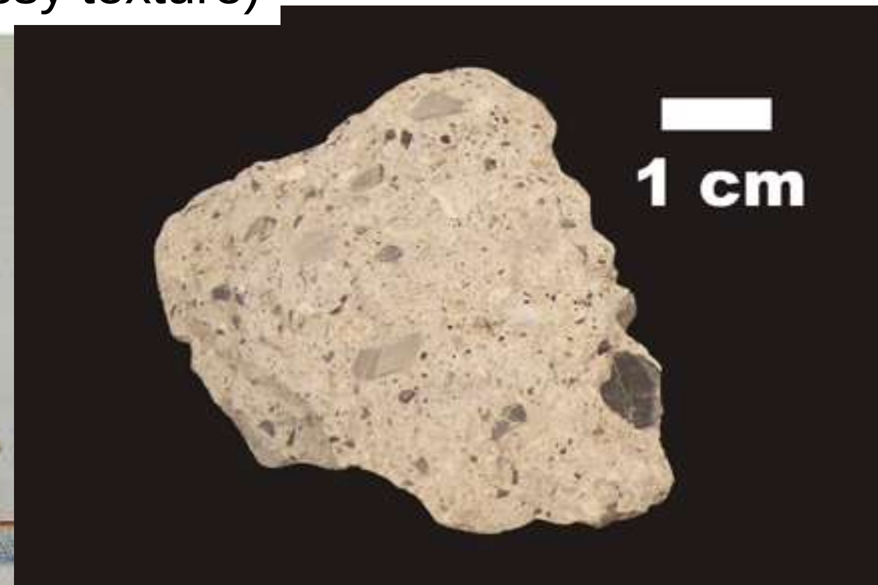


Highly shocked quartz and feldspar rock, Onaping Fm,Sudbury structure, Canada

Complete melt, crustal rock from the Onaping Fm

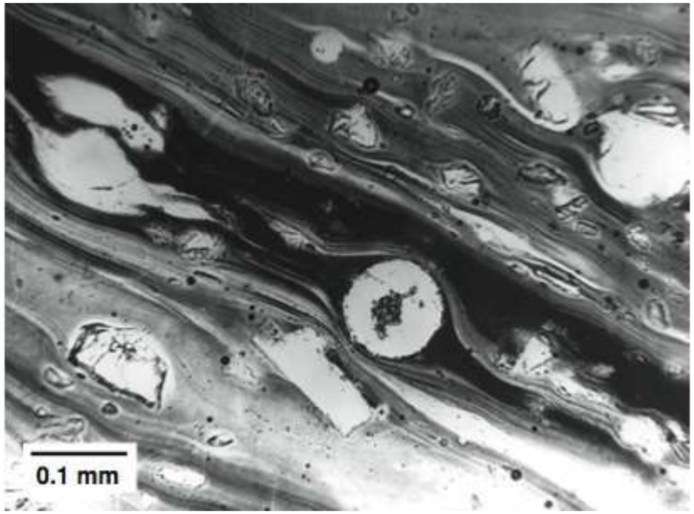
Impact melt & breccia

Impact melt (Glassy texture)

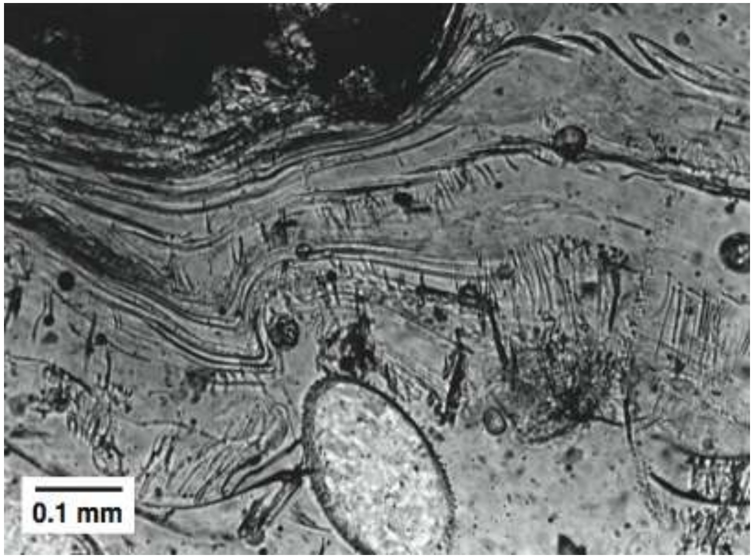


Impact breccia

At higher shock levels, we have melts and melt-supported breccias (Tagamites)

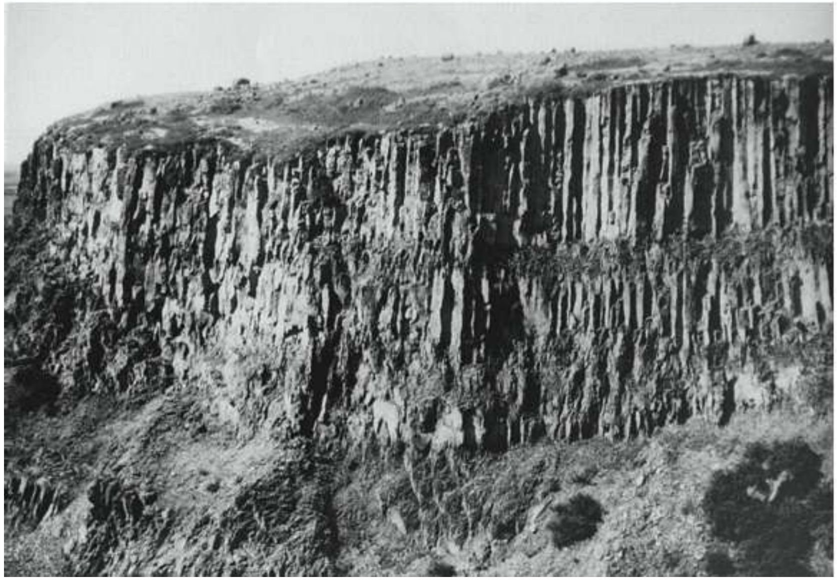


Ries Crater



West Clearwater Lake

Melt rocks can become massive in large impact craters



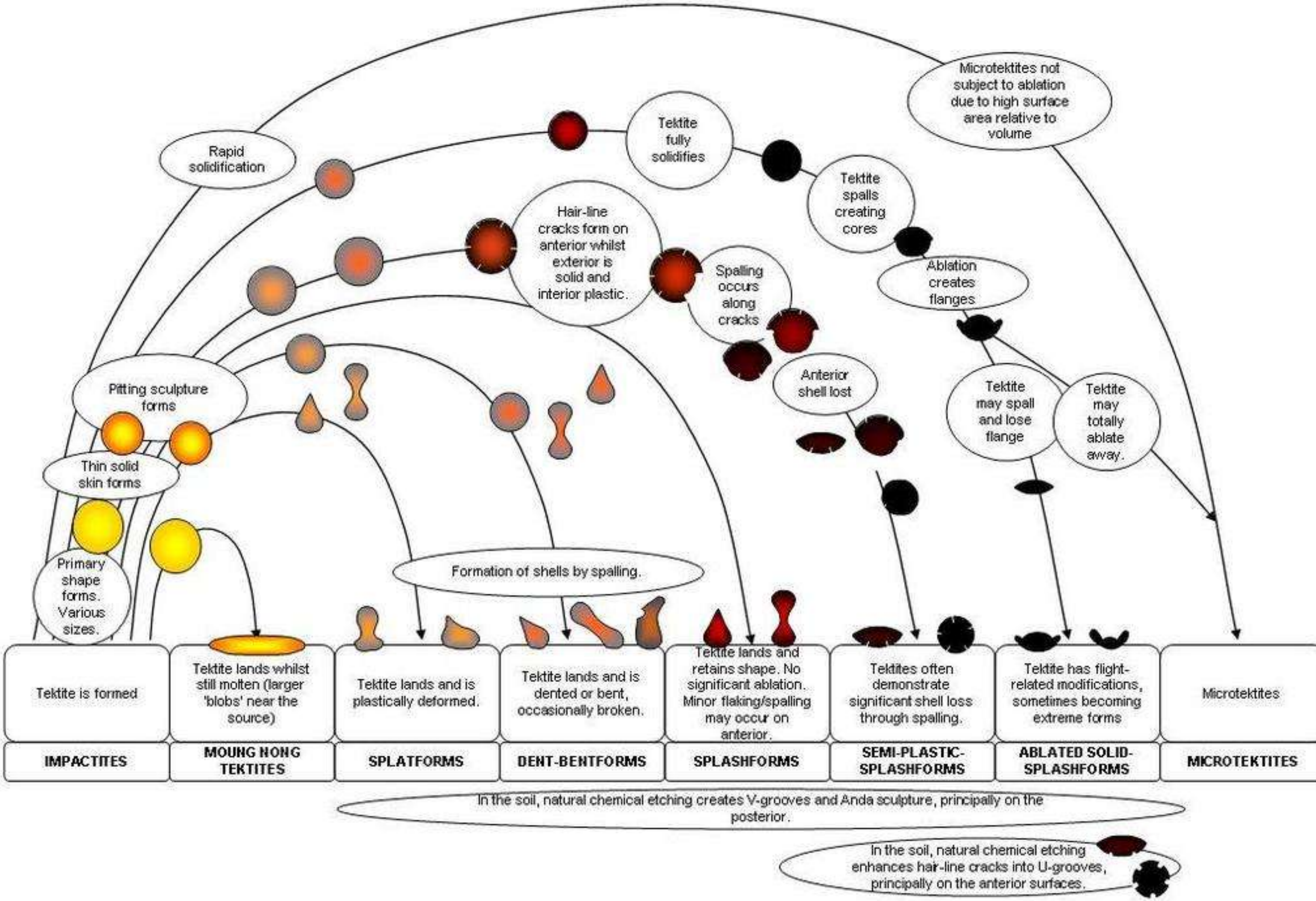
Mistastin Lake, Canada
Outcrop is 80 m tall

Vredefort melt vein

Tektites are now universally believed to originate in terrestrial impacts

The composition of most tektites ranged from about 60 to 60% SiO_2. Tektites are totally devoid of water.

Tektites were formed by the high pressure range developed during impacts on terrestrial rocks. At those pressures the rock target would be molten and the blobs of melt tossed far from the crater into, then out, and then back into the atmosphere, falling land or sea


Microtektites not subject to ablation due to high surface area relative to volume
Rapid solidification
Tektite fully solidifies
Tektite spalls creating cores
Hair-line cracks form on anterior whilst exterior is solid and interior plastic.
Spalling occurs along cracks
Ablation creates flanges
Anterior shell lost
Tektite may spall and lose flange
Tektite may totally ablate away.
Pitting sculpture forms
Thin solid skin forms
Primary shape forms. Various sizes.
Formation of shells by spalling.
Tektite is formed
Tektite lands whilst still molten (larger 'blobs' near the source)
Tektite lands and is plastically deformed.
Tektite lands and is dented or bent, occasionally broken.
Tektite lands and retains shape. No significant ablation. Minor flaking/spalling may occur on anterior.
Tektites often demonstrate significant shell loss through spalling.
Tektite has flight-related modifications, sometimes becoming extreme forms
Microtektites
IMPACTITES
MOUNG NONG TEKTITES
SPLATFORMS
DENT-BENTFORMS
SPLASHFORMS
SEMI-PLASTIC-SPLASHFORMS
ABLATED SOLID-SPLASHFORMS
MICROTEKTITES
In the soil, natural chemical etching creates V-grooves and Anda sculpture, principally on the posterior.
In the soil, natural chemical etching enhances hair-line cracks into U-grooves, principally on the anterior surfaces.

Meteorites

Finding Meteorites

Most meteorites are small and do not produce significant craters.

Good place to find meteorites: Antarctica!

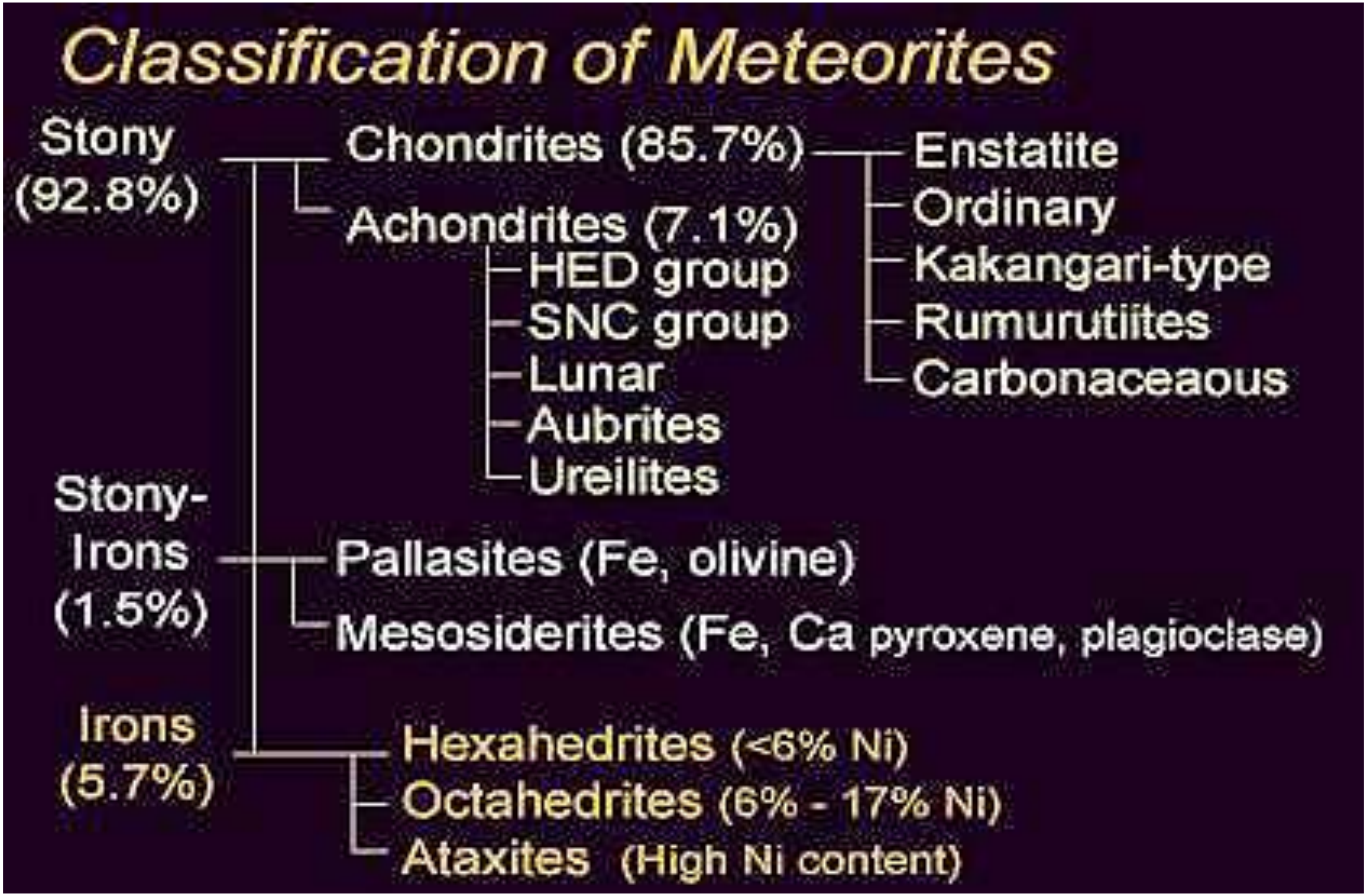
Distinguish between:

- Falls = meteorites which have been observed to fall (fall time known).
- Finds = meteorites with unknown fall time.

Analysis of Meteorites

3 broad categories:

- Iron meteorites
- Stony meteorites
- Stony-Iron meteorites


Classification of Meteorites
Stony
(92.8%)
Chondrites (85.7%)
Enstatite
Ordinary
Kakangari-type
Rumurutiites
Carbonaceaous
Achondrites (7.1%)
HED group
SNC group
Lunar
Aubrites
Ureilites
Stony-
Irons
(1.5%)
Pallasites (Fe, olivine)
Mesosiderites (Fe, Ca pyroxene, plagioclase)
Irons
(5.7%)
Hexahedrites (<6% Ni)
Octahedrites (6% - 17% Ni)
Ataxites (High Ni content)

Chondrites

- Stony Meteorites **are characterized by chondrules--small spheres (average diameter of 1 mm) of formerly melted minerals that have come together with other mineral matter to form a solid rock. Chondrites are believed to be among the oldest rocks in the solar system. Click here to link to an article on the Nature and Origin of Chondrules. Click here to see a close-up picture of chondrules.** 82 percent of meteorite falls are chondrites.

Achondrites

- Stony Meteorites **without chondrules. Scientists believe that some of these meteorites originated on the surface of the Moon or Mars.** 7.8 percent of meteorite falls are achondrites.

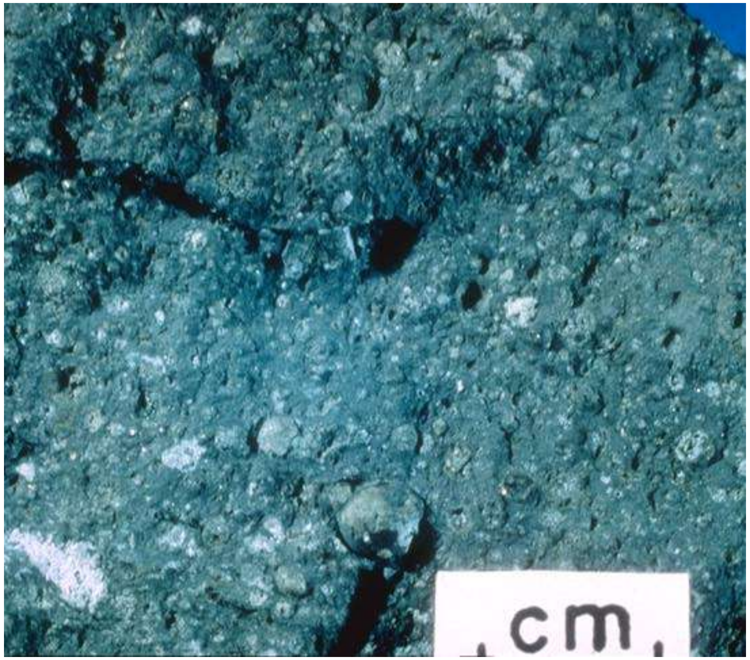
Irons

- Structural classification: **These meteorites are made of a crystalline iron-nickel alloy. Scientists believe that they resemble the outer core of the Earth.** 4.8 percent of meteorite falls are irons.
- Chemical Classification: The determining factors are groupings of meteorites with similar ratios of trace elements to nickel. Generally, the higher the Roman numeral of the classification, the lower the concentration of trace elements. The casual observer cannot see this as one can with the Widmanstatten bandwidth that is the determining factor for structural classification.

Stony Irons

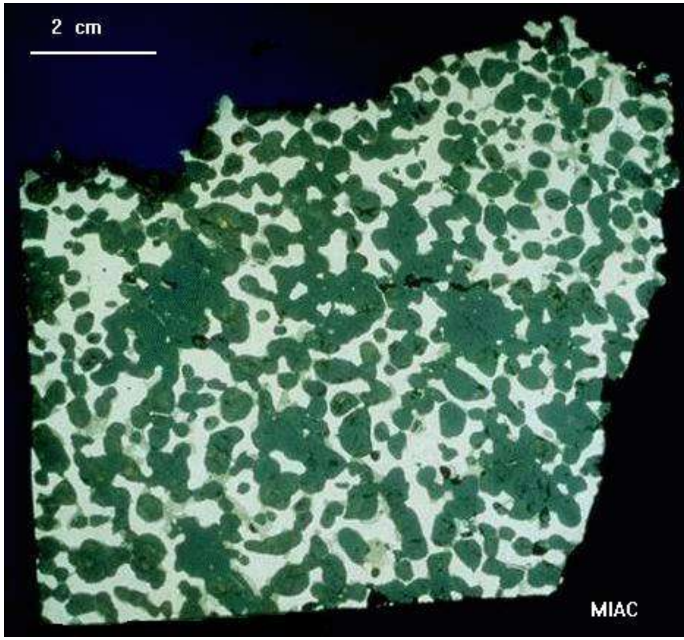
- **These meteorites are mixtures of iron-nickel alloy and non-metallic mineral matter. Scientists believe that they are like the material that would be found where the Earth's core meets the mantle.** 1.2 percent of meteorite falls are stony irons.

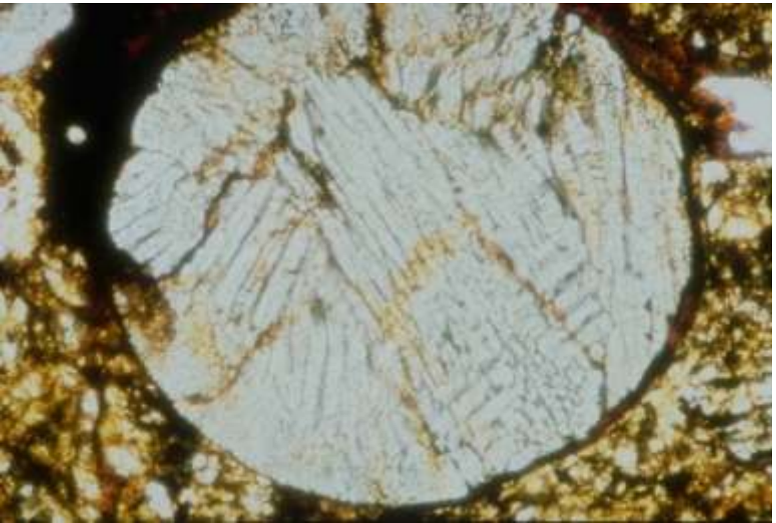
Detalle de cada tipo



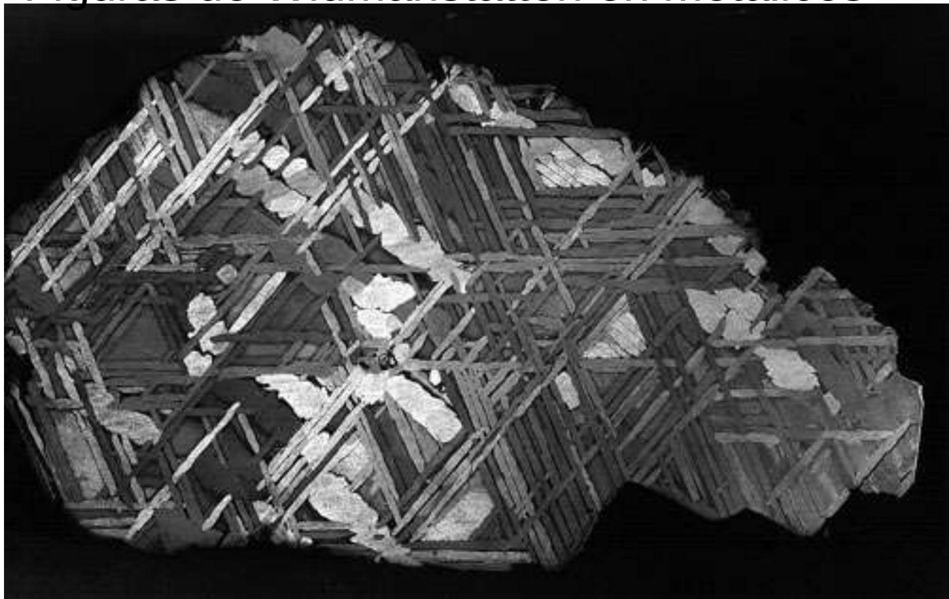
Cóndrulos en las condritas

Metorito
metálico-
rocoso





Figuras de Widmanstatten en metálicos



Los grandes meteoritos de Campo del Cielo (Chaco argentino)

37 Toneladas

What Does a "Meteorite" Look Like?

Table 25-2 | Proportions of Meteorites

Type	Falls (%)	Finds (%)
Stony	92	26
Iron	6	66
Stony-iron	2	8

Selection bias:

Iron meteorites are easy to recognize as meteorites (heavy, dense lumps of iron-nickel steel) – thus, more likely to be found and collected.

The Allende Meteorite

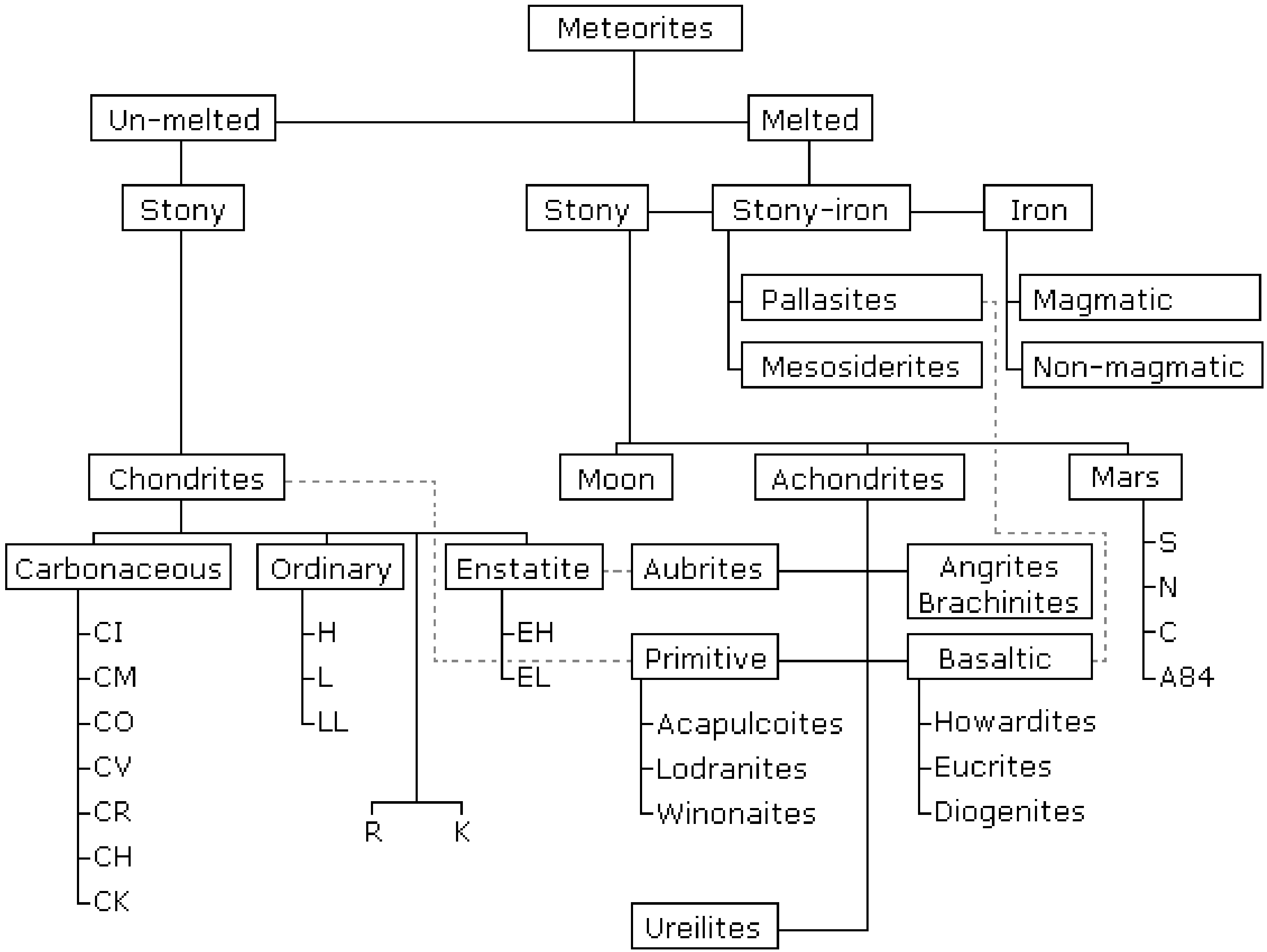
- Carbonaceous chondrite, fell in 1969 near Pueblito de Allende, Mexico
- Showered an area about 50 km x 10 km with over 4 tons of fragments.

Fragments containing calcium-aluminum-rich inclusions (CAIs)

Extremely temperature-resistant materials.

Allende meteorite is a very old sample of solar-nebula material!

Meteorite "family tree"



The Origins of Meteorites

- Probably formed in the solar nebula, ~ 4.6 billion years ago.
- **Almost certainly not from comets (in contrast to meteors in meteor showers!).**
- **Probably fragments of stony-iron planetesimals**
- **Some melted by heat produced by ^{26}Al decay (half-life ~ 715,000 yr).**
- **^{26}Al possibly provided by a nearby supernova, just a few 100,000 years before formation of the solar system (triggering formation of our sun?)**

The Origins of Meteorites (2)

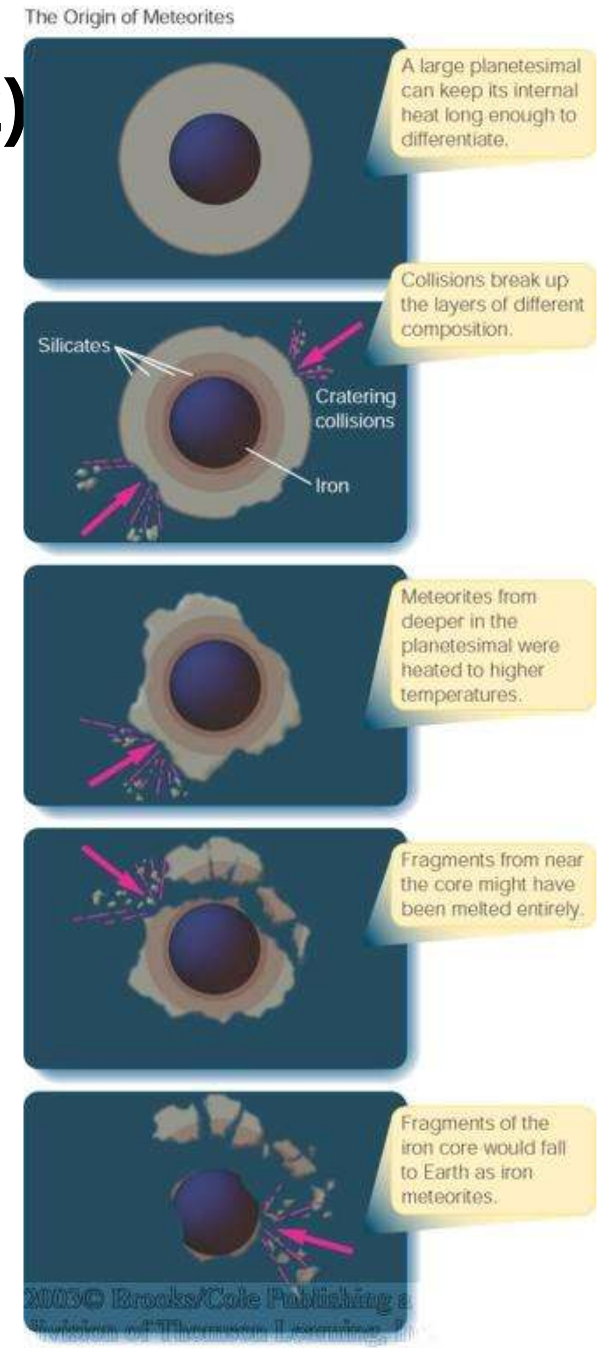
• Planetesimals cool and differentiate

• Collisions eject material from different depths with different compositions and temperatures.

• Meteorites can not have been broken up from planetesimals very long ago

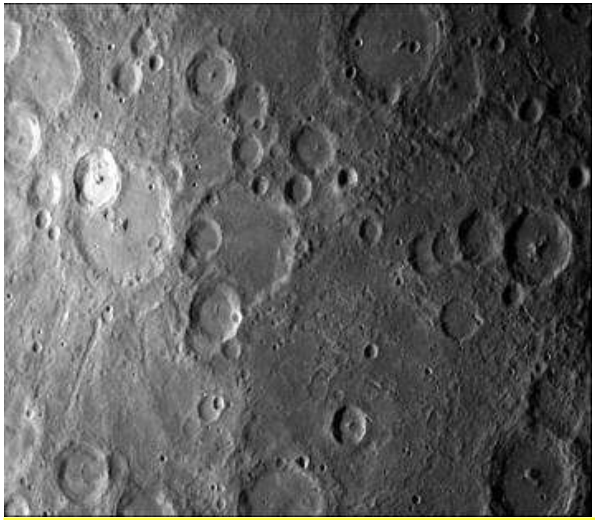
→ so remains of planetesimals should still exist.

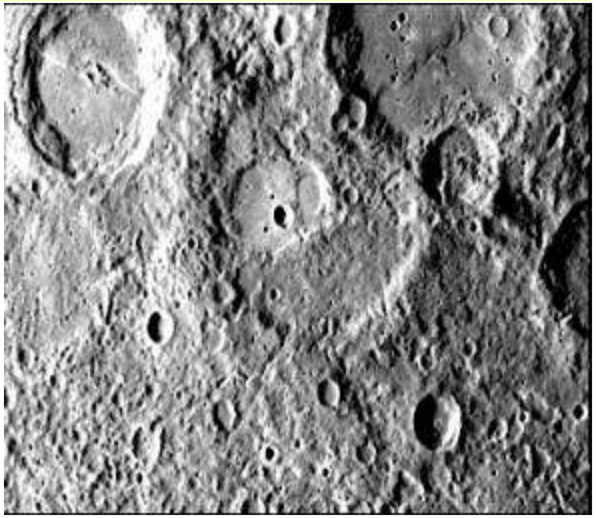
→ **Asteroids**



Cratering
Counting & Dating

- **Older surfaces have more craters**
- **Small craters are more frequent than large craters**
- **Relate crater counts to a surface age, if:**
  - **Impact rate is constant**
  - **No other resurfacing processes**
- **Techniques developed for Lunar Maria**
  - **Telescopic work established relative ages**
  - **Apollo sample provided absolute calibration**



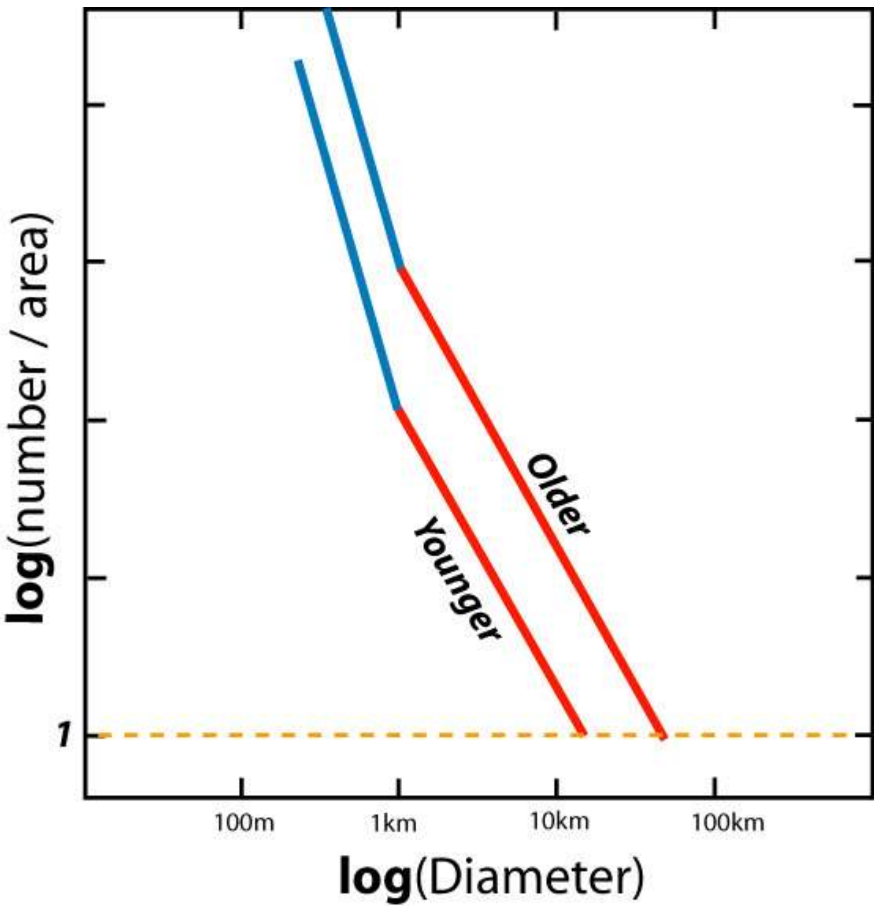


Mercury – Young and Old

An ideal case…

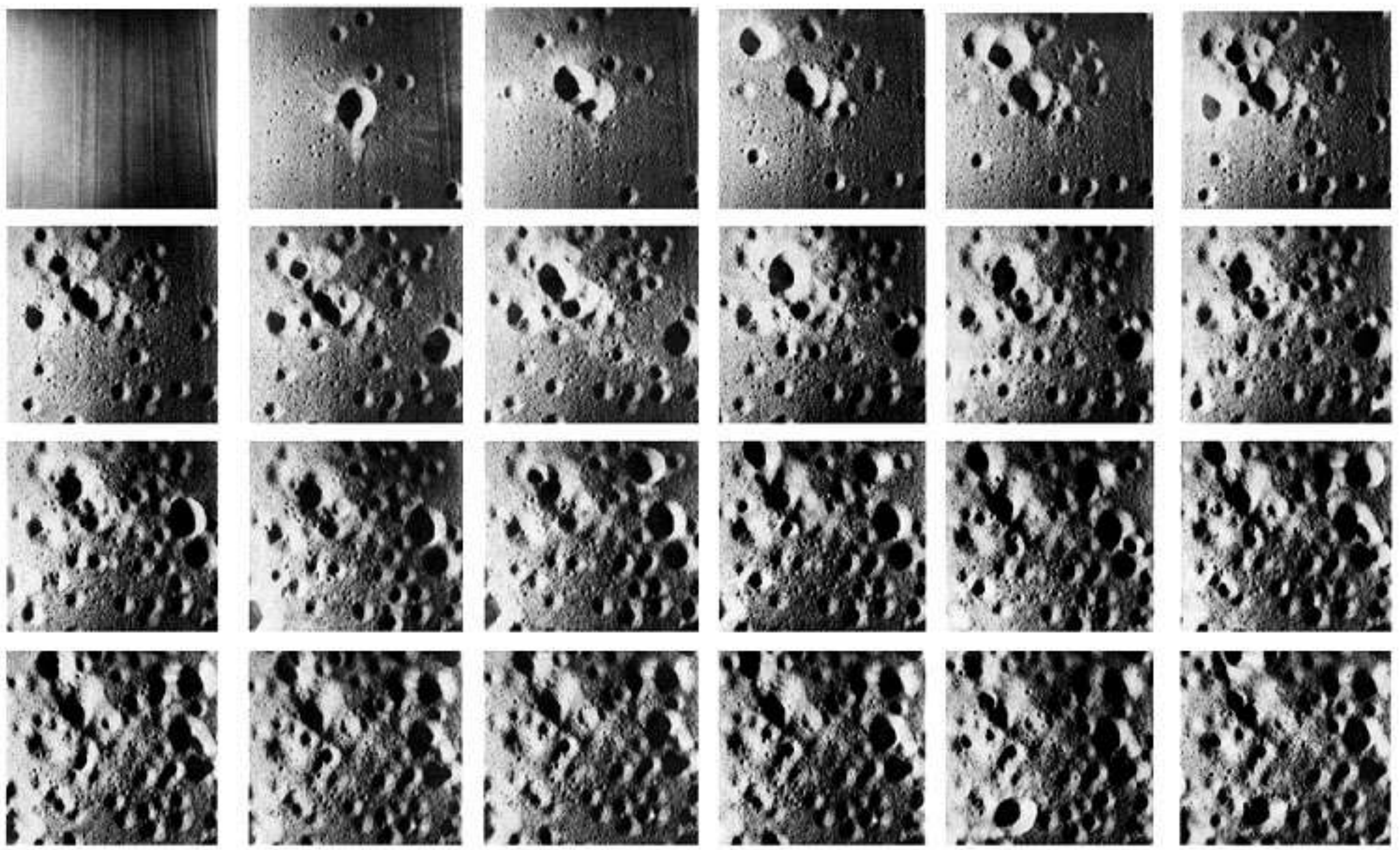
- Crater population is counted
- Size-frequency plot generated
  - In log-log space
  - Frequency is normalized to some area
- Piecewise linear relationship:

$$N(D,\sqrt{2}D) = kD^{-b}$$

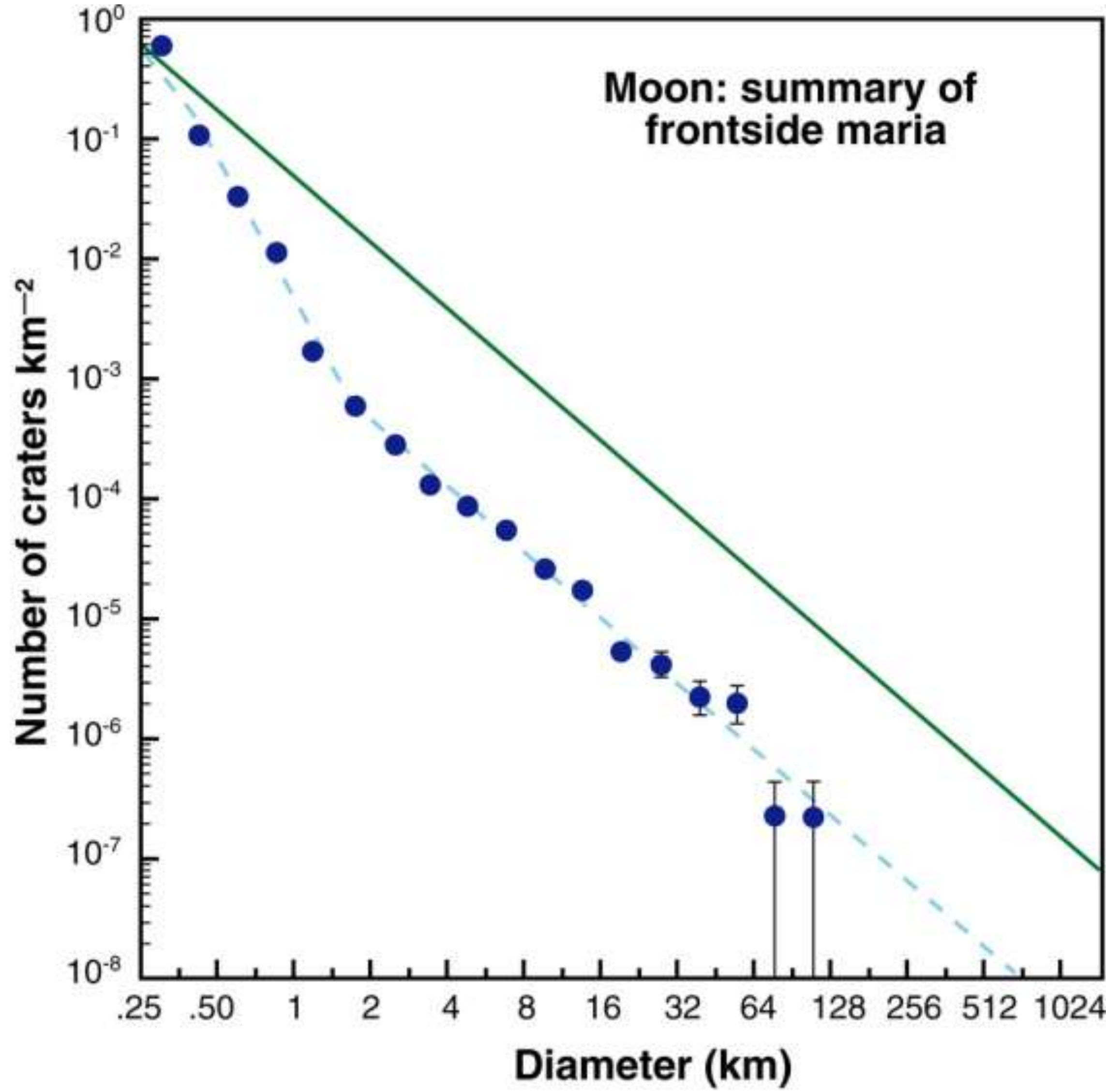


Saturation problem

- When a surface is saturated no more age information is added
  - Number of craters stops increasing



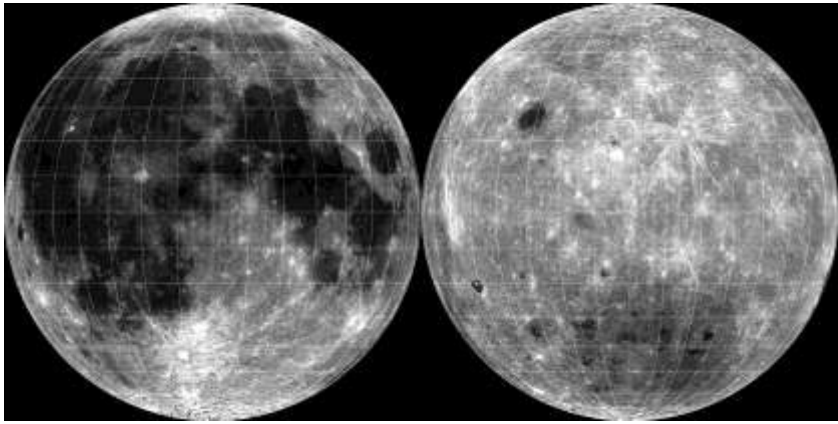
Typical size-frequency curve



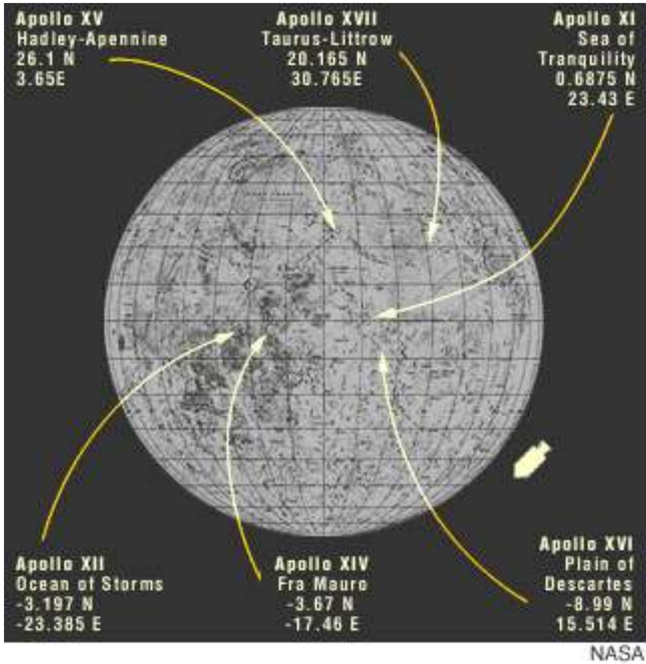
McEwen AS, Bierhaus EB. 2006.
Annu. Rev. Earth Planet. Sci. 34:535–67

Linking Crater Counts to Age

- **Moon is divided into two terrain types**
  - **Light-toned Terrae (highlands) – plagioclase feldspar**
  - **Dark-toned Mare – volcanic basalts**
  - **Maria have ~200 times fewer craters**
- **Apollo and Luna missions**
  - **Sampled both terrains**
  - **Mare ages 3.1-3.8 Ga**
  - **Terrae ages all 3.8-4.0 Ga**
- **Lunar meteorites**
  - **Confirm above ages are representative of most of the moon.**

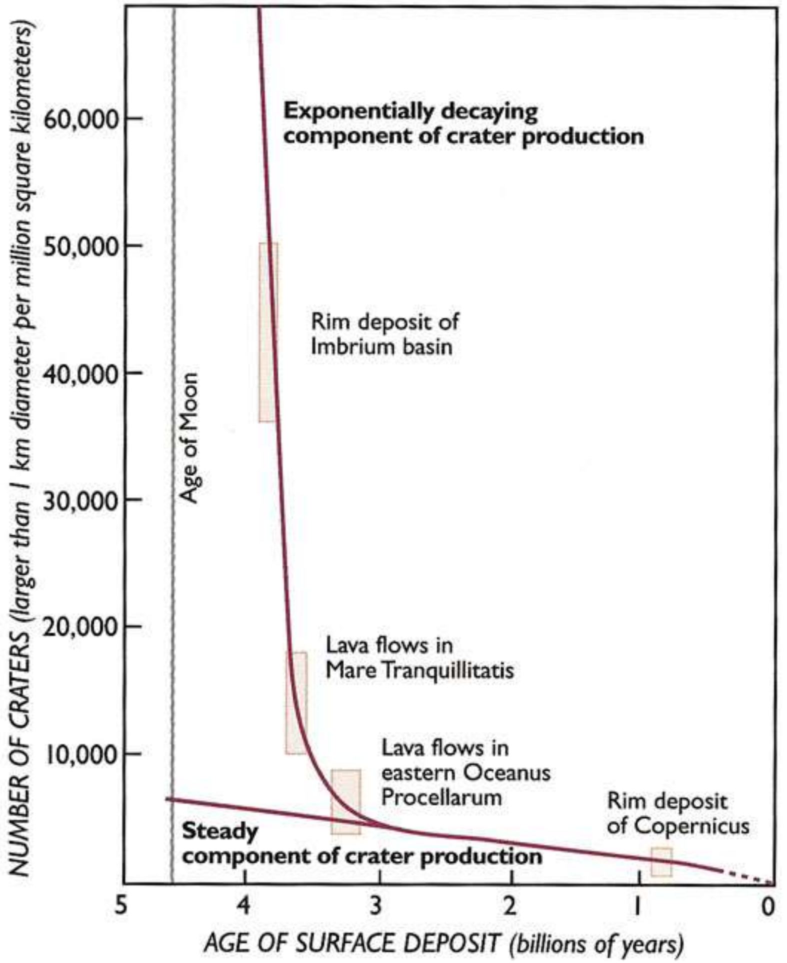


Mission	*Arrival date*	*Landing site*	*Latitude*	*Longitude*	*Sample return*
Apollo 11	20 July 1969	Mare Tranquillitatis	0° 67' N	23° 49' E	21.6 kg
Apollo 12	19 Nov. 1969	Oceanus Procellarum	3° 12' S	23° 23' W	34.3 kg
Apollo 14	31 Jan. 1971	Fra Mauro	3° 40' S	17° 28' E	42.6 kg
Apollo 15	30 July 1971	Hadley-Apennine	26° 6' N	3° 39' E	77.3 kg
Apollo 16	21 Apr. 1972	Descartes	9° 00' N	15° 31' E	95.7 kg
Apollo 17	11 Dec. 1972	Taurus-Littrow	20° 10' N	30° 46' E	110.5 kg
Luna 16	20 Sep. 1970	Mare Fecunditatis	0° 41' S	56° 18' E	100 g
Luna 20	21 Feb. 1972	Apollonius highlands	3° 32' N	56° 33' E	30 g
Luna 24	18 Aug. 1976	Mare Crisium	12° 45' N	60° 12' E	170 g

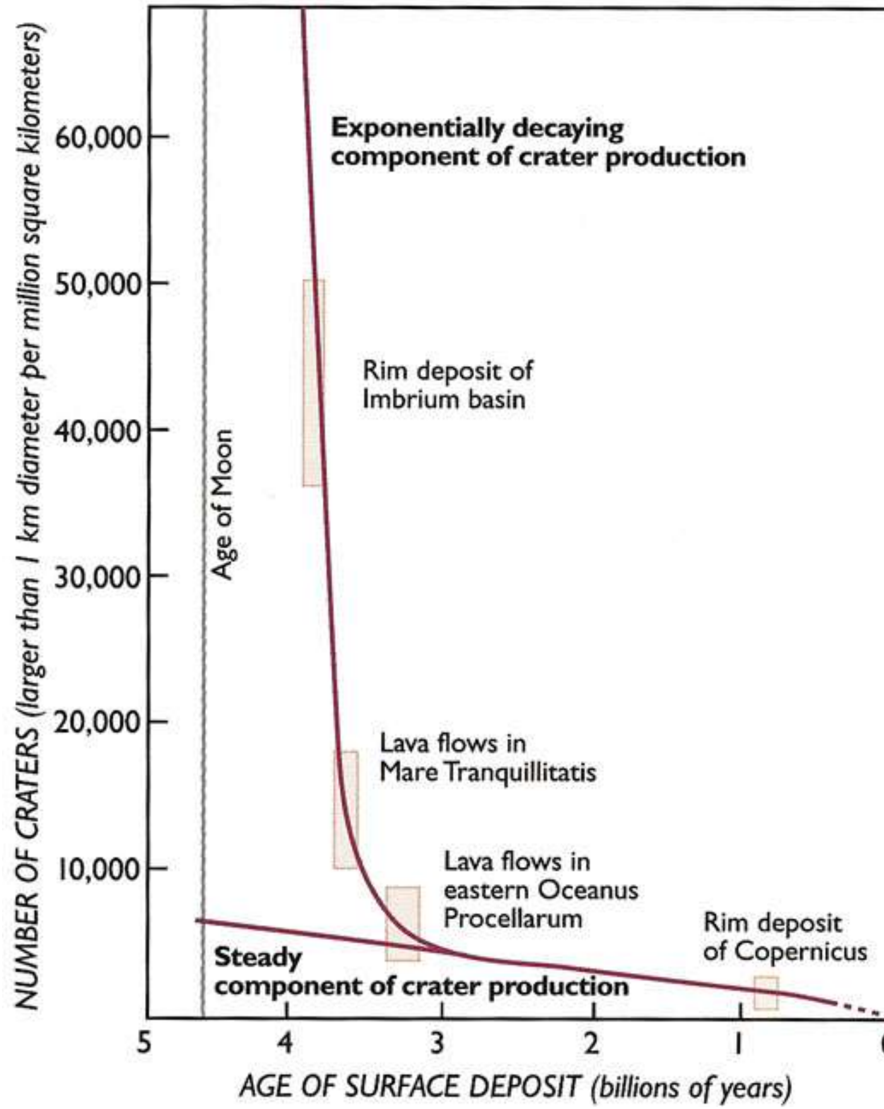


- Crater counts had already established relative ages
  - Samples of the impact melt with geologic context allowed absolute dates to be connected to crater counts
- Lunar cataclysm?
  - Impact melt from large basins cluster in age
    - Imbrium 3.85Ga
    - Nectaris 3.9-3.92 Ga
  - Highland crust solidified at ~4.45Ga
- Cataclysm or tail-end of accretion?
  - Lunar mass favors cataclysm
  - Impact melt >4Ga is very scarce
  - Pb isotope record reset at ~3.8Ga

  } weak
- Cataclysm referred to as '*Late Heavy Bombardment*'

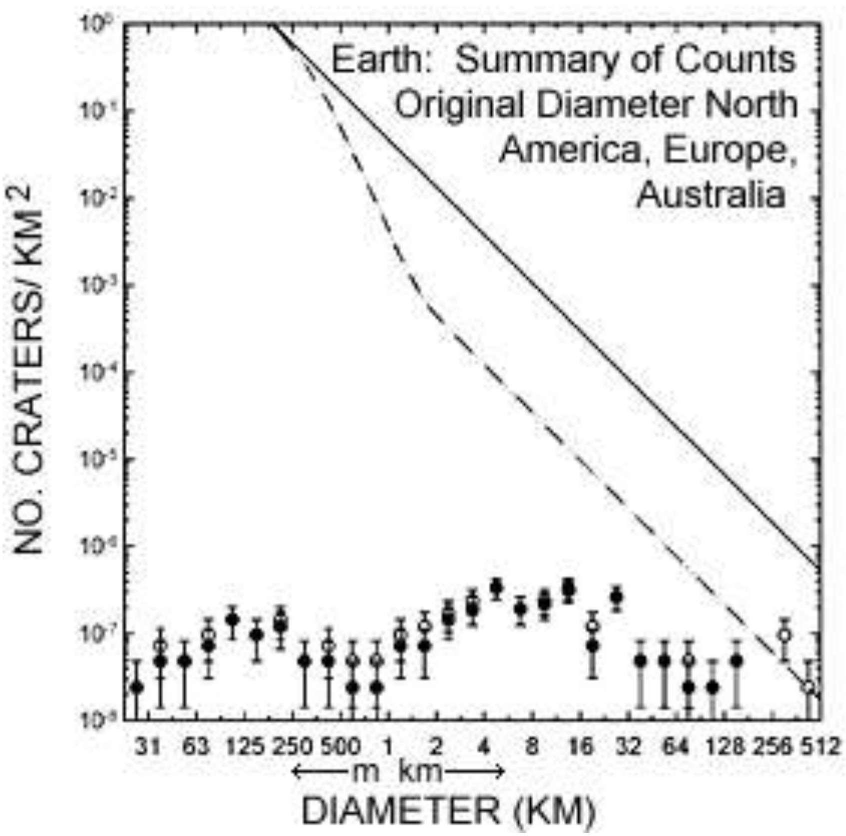


- The worst is over…
  - Late heavy bombardment 3.7-3.9 Ga
  - Impacts still occurring today though
  - Jupiter was hit by a comet ~15 years ago



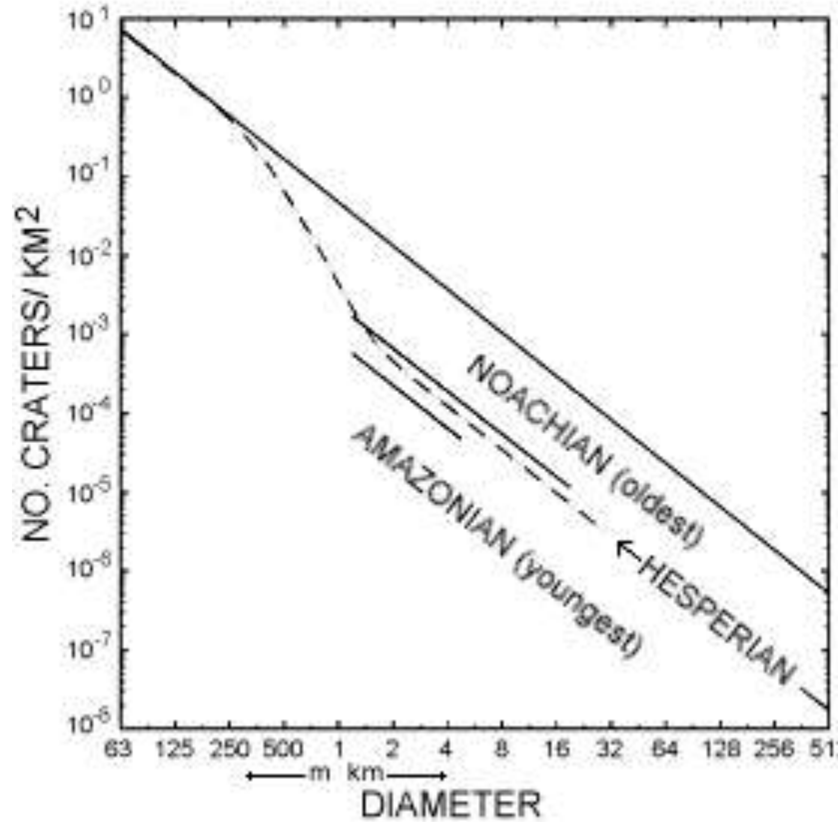
  - Chain impacts occur due to Jupiter's high gravity
  - e.g. Callisto

Earth



Crater size distribution for older regions of Earth. Small craters have been lost by erosion, as measured relative to numbers seen on the moon

Mars



Basic background reference lines for mars crater count plots.

Mars

Isochrons fitting with resurfacing

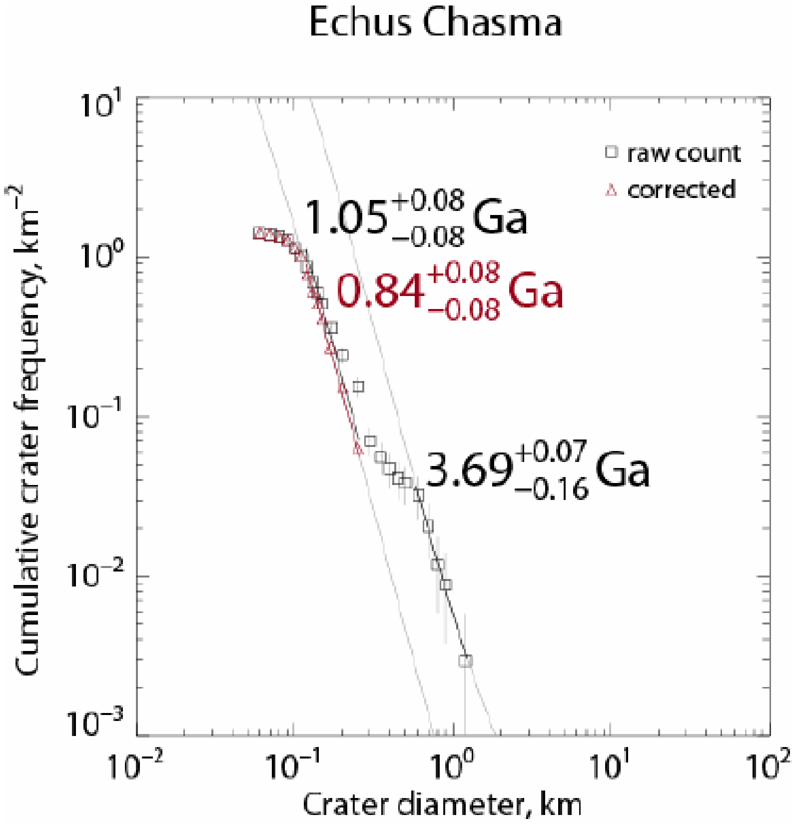


Fig. 1. Sample resurfacing age correction for a count from Echus Chasma. The black squares are the original crater count. The light grey lines are the isochrons for 3.69 and 0.84 Ga. The red triangles are corrected points according to the method here, assuming the range 0.12-0.25 km represents a single age. A fit to this same range without the correction yields an age estimate of 1.05 Ga – an overestimate of about 25%.

Passage through the armosphere

Crater-less impacts

- Impacting bodies can explode or be slowed in the atmosphere
- Significant drag when the projectile encounters its own mass in atmospheric gas: $i.e. \quad D_i \approx 3P_S / 2g_P \rho_i$
  - Where P_s is the surface gas pressure, g is gravity and ρ_i is projectile density
  - If impact speed is reduced below elastic wave speed then there's no shockwave – projectile survives
- Ram pressure from atmospheric shock

$$P_{ram} \approx v^2 \rho_{atmosphere}$$

$$if \quad T \approx const. \quad P_{ram} \approx v^2 \frac{\mu_{ATM}}{kT} P(z) \approx \frac{v^2 P_S}{g H} e^{-z/H}$$

$$where \quad H = kT / g\mu_{ATM}$$

  - If P_{ram} exceeds the yield strength then projectile fragments
  - If fragments drift apart enough then they develop their own shockfronts – fragments separate explosively (pancake model)
  - Weak bodies at high velocities (comets) are susceptible
  - Tunguska event on Earth
  - Crater-less 'powder burns' on venus

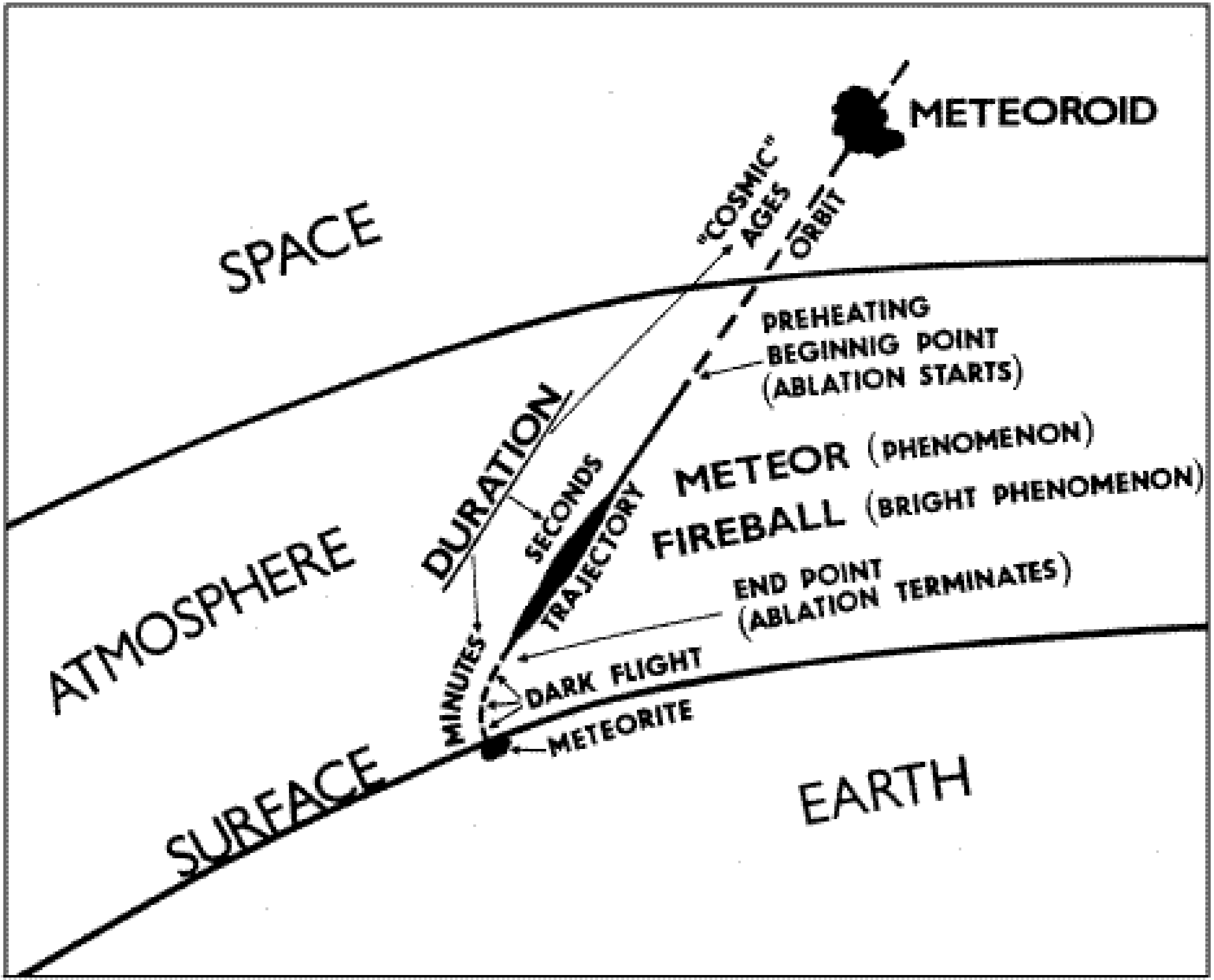
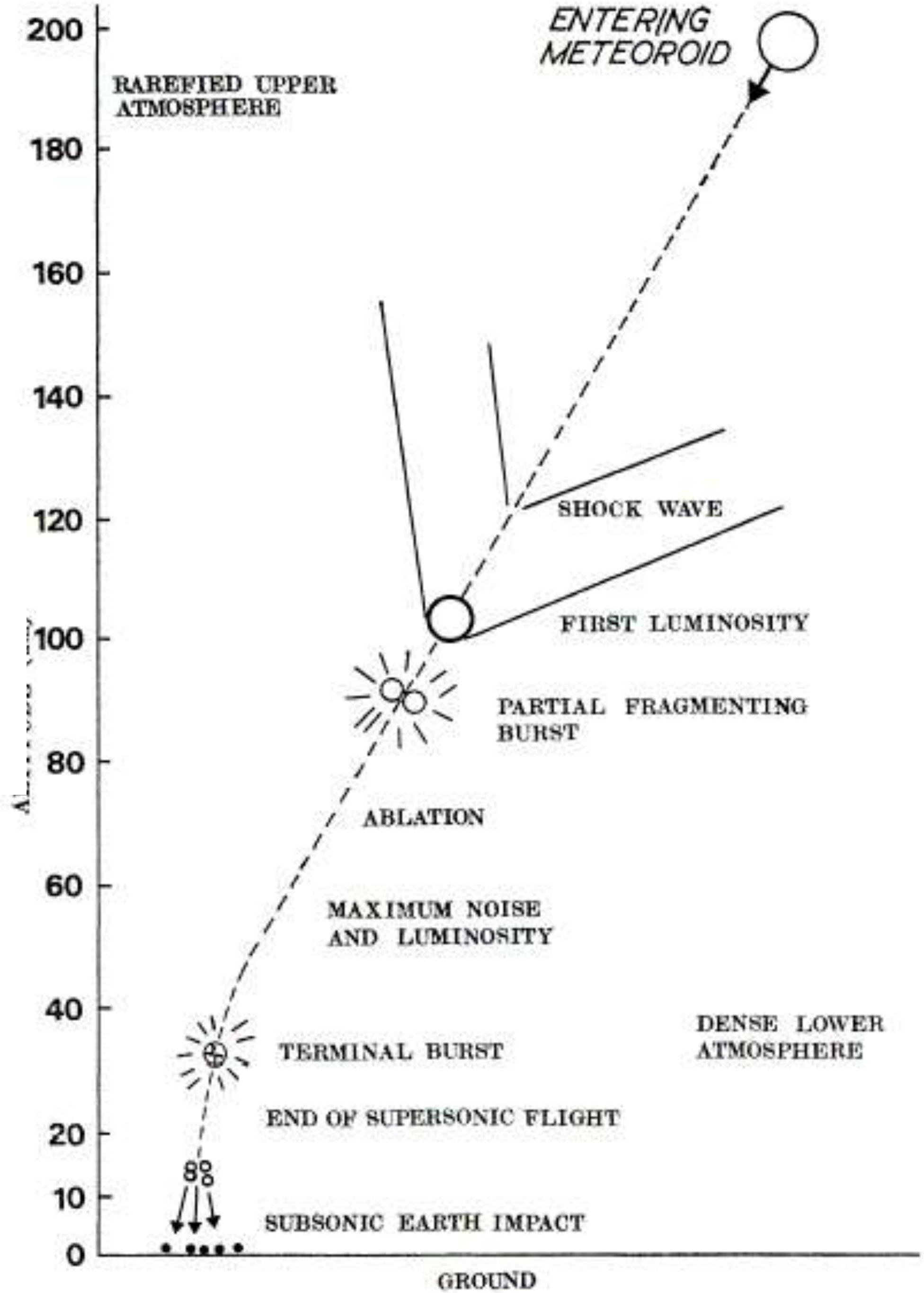


Figure 2. Basic terminology for meteors.

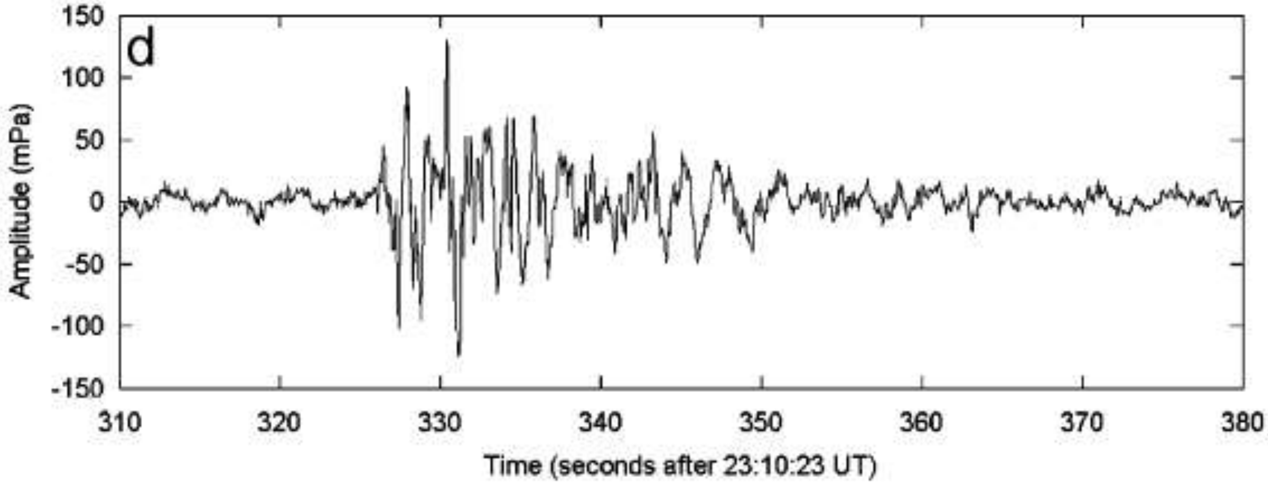
The sounds

Two sounds:
•Sonic Boom sónico: minutes after fireball
•Electrofonic noise: simultaneous with fireball

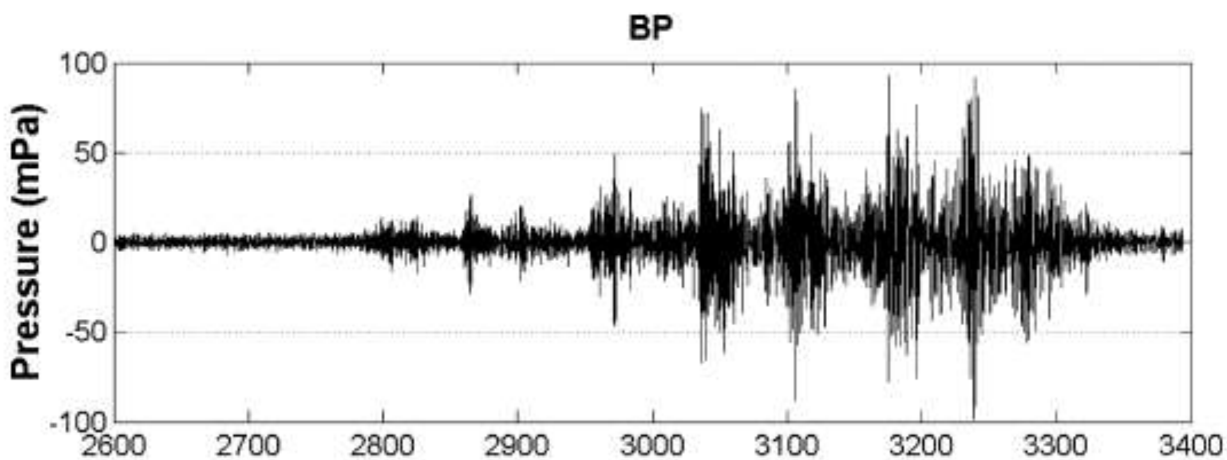


Infrasound records

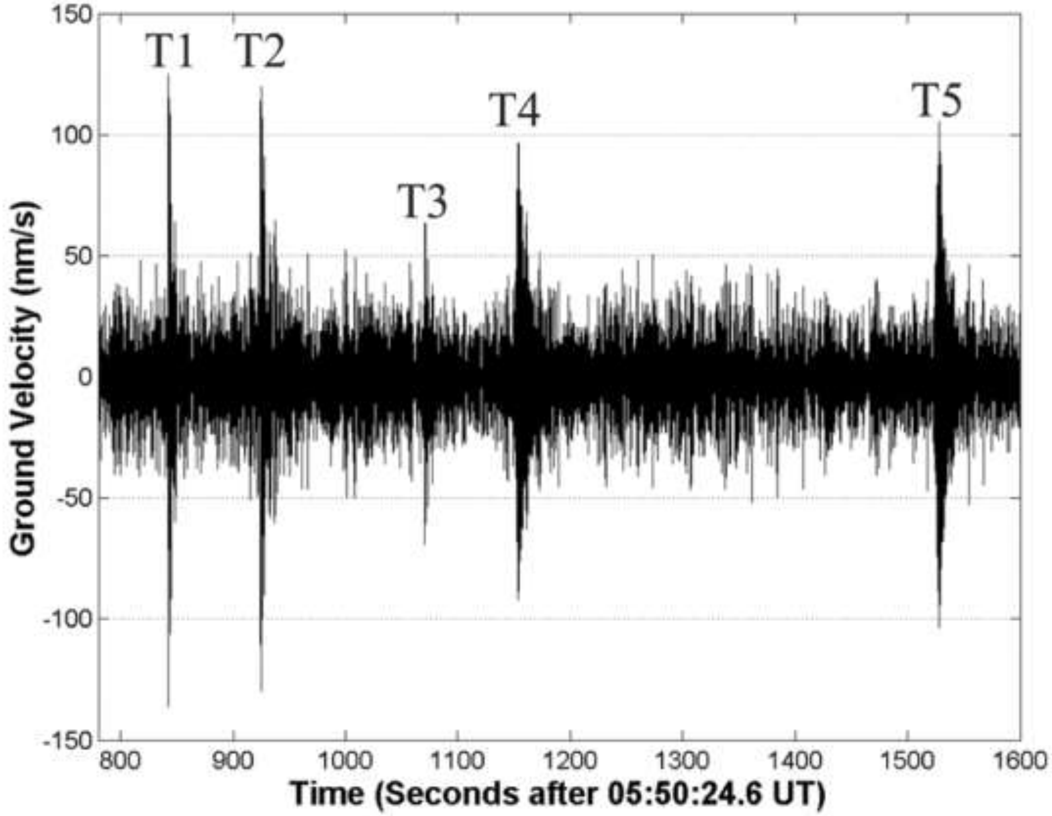
Fireball of the European Network



Fireball Park Forest

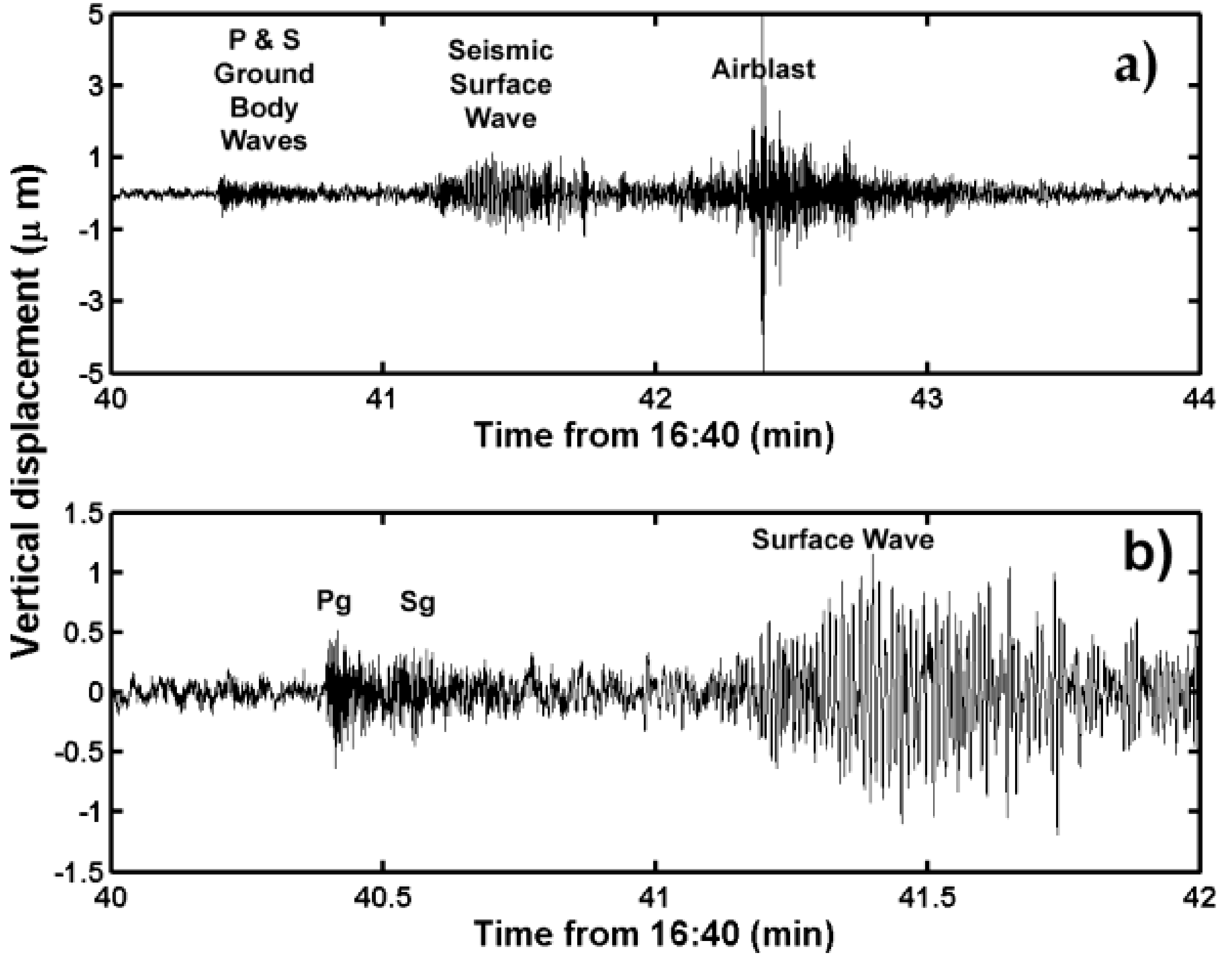


Seismic records of the airblast



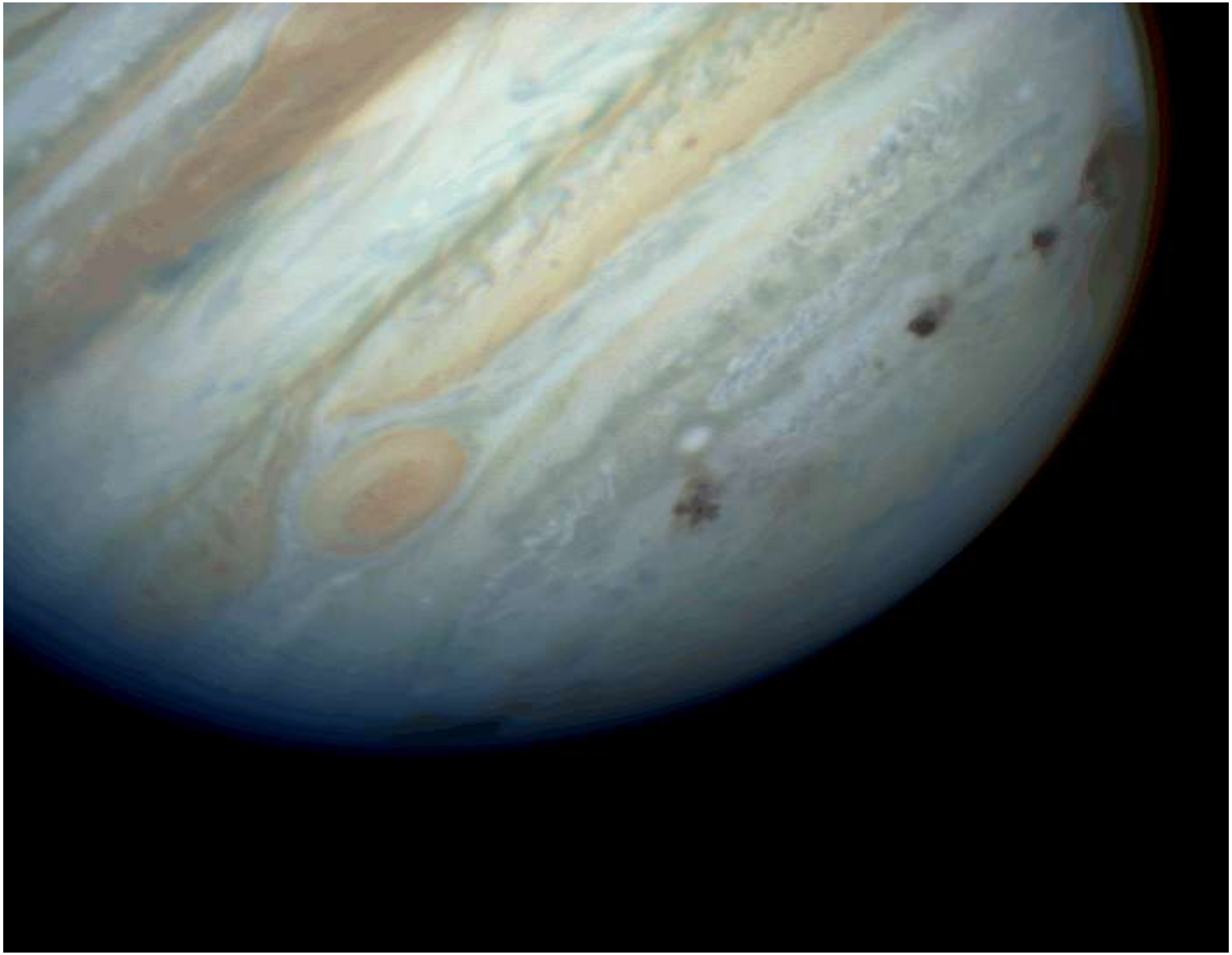
Arrival	Arrival times	Delay (sec)	Origin height (km)	Signal type	Dev (degrees)	Ground range (km)	Seismic amplitude (nm/s)
T1	6:04:28	842	42	Strato	28.6	264	92
T2	6:05:50	924	17	Strato	17	278	105
T3	6:08:16	1070	42	Thermo	55	266	
T4	6:09:39	1153	17	Thermo	62	277	
T5	6:15:52	1526	–	–	–	–	

Seismic detections of Carancas



First seismic detection of an extraterrestrial impact on Earth


Comet P/Shoemaker-Levy 9 (1993e) • May 1994
A B C D E F G H K L N P Q R S U V W



Morphology

- Craters occur on all solar system bodies
- Crater morphology changes with impact energy
- Impact craters are the result of point source explosions

Mechanics

- Craters form from shockwaves
- Contact and compression <1 s
- Excavation of material 10’s of seconds
- Craters collapse from a transient cavity to their final form

- Ejecta blankets are ballistically emplaced
- Low-density projectiles can explode in the atmosphere

Summary of recognized impact features

- **Primary crater**
- **Ejecta blanket**
- **Secondary impact craters**
- **Rays**
- **Rings and multirings**
- **Breccia**
- **Shock metamorphism: Planar Deformation Features (PDFs)**
- **Melt glasses**
- **Tektites**
- **Regolith**
- **Focusing effects in the antipodes**
- **Erosion and catastrophic disruption**

Aspectos positivos

¿de donde provienen los océanos?

- **El agua terrestre <u>no es primordial</u>, proviene de mayores distancias al Sol (no se condensa a 1 Unidad Astronómica).**

- **Fernández-Ip (1988-1996) y Brunini-Fernández (1999):**

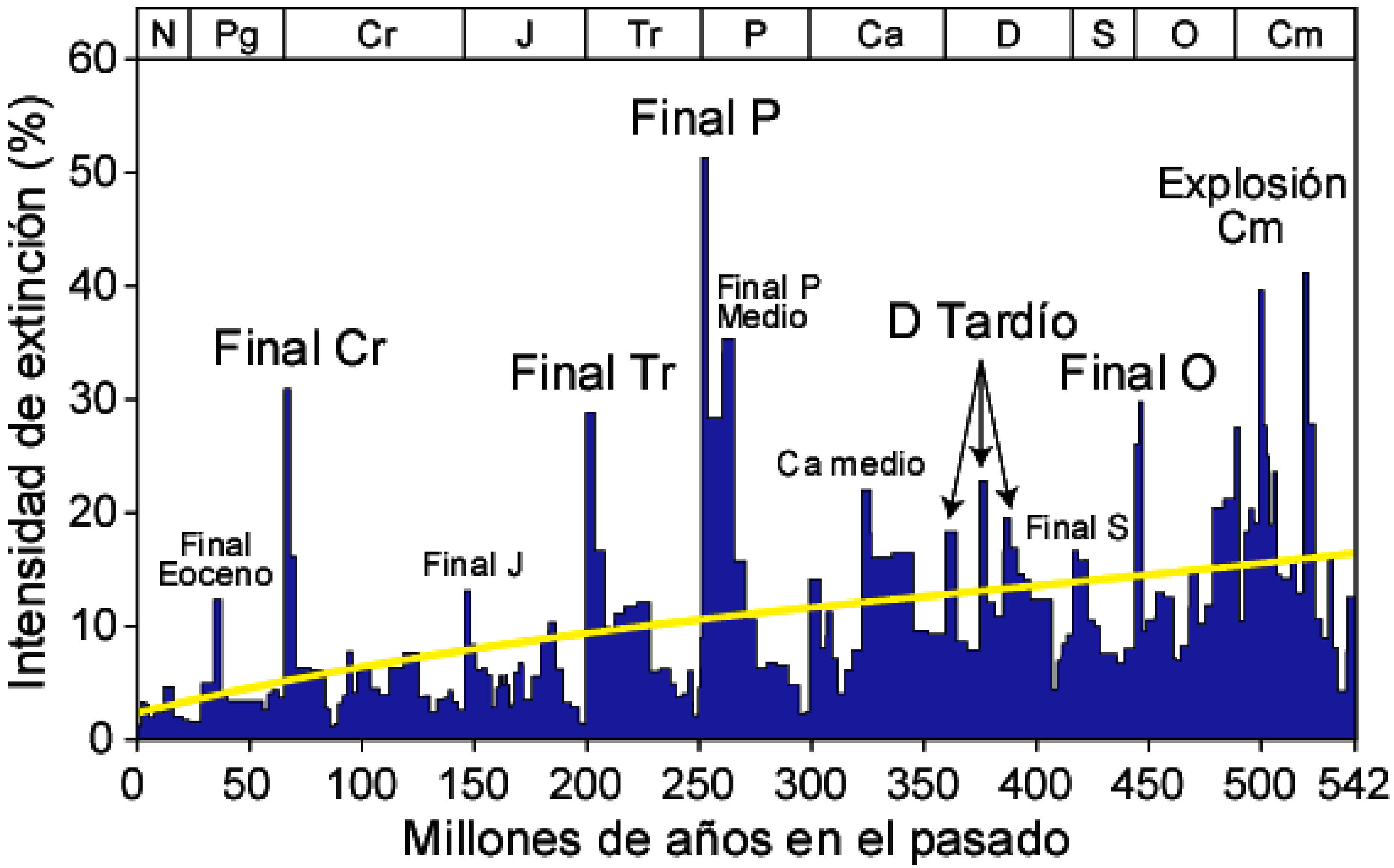
Table III. Cometary matter trapped by solar system bodies.

	Cometary matter (g)	*Time-span*	*Reference*
Venus	4.0×10^{20}	2×10^{9} years	Lewis, 1974
Moon	2.0×10^{20}	Late-accretion	Wetherill, 1975
Earth	$2.0\times10^{14-18}$	2×10^{9} years	Orò, 1961
	$1.0\times10^{25-26}$	Late-accretion	Whipple, 1976
	3.5×10^{21}	Late-accretion	Sill and Wilkening, 1978
	7.0×10^{23}	4.5×10^{9} years	Chang, 1979
	2.0×10^{22}	4.5×10^{9} years	Pollack and Yung, 1980
	1.0×10^{23}	2.0×10^{9} years	Orò *et al.*, 1980
	$1.0\times10^{24-25}$	1.0×10^{9} years	Delsemme, 1984, 1991
	$6.0\times10^{24-25}$	1.0×10^{9} years	Ip and Fernandez, 1988
	$1.0\times10^{23-26}$	4.5×10^{9} years	Chyba *et al.*, 1990

Agua en océanos:
1,24 x 10^{24} g

- **Conclusión: los océanos se formaron con agua que llegó después de 100 - 150 millones de años desde la formación del Sistema Solar.**

Diversidad de géneros marinos: Intensidad de extinción

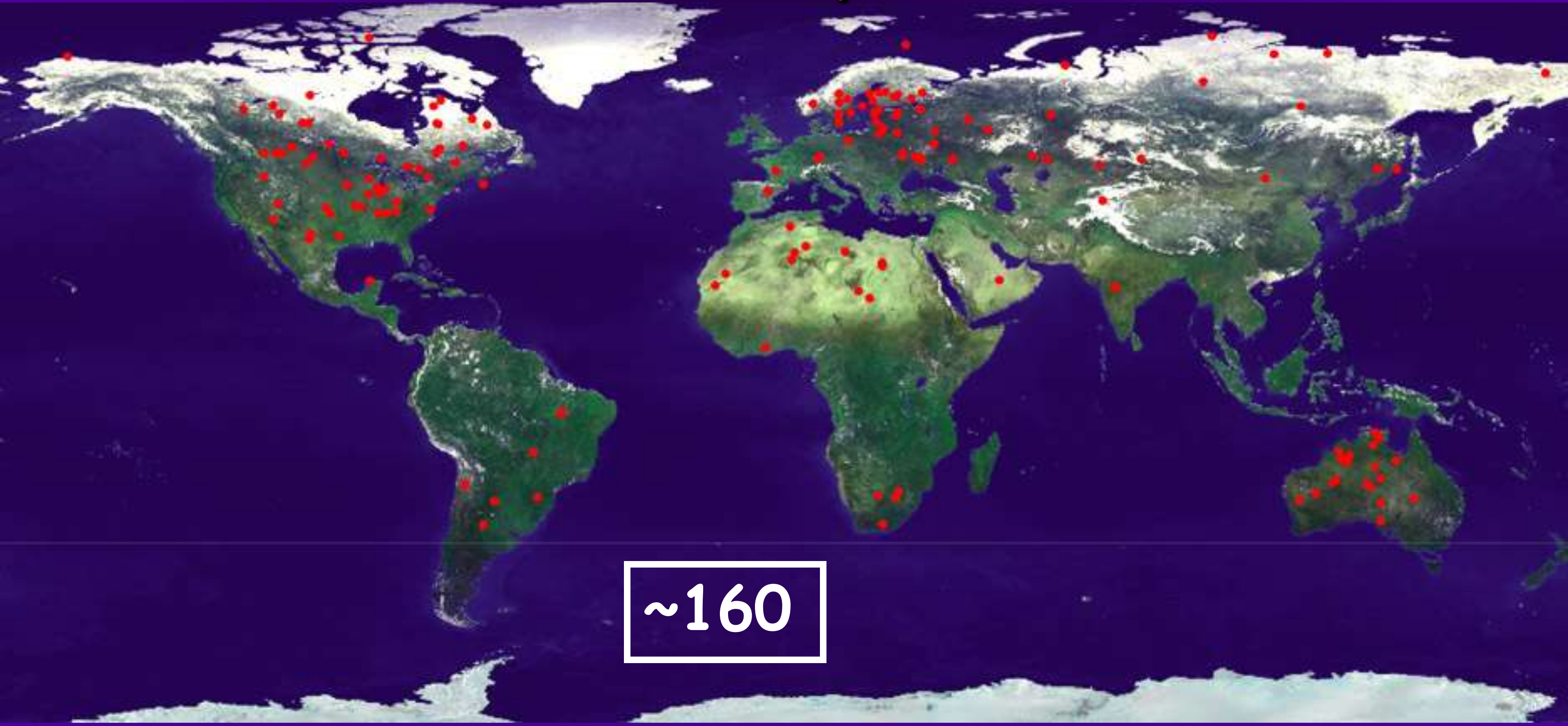


Environmental Effects of Impact Events

Elisabetta Pierazzo

Planetary Science Institute

Earth's Known Impact Structures



Earth has the smallest number of impact craters among terrestrial planets

WHY?

Few impact craters are well preserved on the Earth surface

June 30, 1908
The Tunguska Event

Early morning:

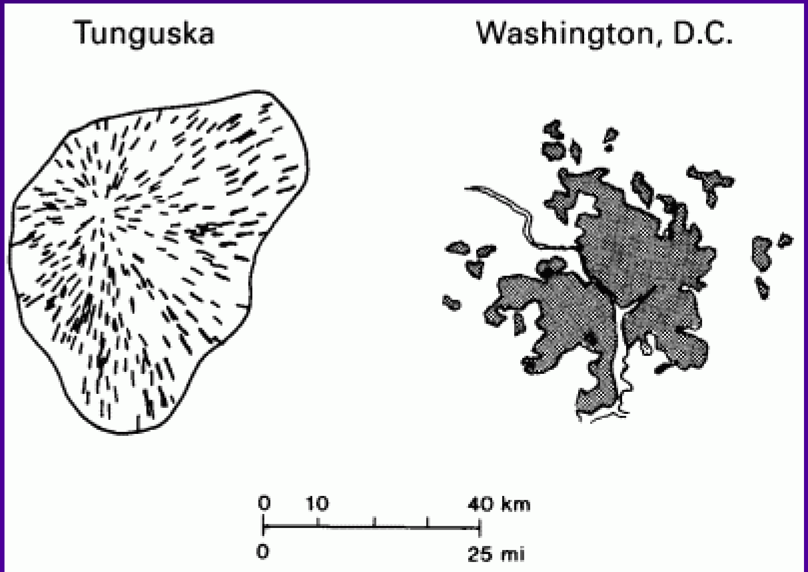
A big fireball raced through the dawn sky over Siberia (Russia)

It exploded in the atmosphere over the Tunguska region with an estimated force of 1,000 Hiroshima bombs

- The atmospheric shock wave knocked people off their feet and broke windows up to 650 km (400 miles) away
- For few weeks, night skies were so bright that one could read in their light

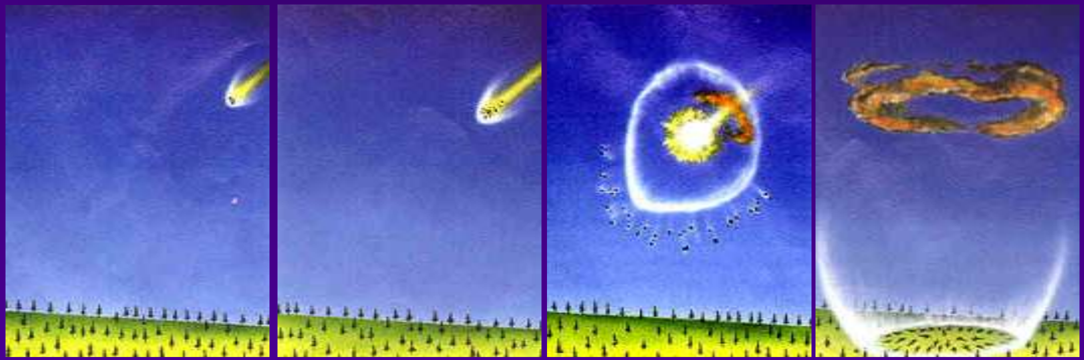
Tunguska: No crater!

- **1927:** The first expedition to the site found a region scorched trees about 50 km across and no crater!
  - Most trees had been knocked down pointing away from the center ("ground zero")
- Later expeditions found evidence of extraterrestrial material



What happened?

- It was the airburst of a meteor 6 to 10 kilometers above the Earth's surface
- Near ground zero, the tree were knocked down by the shock wave produced by such large explosion, similar to the effects observed in atmospheric nuclear tests in the 1950s and 1960s



- Alternate Explanation: the Tunguska event is the result of an exploding alien spaceship or an alien weapon going off to "save the Earth from an imminent threat"
  - ➥ No evidence was ever found by UFO simpathizers

Asteroids Hazard

Bolides (energy < 5 MT) – ***no crater***

- Great fireworks display, no damage

Small Impact (< 15 MT; *Tunguska-class*) –***crater ~1 km***

- Damage similar to large nuclear bomb (*city-destroyer*)
- Average interval for whole Earth: 100 years
- Minor risk relative to other natural disasters (*earthquakes, etc.*)

Larger local catastrophes (*e.g.* 10,000 MT) – ***crater ~10 km***

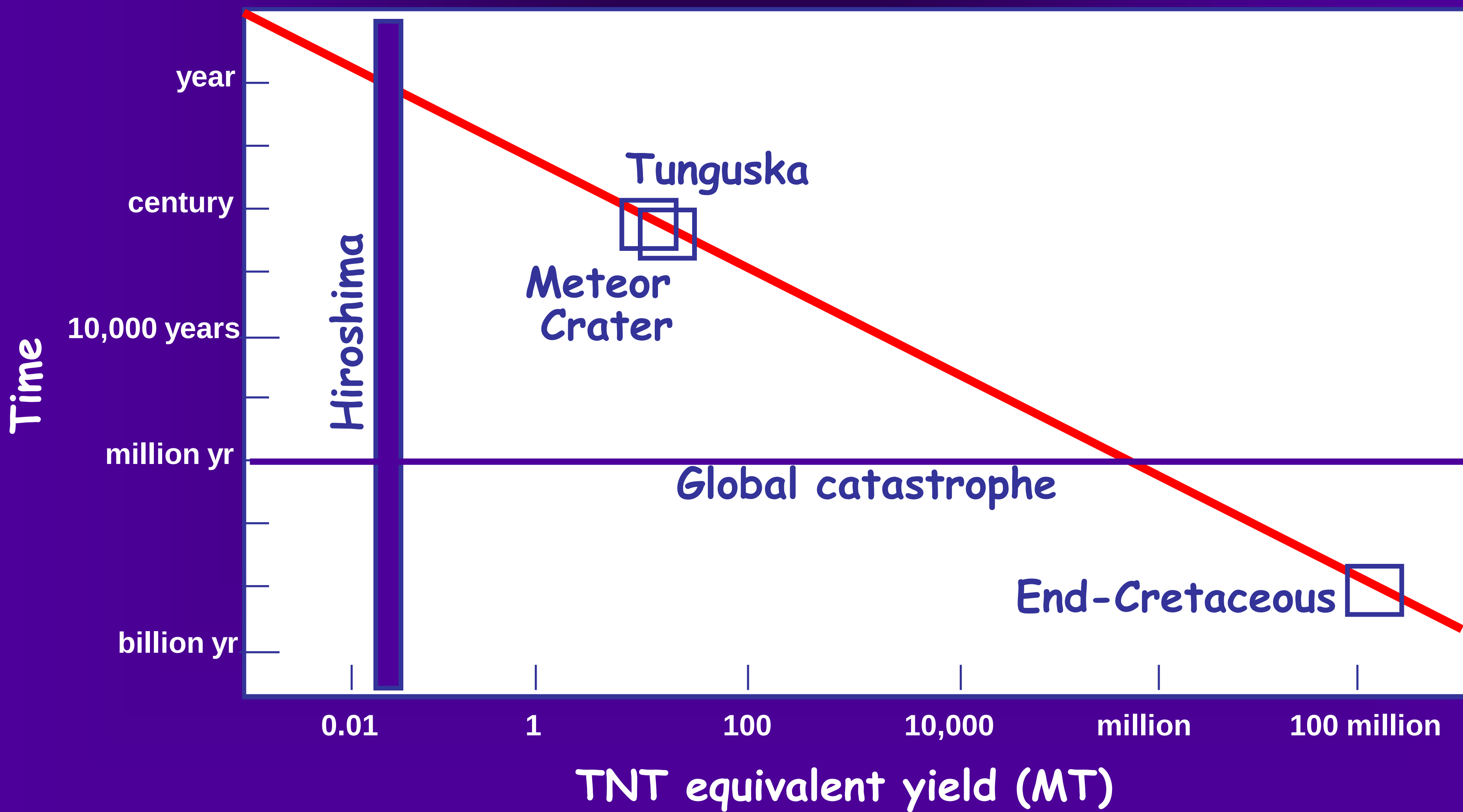
- Destroys area equivalent to small country
- Average interval for whole Earth: 100,000 years
- Moderate risk relative to other natural disasters

Global catastrophe (> 1 million MT) – ***crater >50 km***

- Global environmental damage, threatening civilization
- Average interval for whole Earth: 1 million years
- Major risk relative to other natural disasters

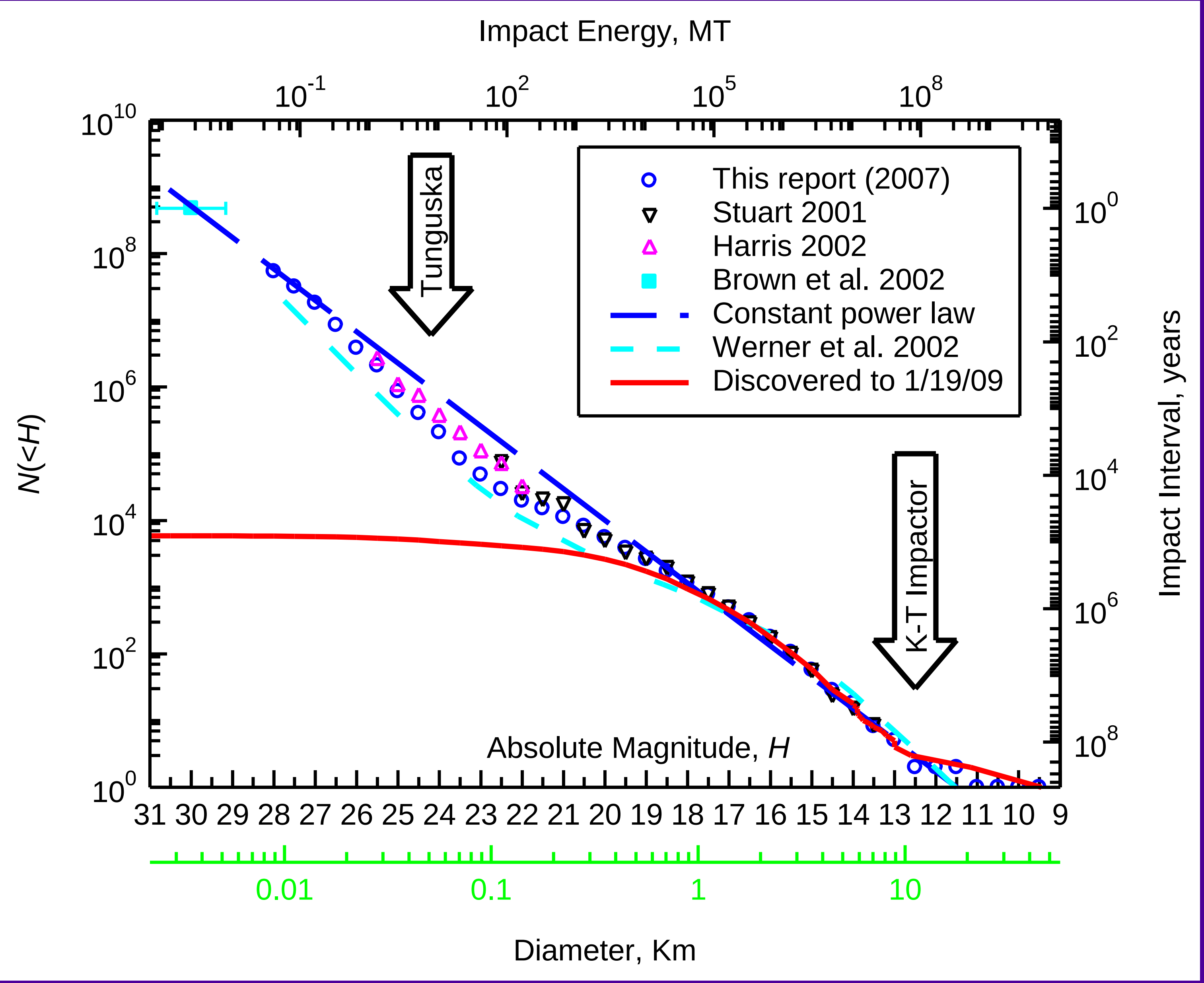
1 MT= 1 Mton TNT equivalent= 4.2×10^{15} J

Terrestrial Impact Frequency



1 MT= 1 Mton TNT equivalent= 4.2×10^{15} J

Cumulative Population



Asteroids Hazard:
Comparison with Other Risks

Statistical risk of death from impacts: ~1 **in a million per year**
(risk is about 1:20,000 over lifetime)

- Much less than auto accidents, shootings (in U.S.)
  Comparable with other natural hazards (earthquakes, floods)
  Near threshold for hazards most people are concerned about

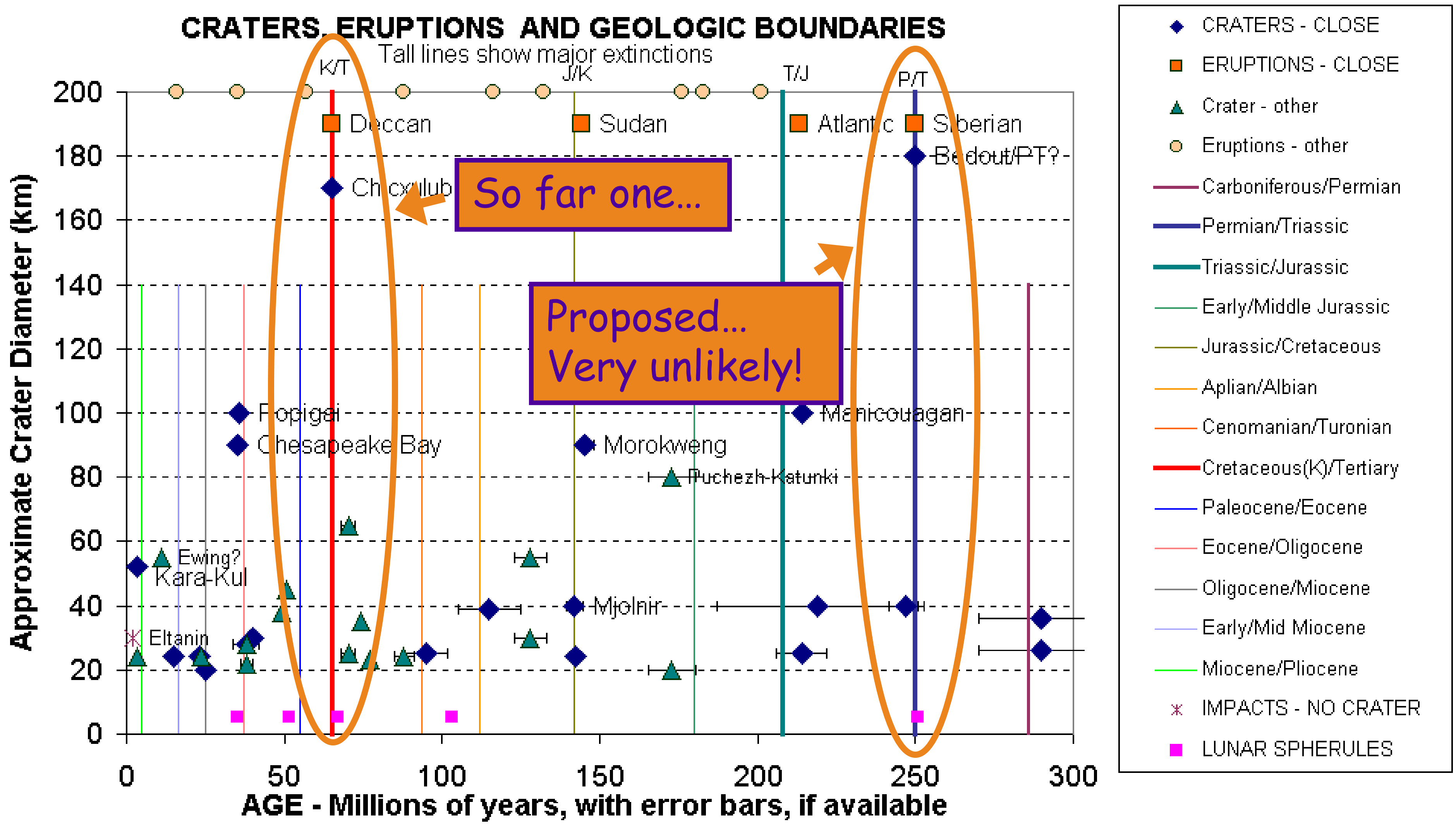
- But…
  A single event can kill millions of people (and other living things) !

- Unique as major threat to civilization (comparable to a global nuclear war)
  - Places the impact-related disaster in a class by itself

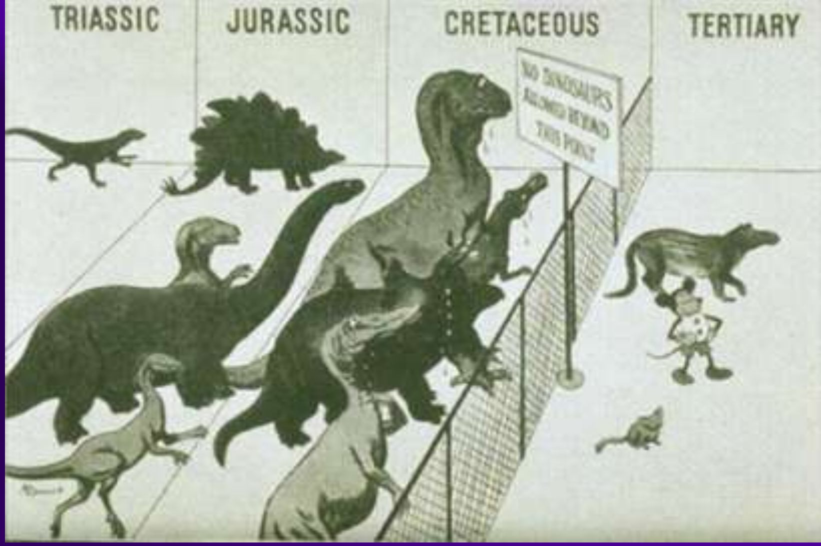
- *Average interval between major impact disasters is larger than for any other hazard we face (millions years)*
  - Causes some to question credibility of hazard

Do Impacts Cause Mass Extinctions?

Nobody knows what causes mass extinctions – Maybe various causes



Cretaceous/Tertiary (KT) Mass Extinction



Mass Extinction:

An episode in history of life where a large number all known species living at that time went extinct in a short period of time (less than 2 million years or so)

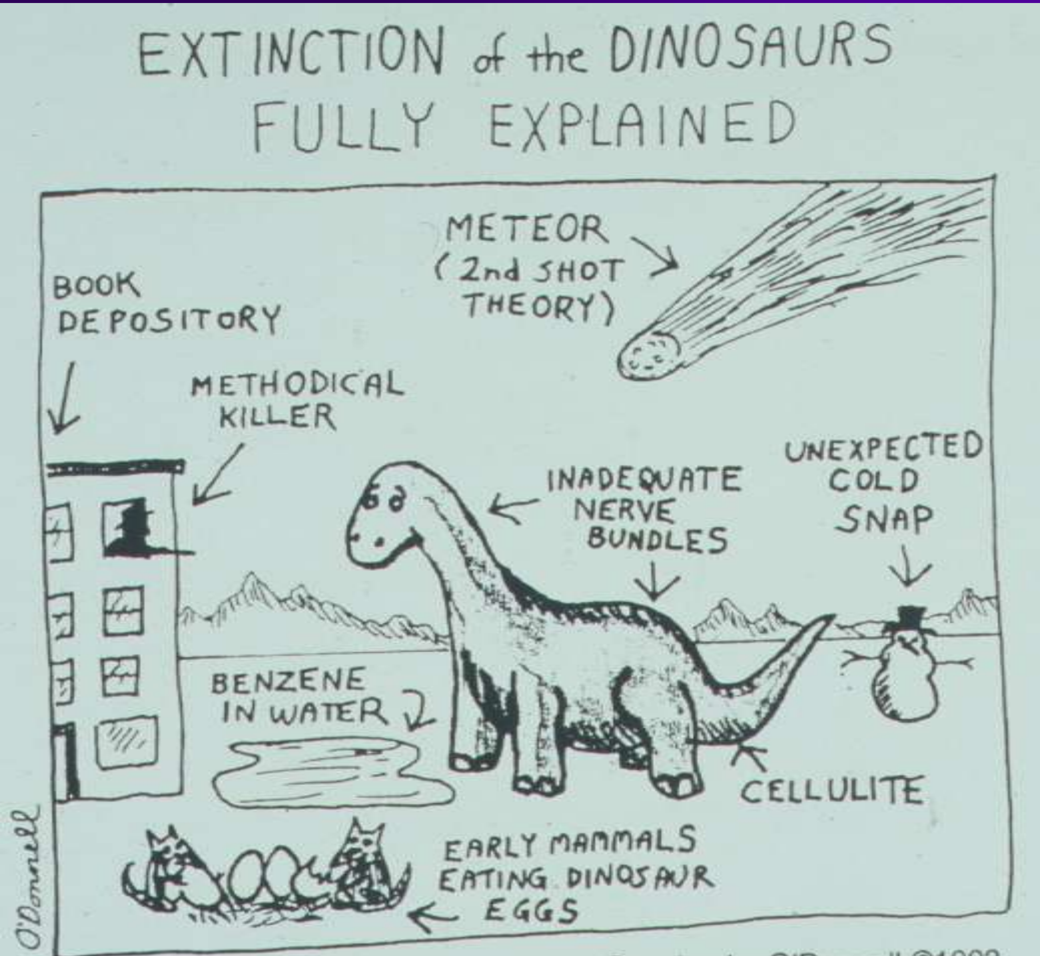
End-Cretaceous (KT) Extinction:

- 65 million years ago at least 75% of animal species went extinct, making it the second largest mass extinction known
  - ↪ fossils found above the boundary are much smaller and less abundant than below
- Many types of fossil disappeared
- Occurs both on land and in the oceans

Is there a connection between the KT impact event and the KT mass extinction?

- Is there a temporal connection?
- Is there a cause-effect connection?
- Are there alternative hypotheses?

What about volcanism, climate change, sea level variations, etc?



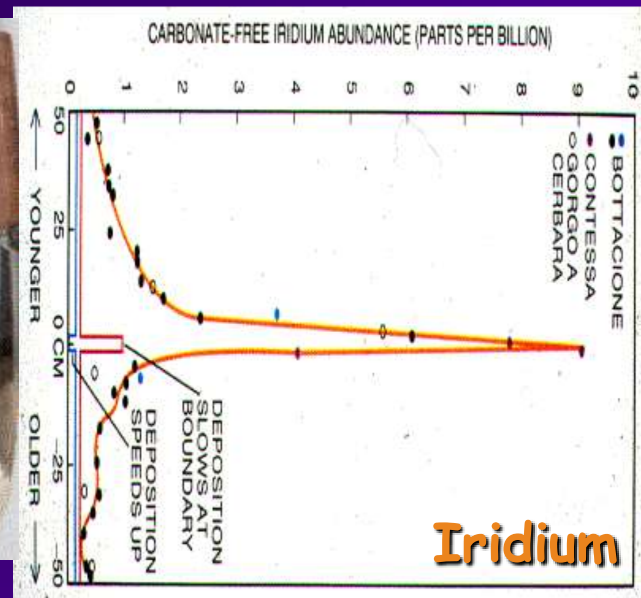
Drawing by O'Donnell ©1992
The New Yorker Magazine, Inc.

Cretaceous/Tertiary (KT) Boundary

- First major stratigraphic boundary identified (*early 1800*)
  - ➥ dramatic change in the types of fossils deposited on either side of this boundary
- Divides the "Age of Dinosaurs" from the "Age of Mammals“

Raton Basin, NM, USA

The Impact Theory

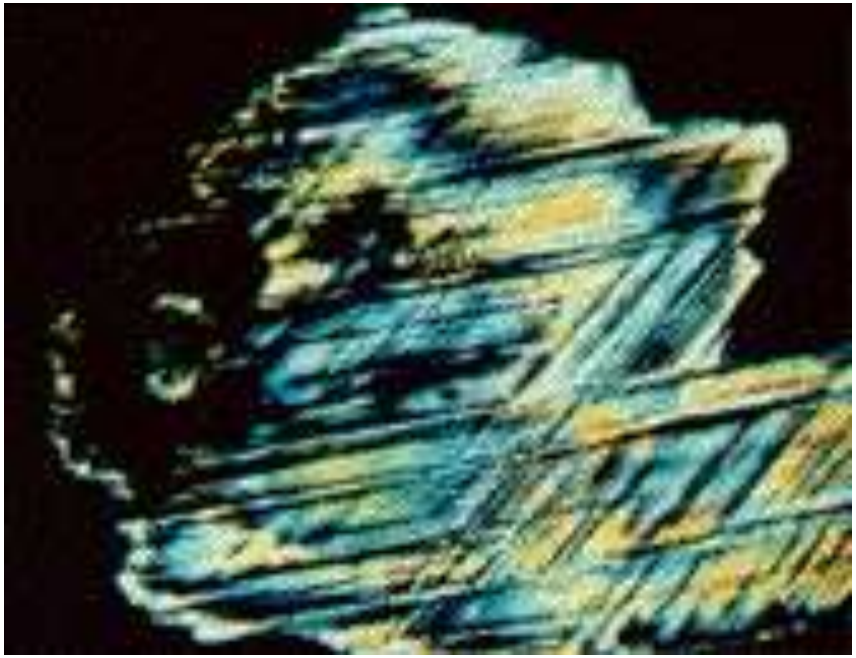


At KT sites worldwide, a thin clay layer separates rocks deposited in the Cretaceous and Tertiary Periods

1980: a team of scientists led by Luis Alvarez (a famous physicist) and his son Walter (a geologist) discovered that the clay layer contains an anomalous high concentration of iridium

- Iridium is more abundant in meteorites, i.e., asteroids than in Earth's surface rocks, so **they proposed that a large asteroid impacted Earth at that time**

One small problem… no obvious crater!



Quartz

Tectitas

Ejemplo: Límite P-T

250 Ma

+

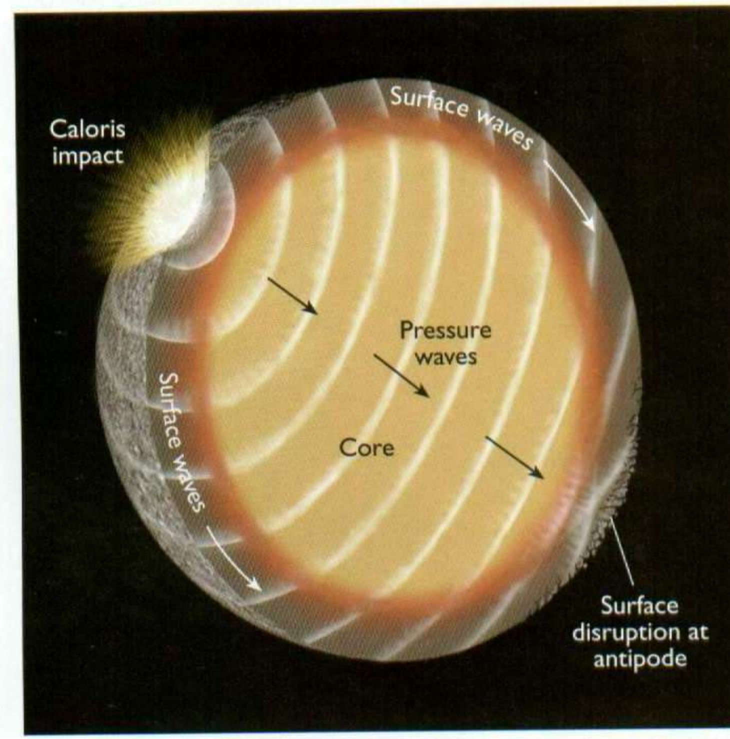
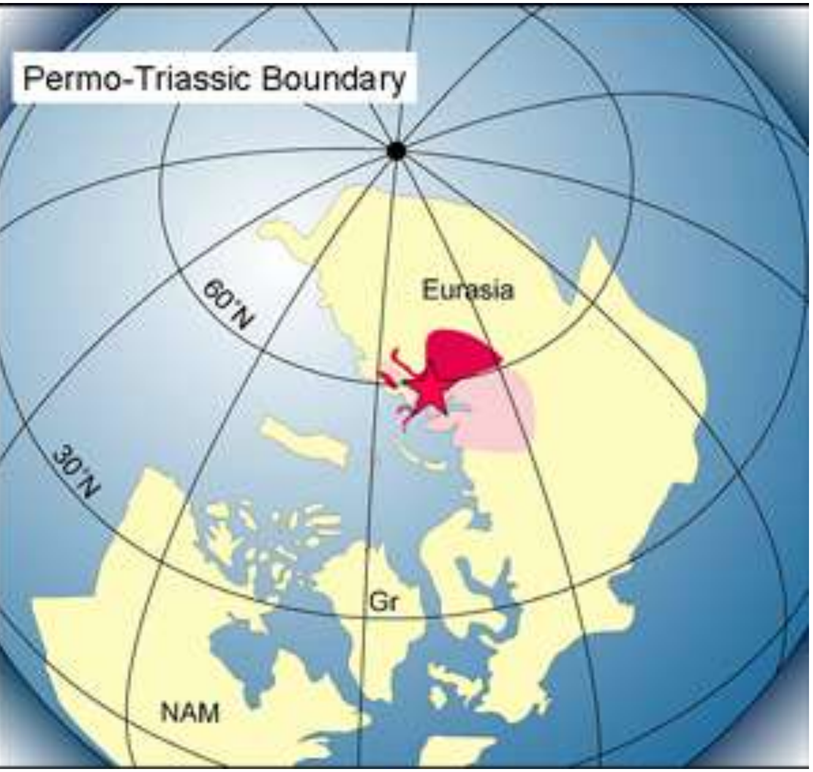


Figure 11. The gigantic impact that created Caloris basin 3.85 billion years ago sent intense seismic waves around and throughout the planet. These came to a focus at the antipodal point, where the ground shook and heaved violently.

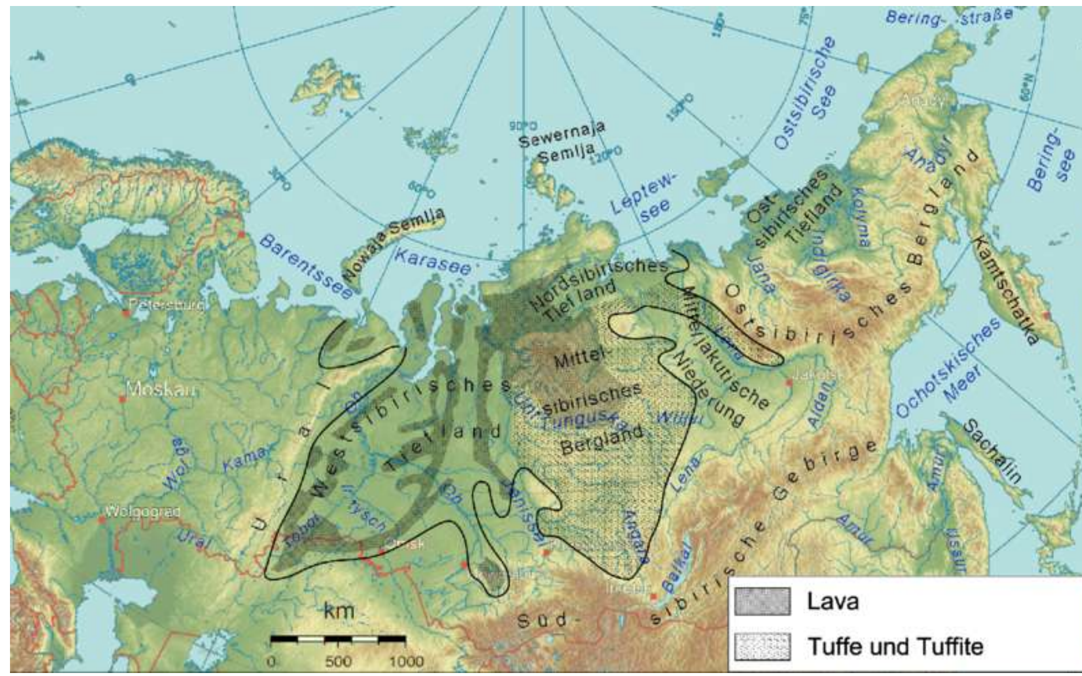
Mercurio

Siberian Traps



Lawver et al. (2002)

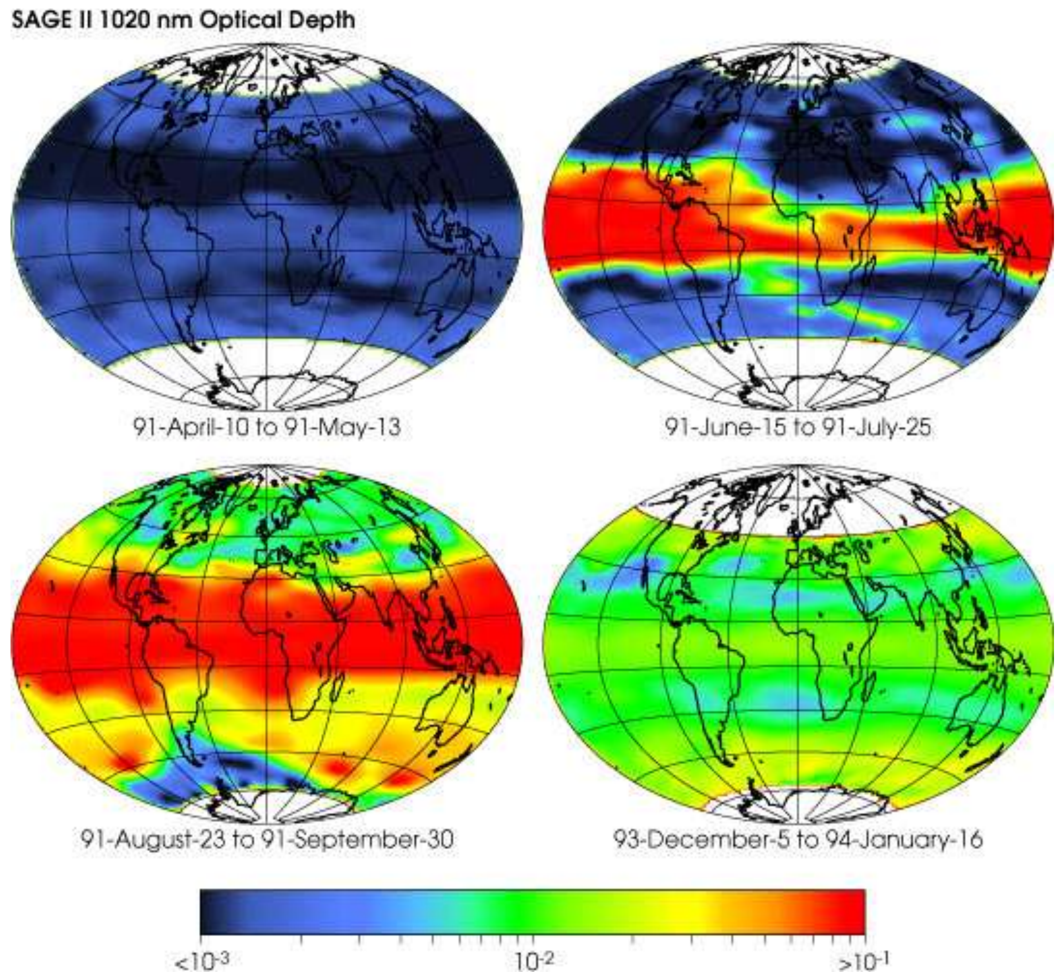
Remanente de intensa y extensa actividad volcánica al N de Pangea en el P-T.



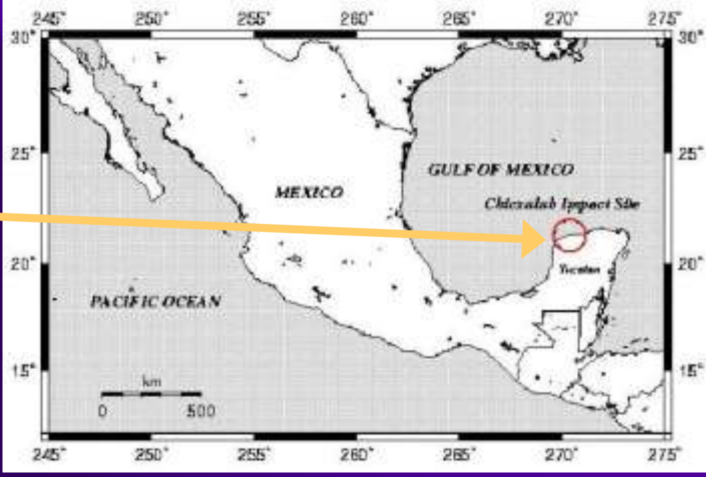
Tipo de roca mas común: basalto, erupciones prolongadas, de años o décadas
Además: dolerite y gabbro

Para tener una idea

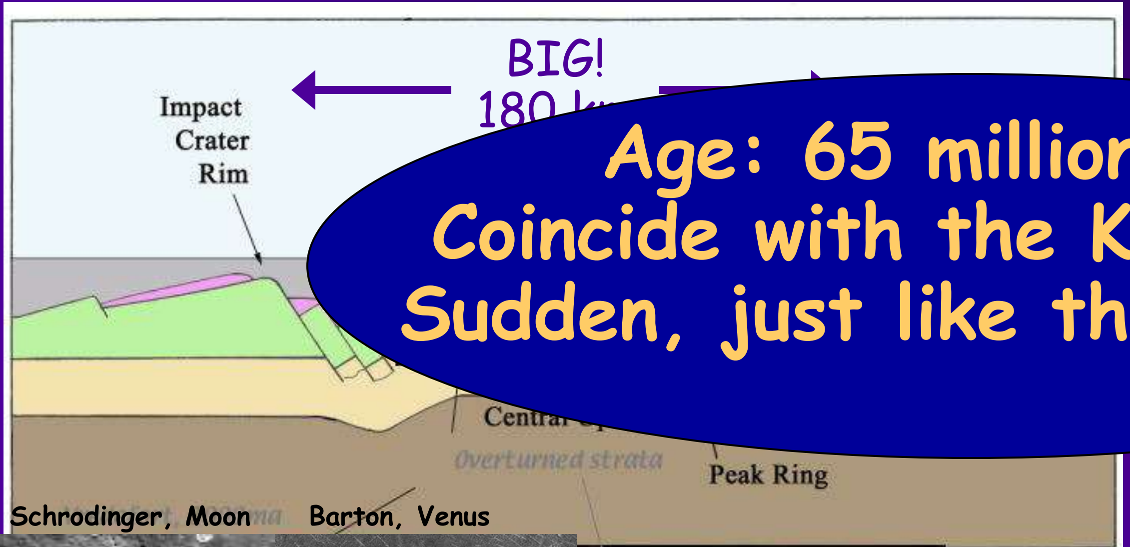
Monte Pinatubo,1991



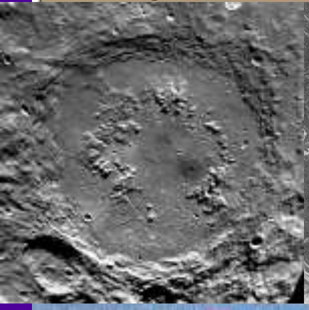
10 years later…
the KT crater!



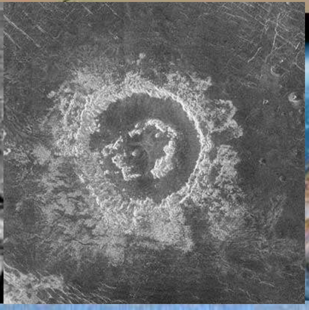
- In the 1990s the Chicxulub crater in the Yucatan peninsula, Mexico was confirmed to be the KT impact crater



Schrodinger, Moon

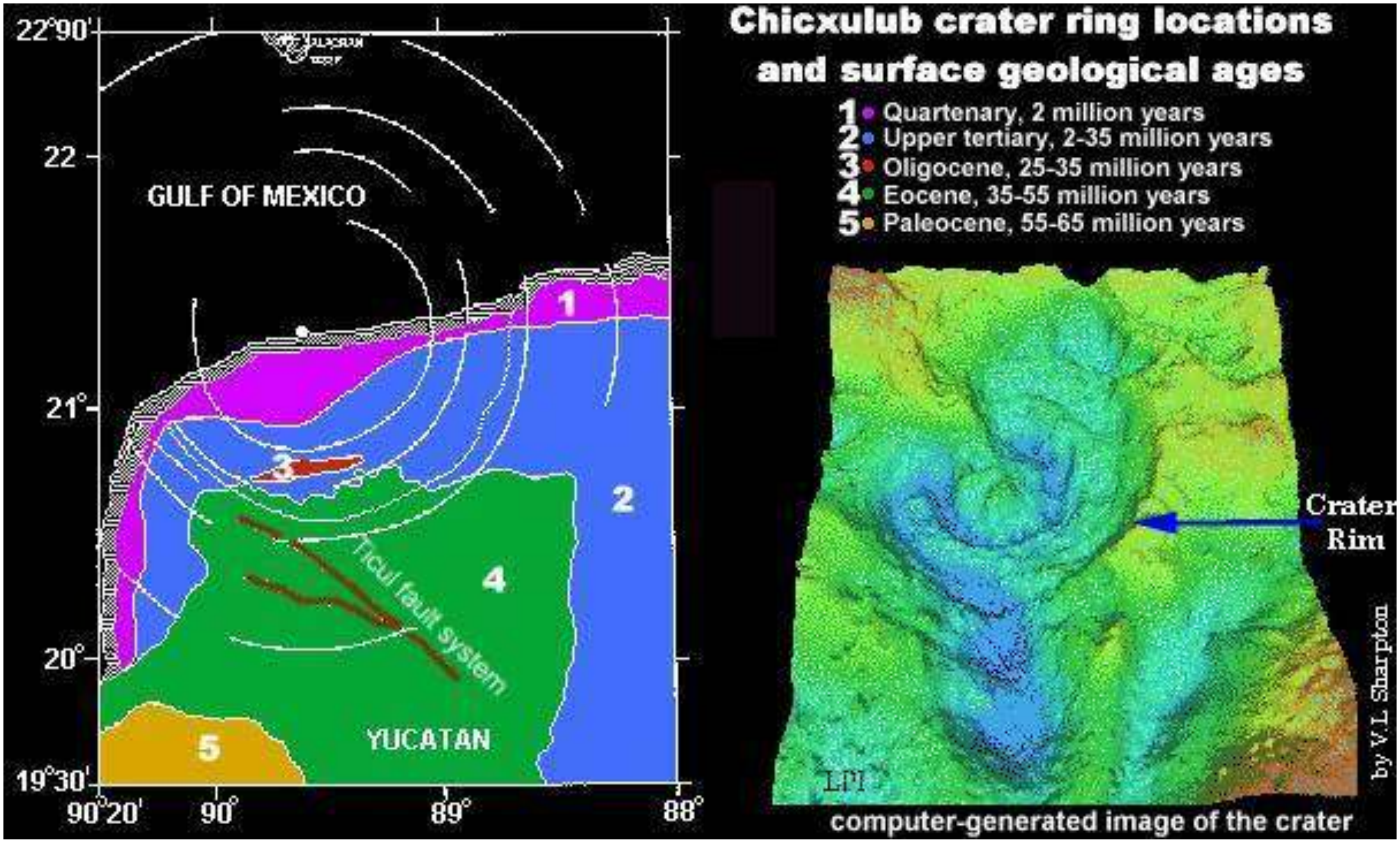


Barton, Venus



Age: 65 million years
Coincide with the KT boundary
Sudden, just like the extinction!

Cráter de Chicxulub



Environmental Perturbations from KT impact:
Short Duration

Tsunami → **Hours**

Waves created by a meteoroid impact in the ocean

Only affects coastal regions

After initial devastation, back to normal

Heat Pulse & Global Wildfires → **Days-Weeks**

IR Radiation emitted by strongly heated upper atmosphere (impact ejecta reentry)

Affects land regions, burning forests and killing above ground animals

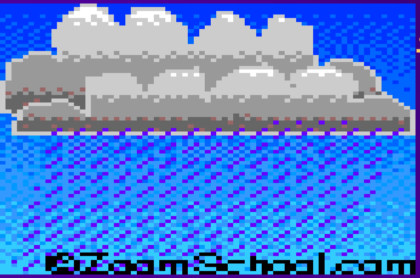
After fires, environment takes a while to recover (smoke filled atmosphere)

Environmental Perturbations from KT impact:
Long Duration

Climate Perturbation → Several Years

Cooling from injection of dust and formation of sulfate aerosols (from S-bearing gases) in stratosphere

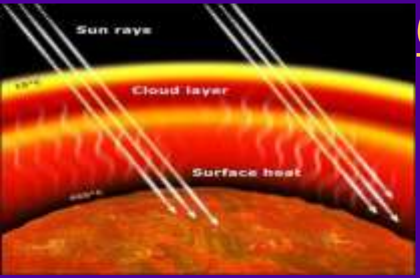
Darkness lasting for months! No photosynthesis



Acid Rain → Several Years

Acid rain due to rainout of sulfate aerosols

Damage to vegetation



Greenhouse Effect → Decades or Longer

Warming from injection of CO_2 in the atmosphere

A bad day 65 million years ago…

…followed by a bad few years!