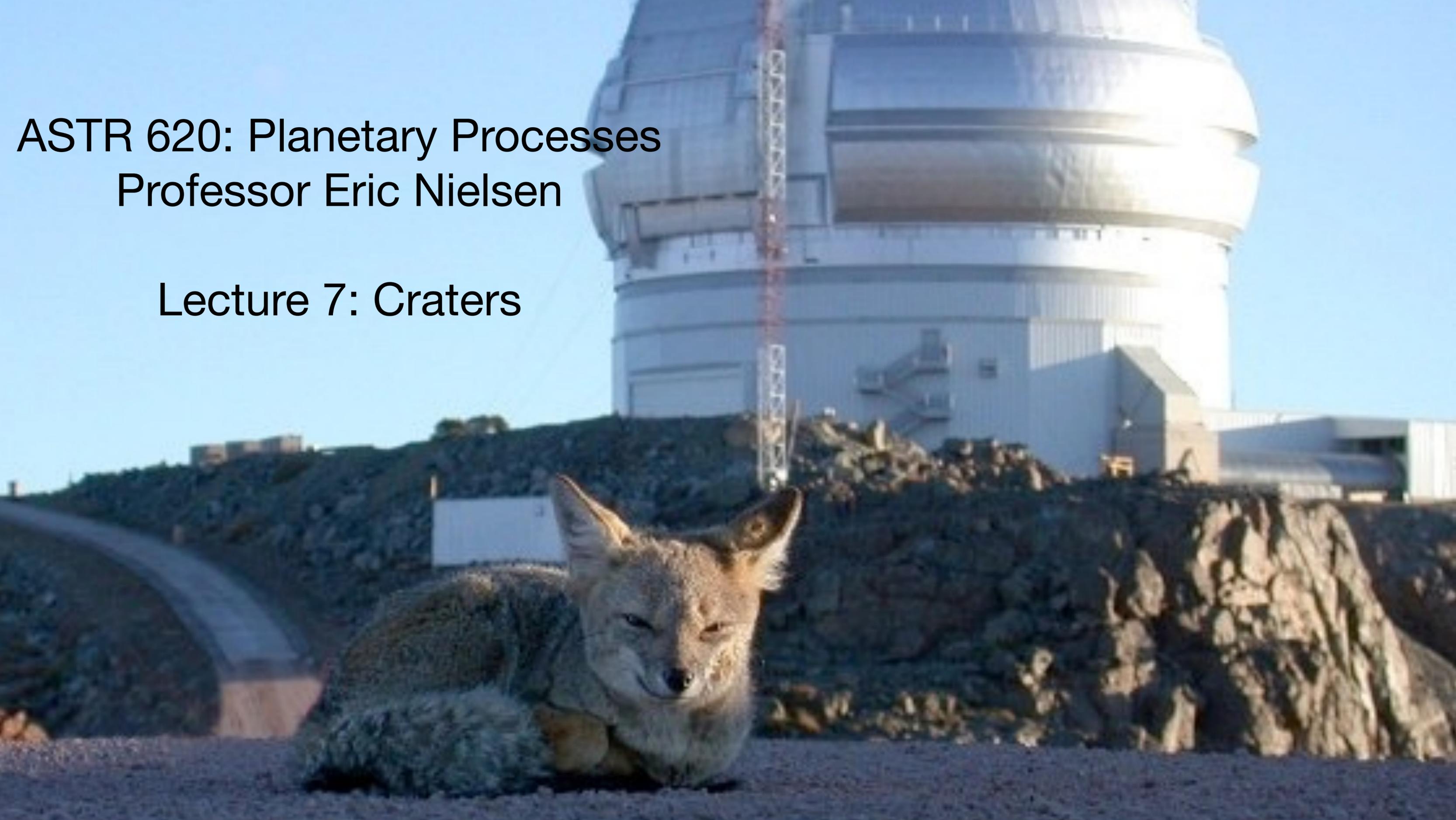


ASTR 620: Planetary Processes
Professor Eric Nielsen

Lecture 7: Craters



Logistics

- Masks are encouraged
- No laptops, phones, or other electronic devices during class (I'll let you know in advance if we'll need laptops for an activity) **You may use a tablet to take notes if prefer, but please only use it for note-taking.**
- Remember to bring you response card to class
- Homework 2 is due Wednesday September 14, 11:59pm

Review of the last class

- Which effects can cause an object to move toward the Sun?
 - (A) — YORP, radiation pressure, Poynting-Robertson Drag, Corpuscular Drag
 - (B) — Yarkovsky Effect, radiation pressure, Poynting-Robertson Drag, Corpuscular Drag
 - (C) — Yarkovsky Effect, Poynting-Robertson Drag, Corpuscular Drag
 - (D) — YORP, Poynting-Robertson Drag, Corpuscular Drag
 - (E) — YORP, Yarkovsky Effect, radiation pressure, Poynting-Robertson Drag, Corpuscular Drag

Review of the last class

- Which effects can cause an object to move away from the Sun?
 - (A) — YORP, radiation pressure, Poynting-Robertson Drag, Corpuscular Drag
 - (B) — Yarkovsky Effect, radiation pressure, Poynting-Robertson Drag
 - (C) — Yarkovsky Effect, radiation pressure
 - (D) — YORP, radiation pressure
 - (E) — YORP, Yarkovsky Effect, radiation pressure, Poynting-Robertson Drag, Corpuscular Drag

Review of the last class

- An object that experiences the “YORP” process:
 - (A) — slows down due to a headwind from solar photons
 - (B) — slows down due a headwind from solar wind particles
 - (C) — changes its orbit due to day/night temperature differences and rotation
 - (D) — changes its rotation rate due to day/night temperature differences and rotation
 - (E) — moves outward due to momentum transfer from solar photons

Review of the last class

- The force of gas drag is larger for:
 - (A) — Larger objects, traveling faster, in a denser atmosphere
 - (B) — Smaller objects, traveling faster, in a denser atmosphere
 - (C) — Larger objects, traveling slower, in a denser atmosphere
 - (D) — Larger objects, traveling faster, in a less dense atmosphere
 - (E) — Smaller objects, traveling slower, in a less dense atmosphere

Review of the last class

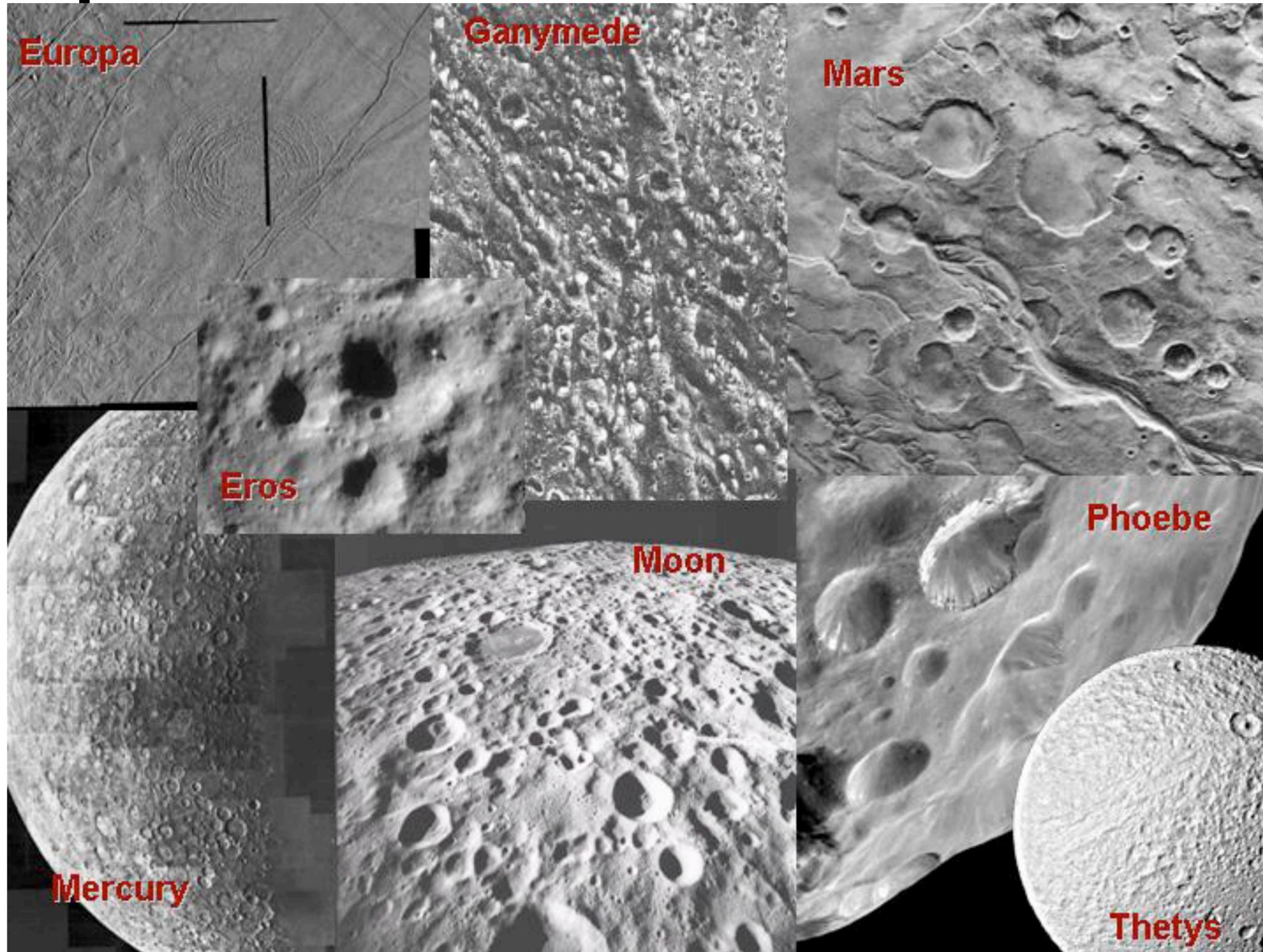
- The reason the Yarkovsky Effect is less important for larger asteroids is:
 - (A) — Large asteroids don't rotate
 - (B) — Surface area scales as R^2 , volume as R^3
 - (C) — Large asteroids have a very different albedo from small asteroids
 - (D) — The day/night temperature difference on large asteroids is very small
 - (E) — Large asteroids are transparent

Impact Craters

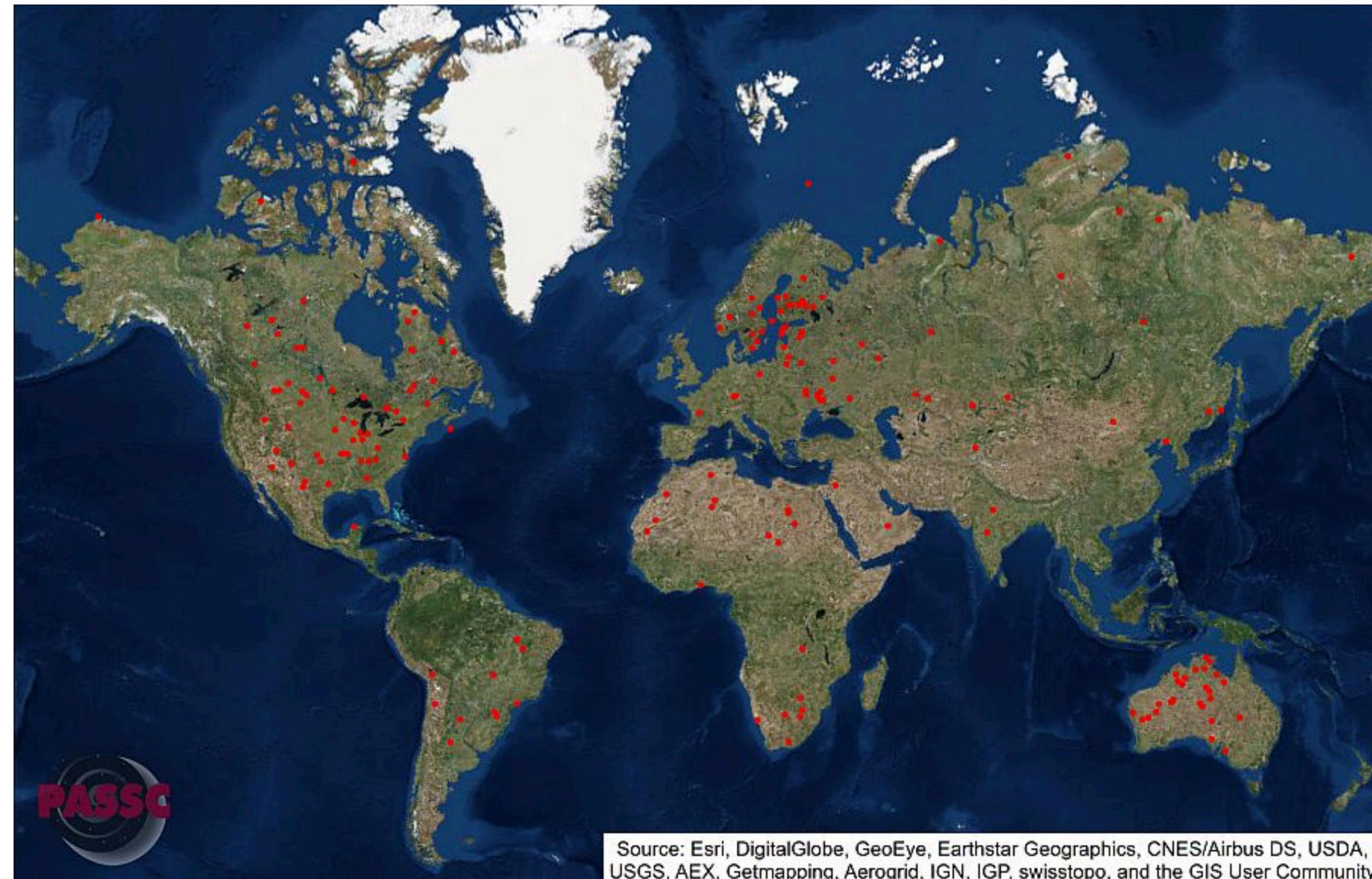
- Solar system bodies with solid surfaces (like Earth!) have been significantly shaped by impact craters
- Collisions on Earth have shaped the crust and altered its geological history
- State-of-the-art has been advanced by spacecraft images of other bodies, and better detection of craters here on Earth



Impact Craters



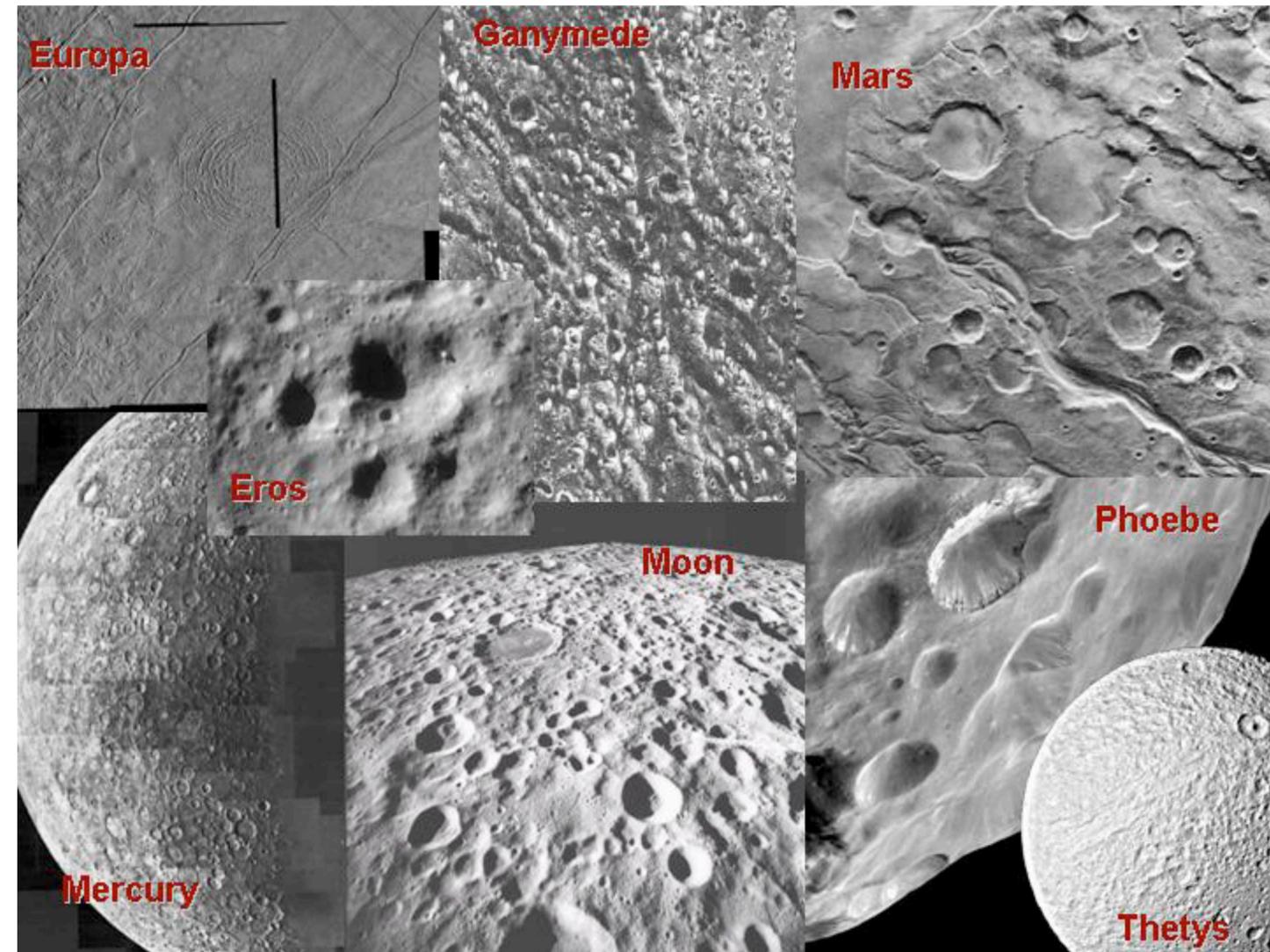
Impact Craters



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

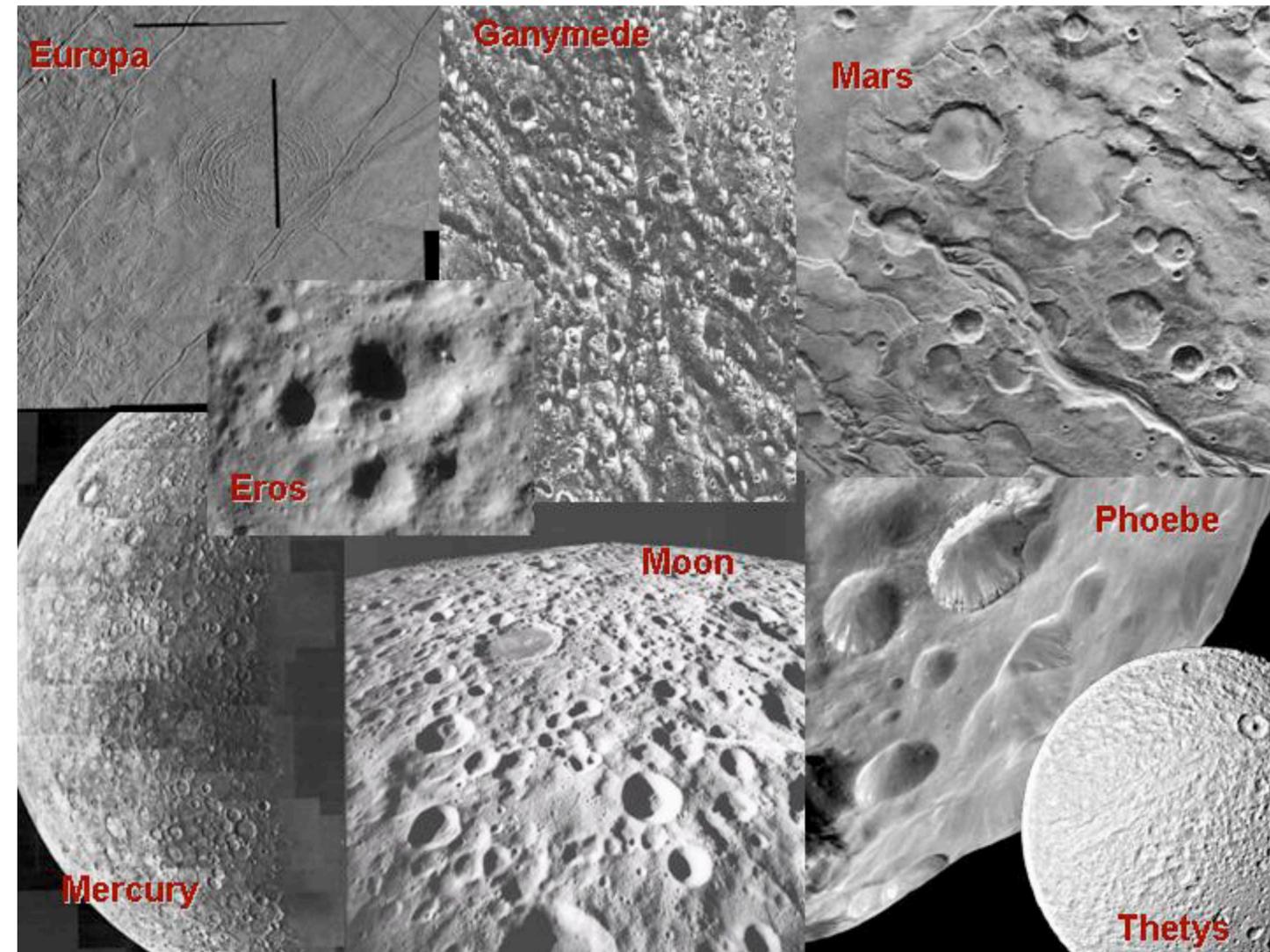
Impact Events

- Compared to other geological events (e.g. volcanism, plate tectonics):
 - Rare
 - Immense energy (an impactor a few meters across releases energy equivalent to an atomic bomb)
 - Energy is released over a timescale of seconds
 - Extreme physical conditions (temperature, pressure)
 - shock-metamorphic effects (rocks react differently to extreme conditions imposed by shock wave)



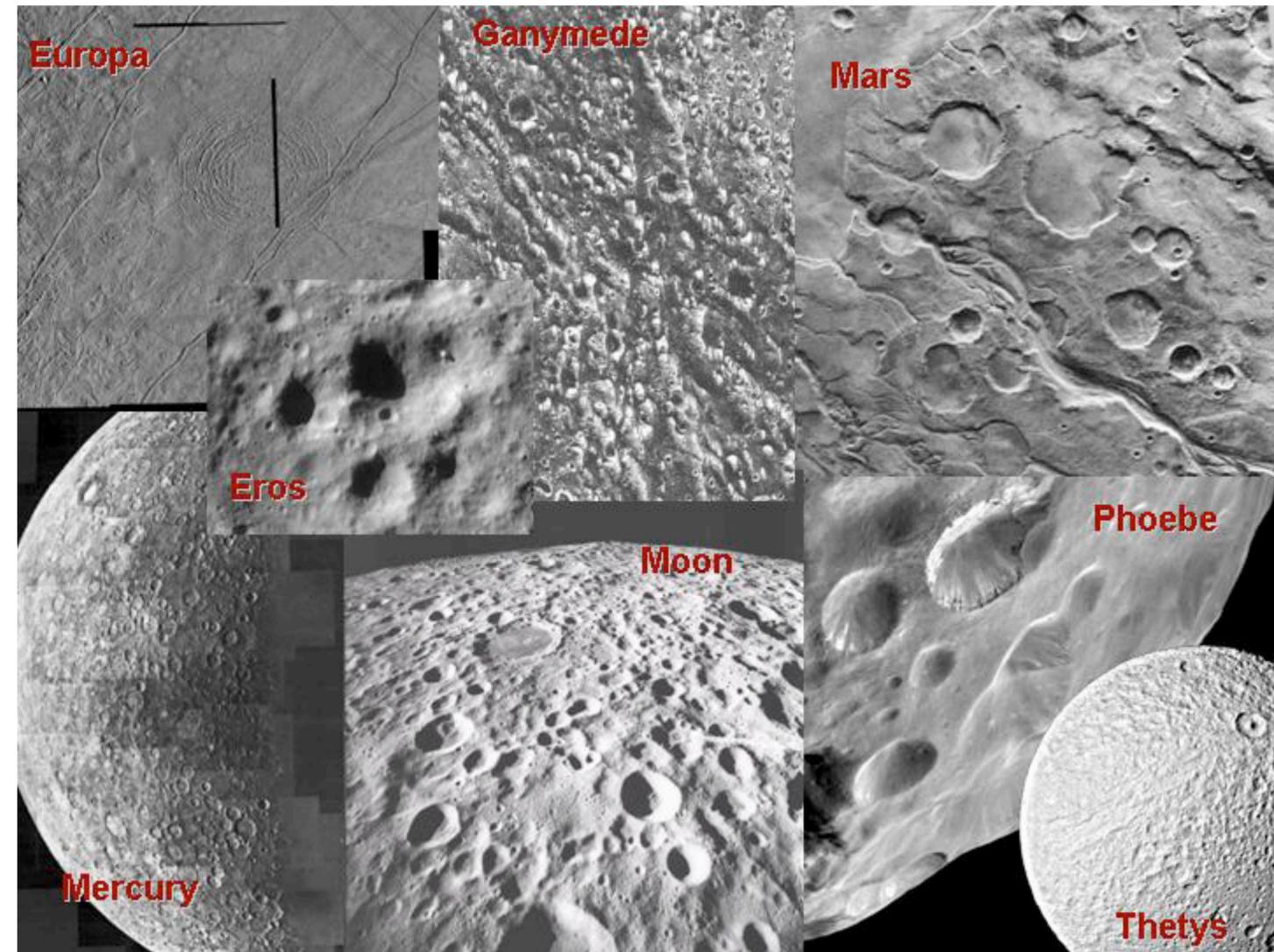
Scientific Value of Impacts

- Crater number provides a relative age of a surface
- Crater size distribution (number per crater diameter bin) provide an estimate of size distribution of impactors
- Crater-forming impacts can reveal typically-hidden sub-surface material



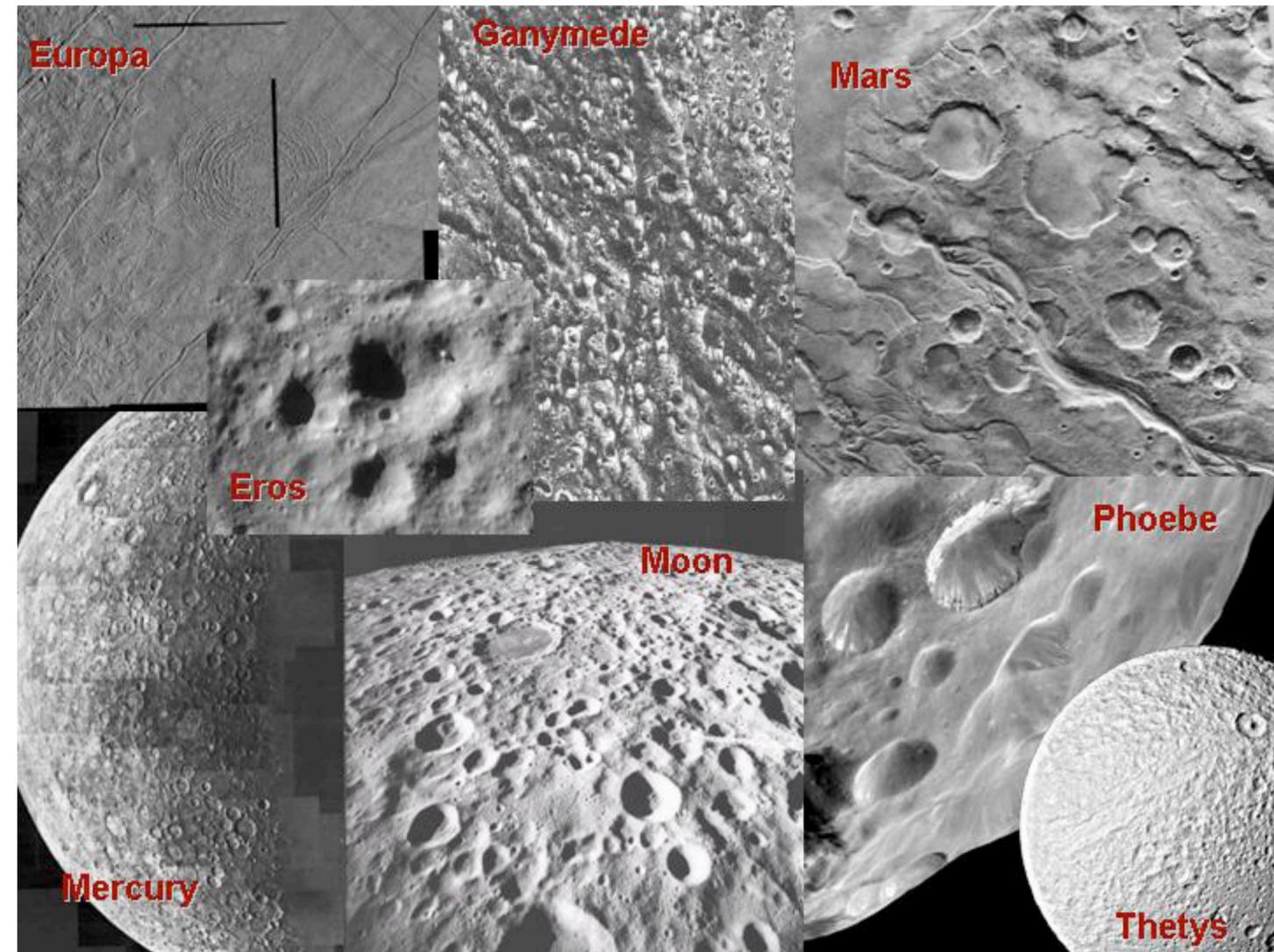
History of Crater Study

- Galileo observed craters on the Moon
- Long thought to be volcanic in origin
- In 1970s were connected to impacts
- Study of craters blends astronomy, geology, and theoretical/experimental work on impact physics



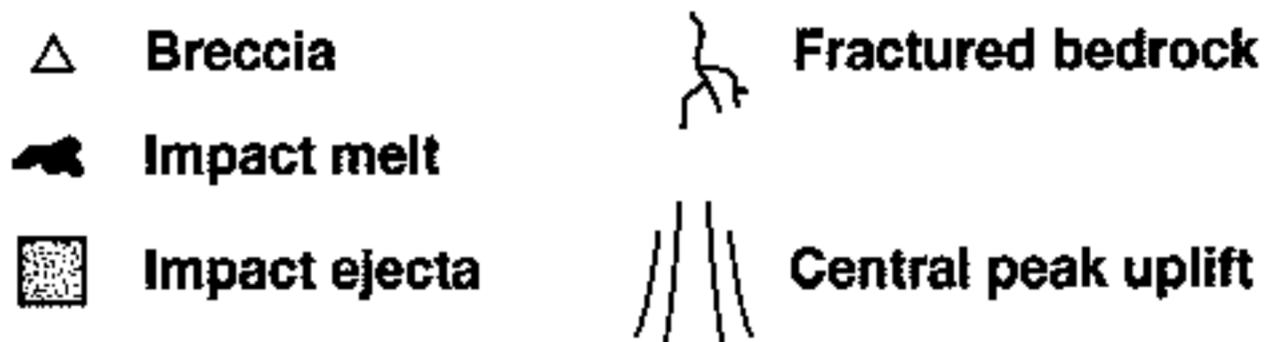
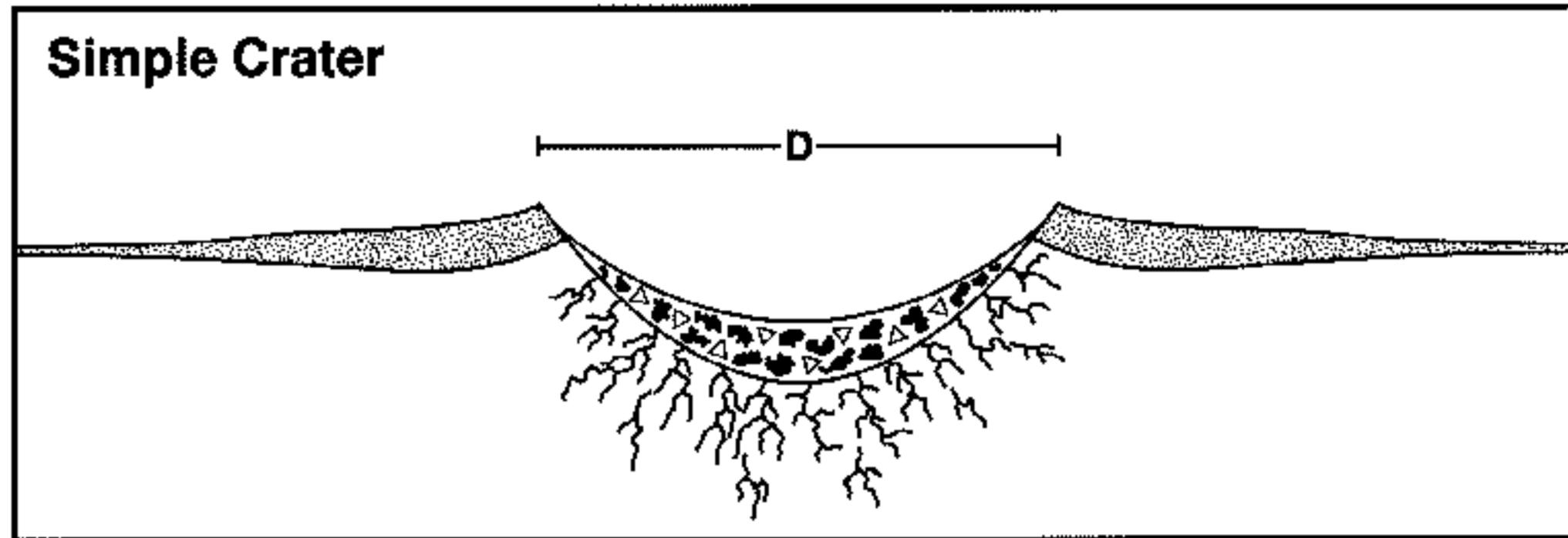
Types of Craters

- Morphology of Craters depends on impactor energy (and so size)
- Simple craters (smaller impact energies)
- Complex craters (larger impact energies)
- Multi-ring basins (even larger impact energies)



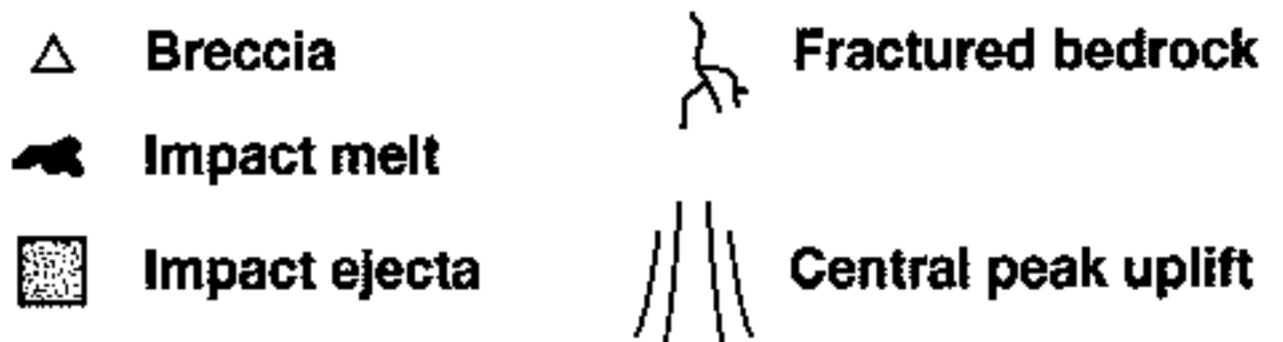
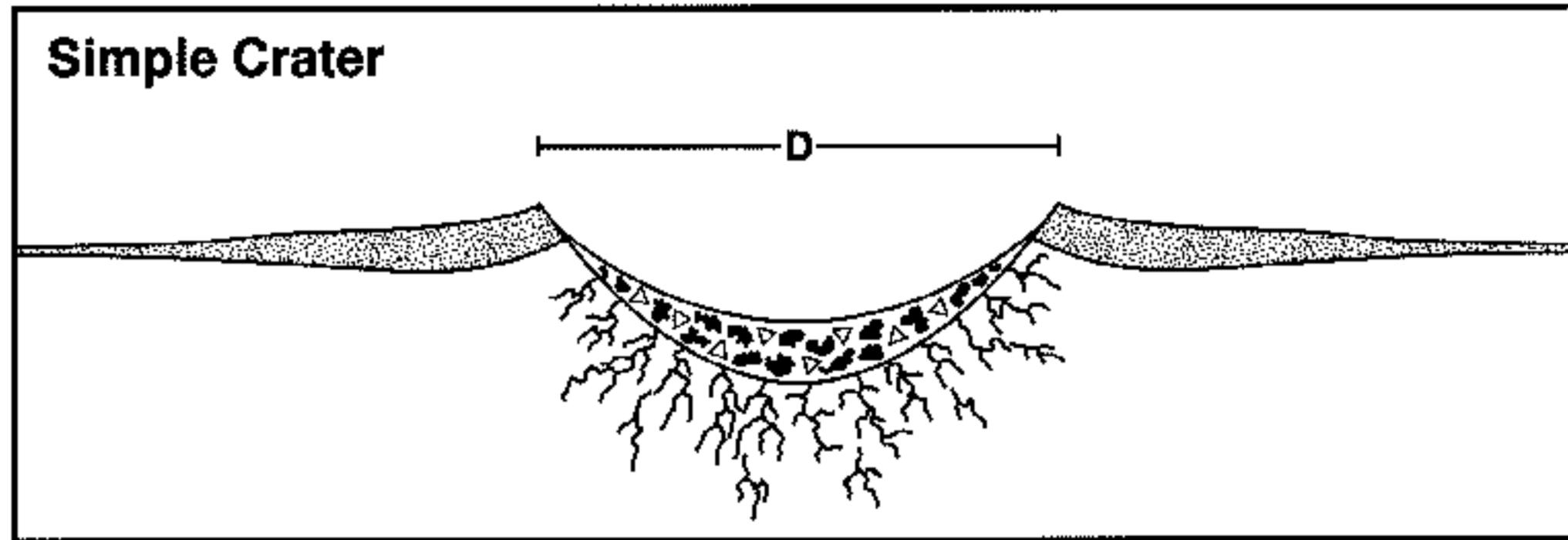
Simple Craters

- (smaller impact energies)
- Circular raised rim
- Profile of crater's interior nearly parabolic
- No central peak
- Breccia: sedimentary rock created in the impact event



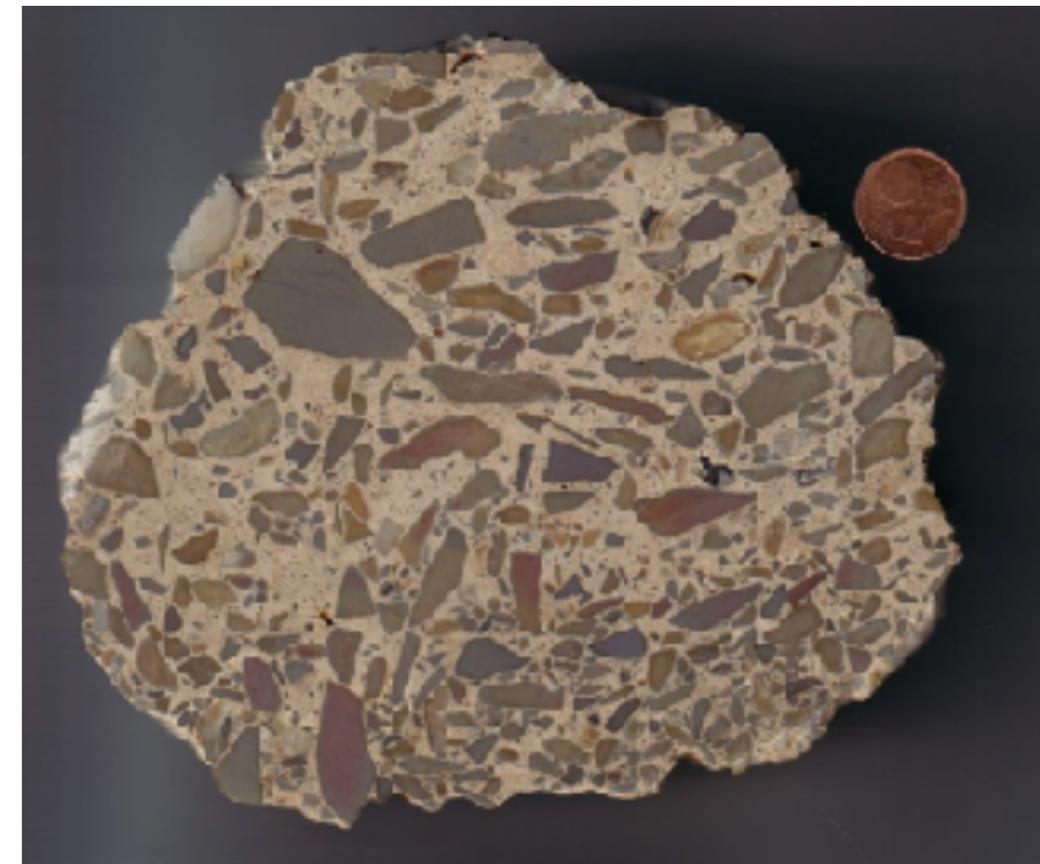
Simple Craters

- Ratio of depth to diameter about 0.2
- Rim height (above unperturbed, pre-impact surface) about $0.04 \times$ rim-to-rim diameter
- No lower diameter boundary, but maximum diameter boundary that depends on gravitational acceleration g
 - above that maximum diameter get complex craters



Breccia

- Created during impacts
- Sedimentary rock composed of large (>2 mm) angular fragments that are cemented together
- Angular fragments suggest they have not been transported far from their source
- Matrix (the stuff in between the angular fragments) that cements it together is fine-grained silt



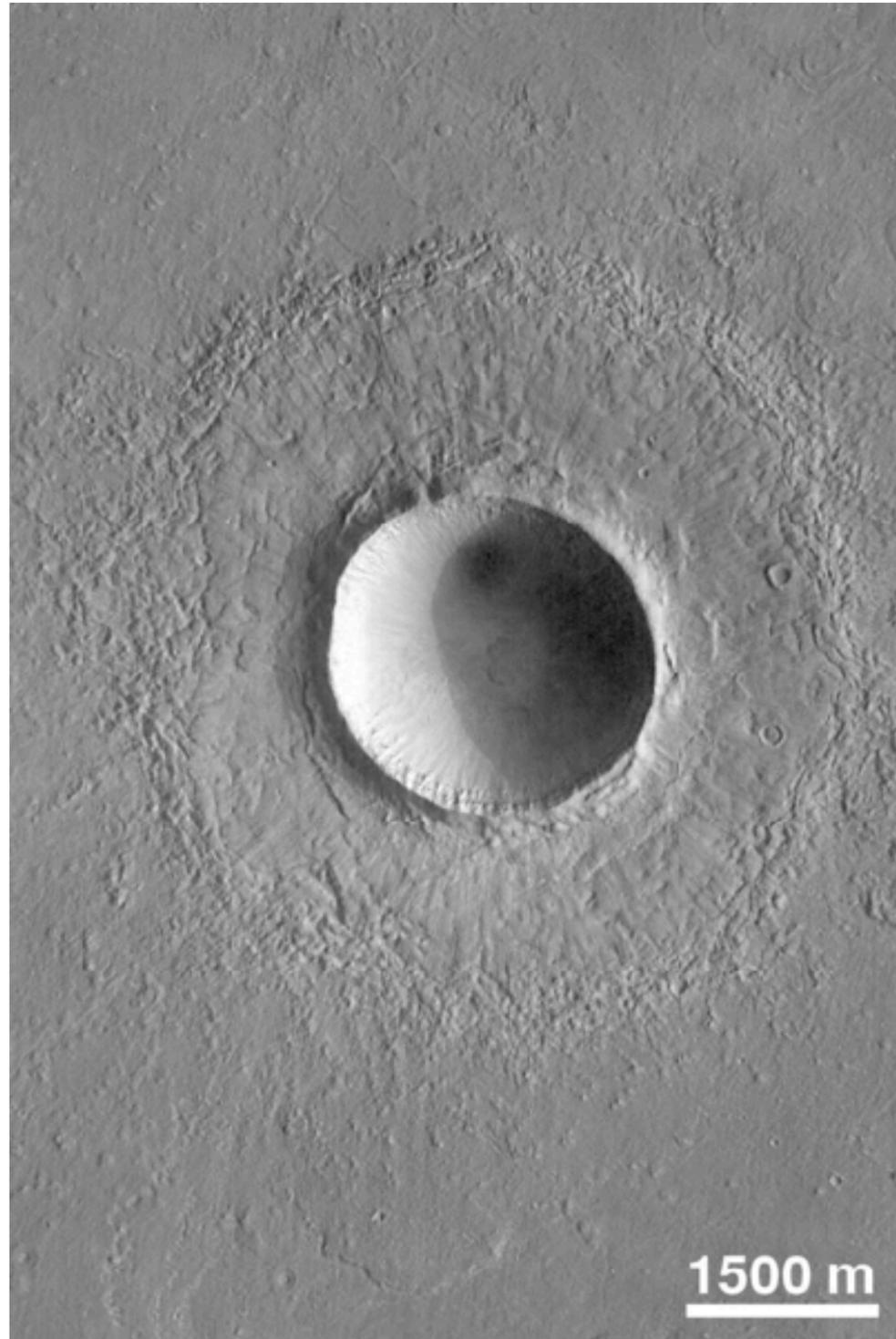
impact-structures.com



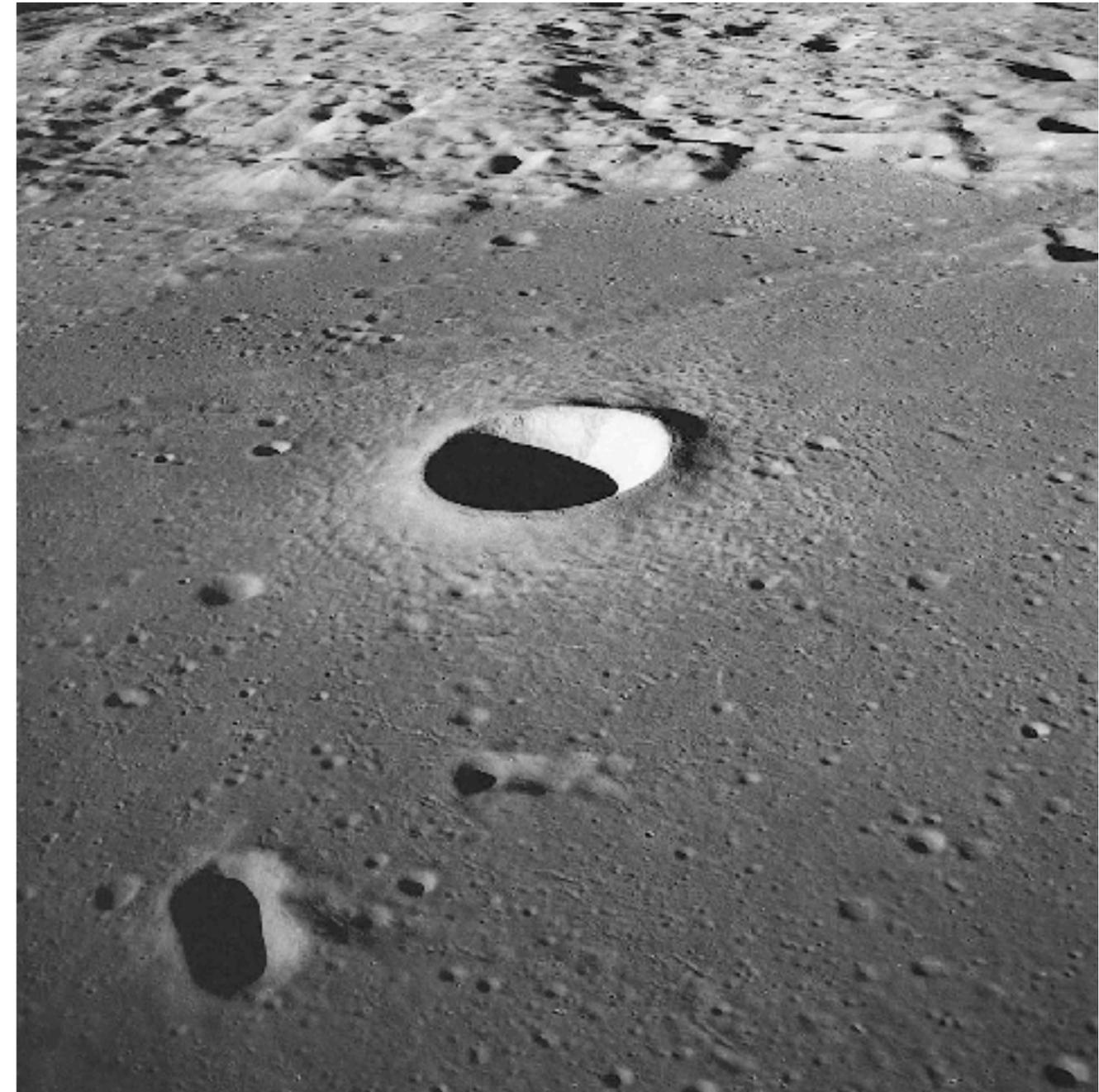
Titus Canyon, Death Valley



Simple Craters

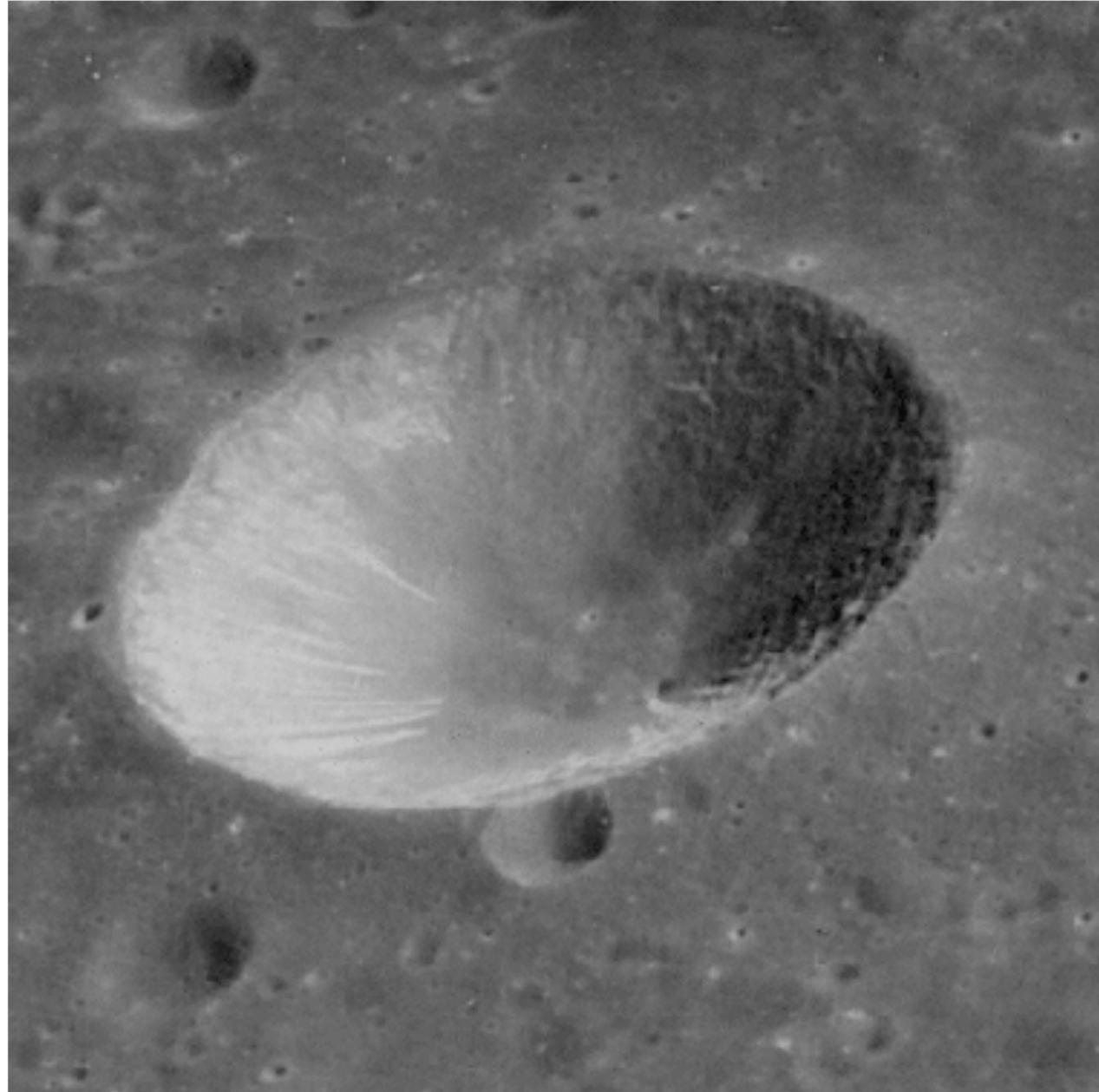


Mars



Moon

Simple Craters



- The largest simple craters have oversteepened walls that collapse over time

- Meteor Crater, AZ
 - $D \sim 1100$ m
 - depth ~ 150 m (at time of formation)
 - rim height ~ 65 m (at time of formation)



Complex Craters

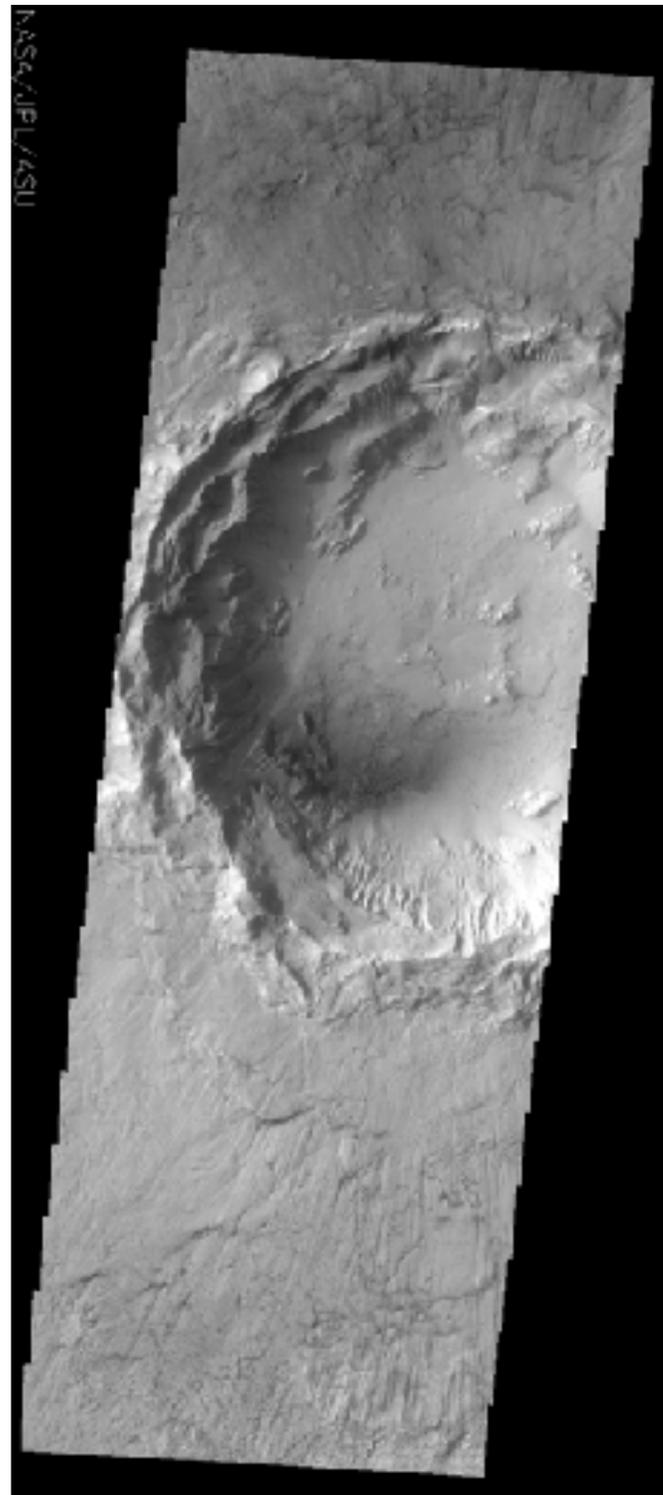
- Central peak composed of uplifted material from below crater center
 - Central peak is the major structural difference between complex craters and simple craters
- Depth-to-diameter ratio decreases
- More flat-bottomed structure
- Land slides (slumping) near crater rim
- More melting of surface material



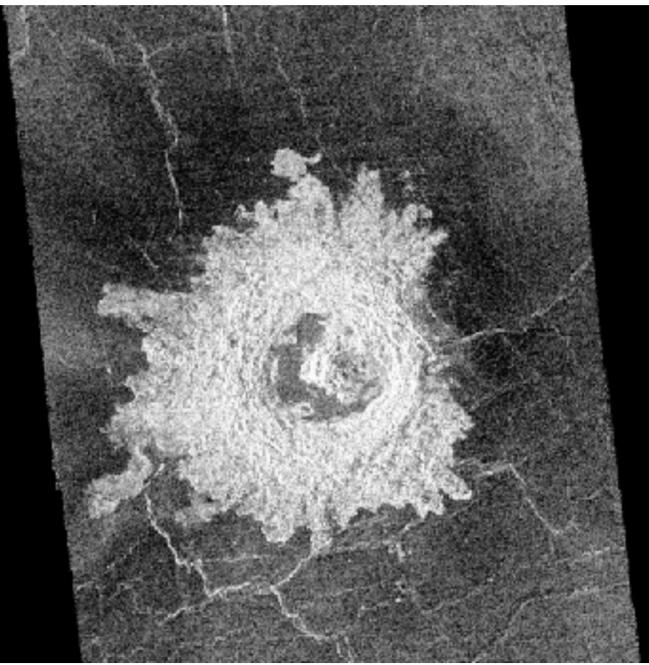
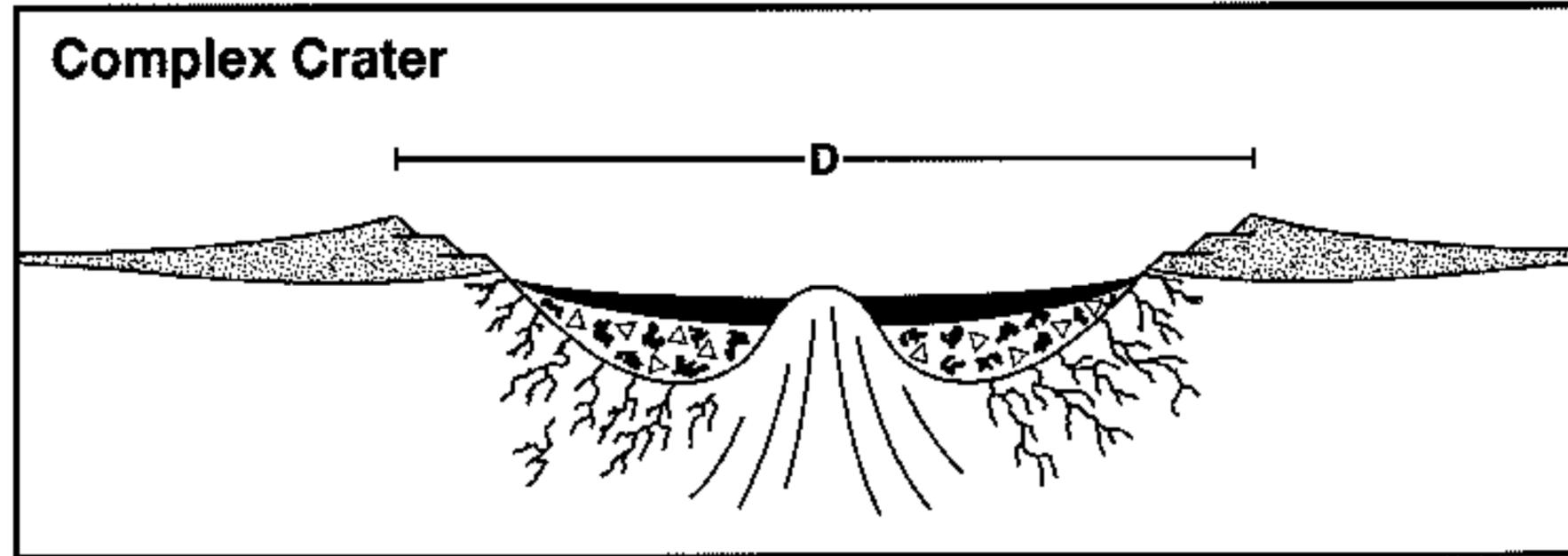
Complex Craters



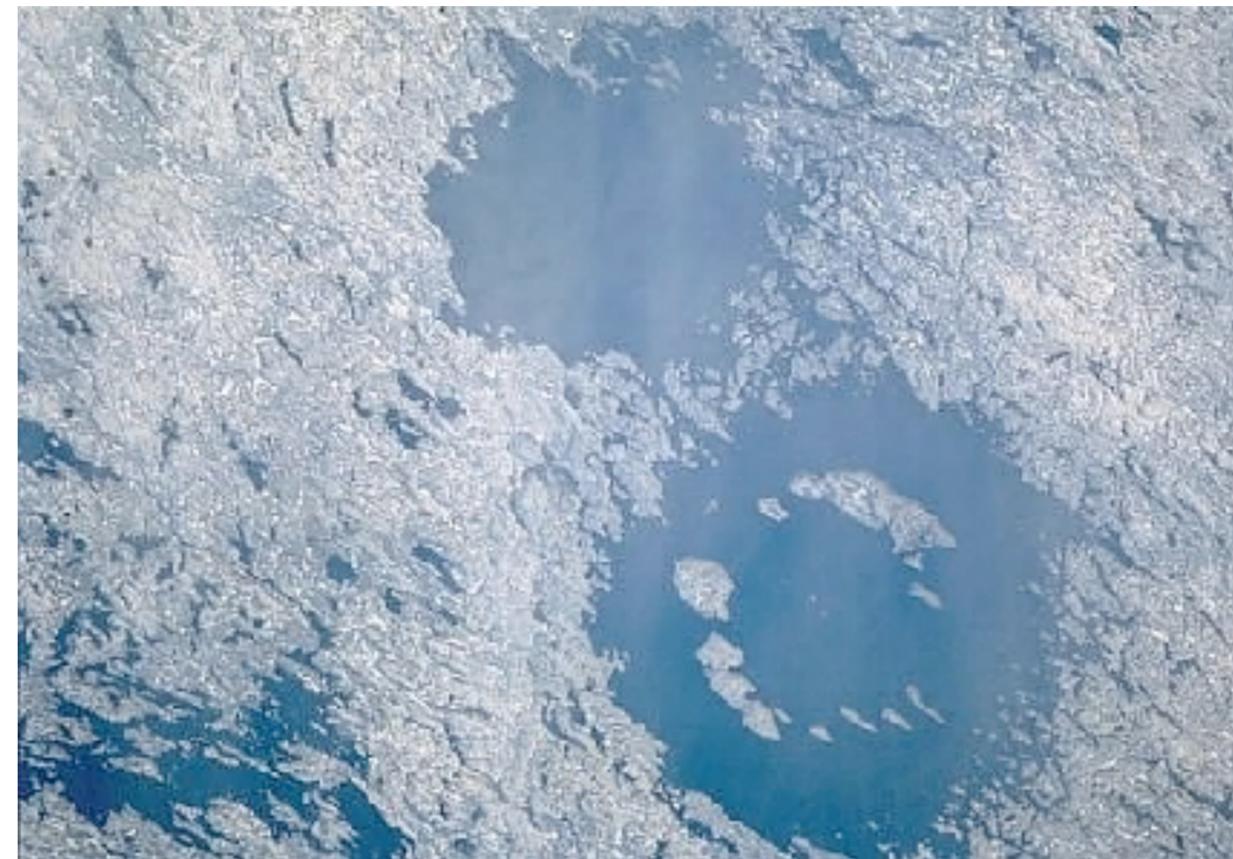
Moon



Mars

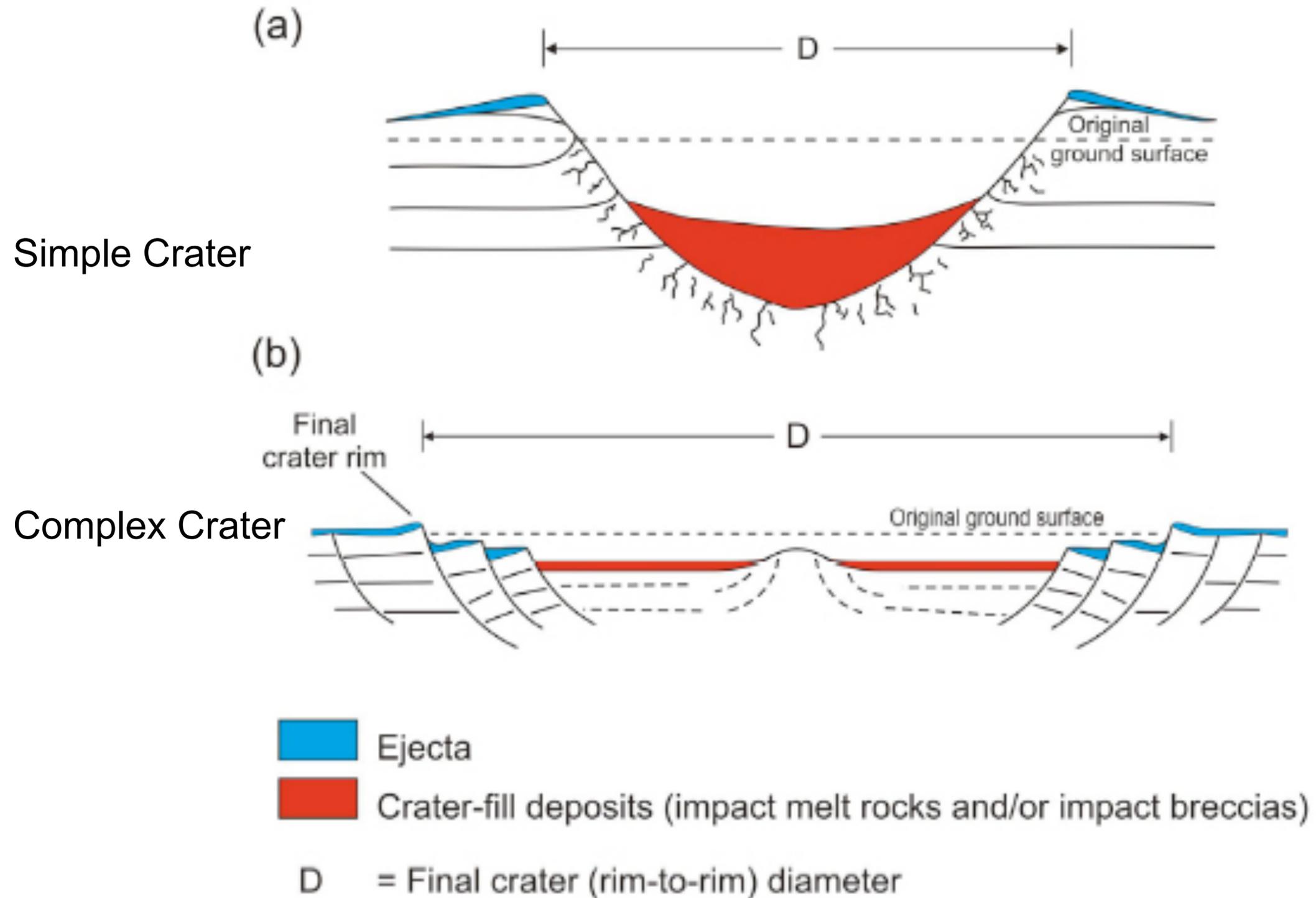


Venus



Earth

Complex Craters



Complex Craters

- Empirical relations:
 - Central peak $\sim 8\%$ of crater diameter
 - Diameter of central peak $\sim 22\%$ of rim-to-rim diameter
 - For larger complex craters, central ring+peak, with ring diameter $\sim 50\%$ of crater diameter



Craters are point-source explosions

- Fully realized in 1940s and 1950s after nuclear weapon tests
- Crater depends on impactor's kinetic energy: NOT JUST SIZE
- Impactor is MUCH smaller than the crater it produces (Meteor Crater impactor was ~50 m diameter)
- Oblique (not head-on) impacts still make circular craters, unless impact angle is extremely grazing ($< 5^\circ$)



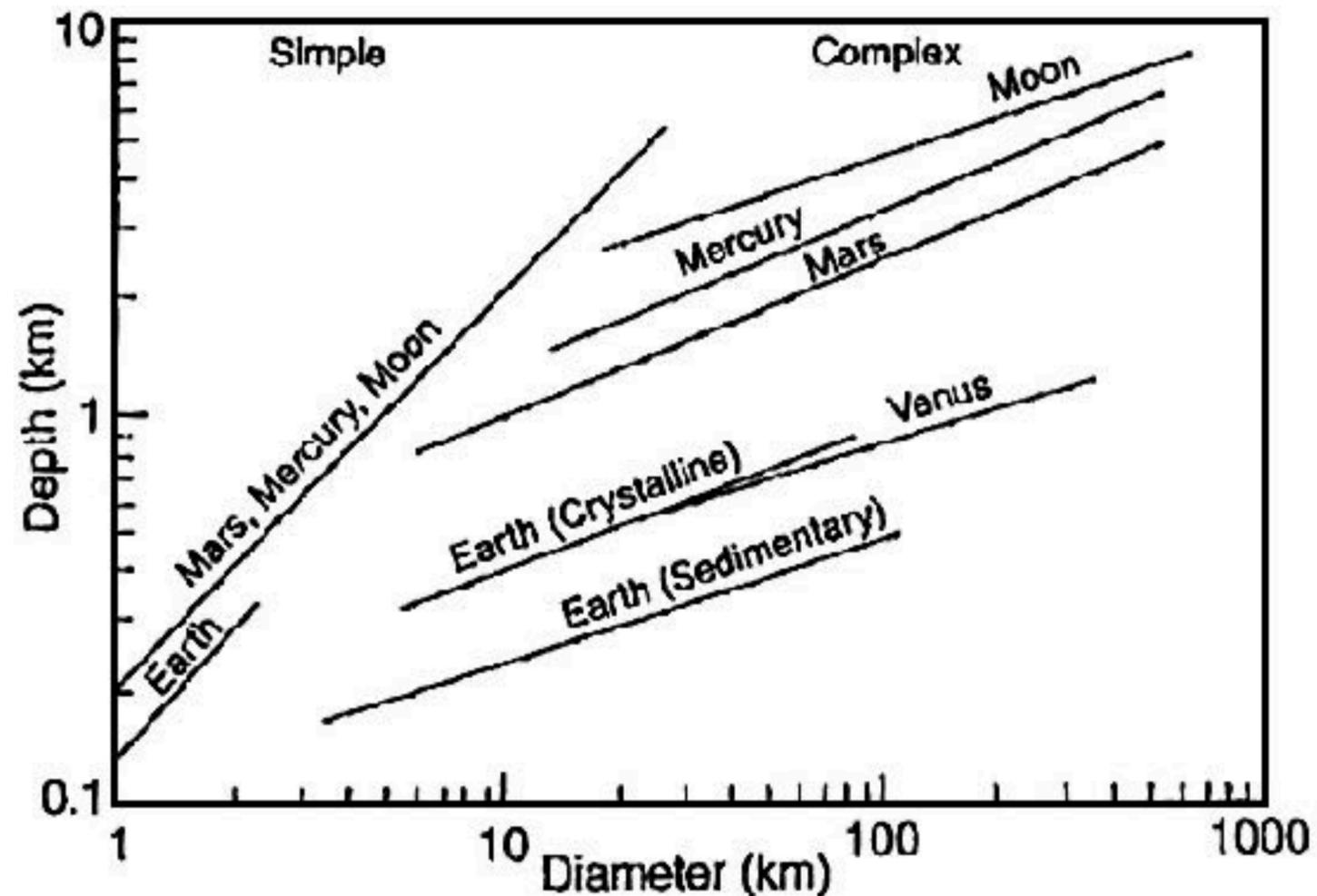
Meteor Crater: ~1200 m



Sedan Crater (nuclear test): ~300 m

Transition from Simple to Complex Craters

- Transition diameter varies from planet to planet and material to material
- Transition is higher when:
 - material strength is higher
 - density is lower
 - gravity is lower



Moltke: ~1 km



Euler: ~28 km

Transition from Simple to Complex Craters

Target	Transition Diameter (km)	g (m/s/s)
Moon	20-25	1.6
Mars	6	3.7
Mercury	13	3.8
Earth	3	9.8



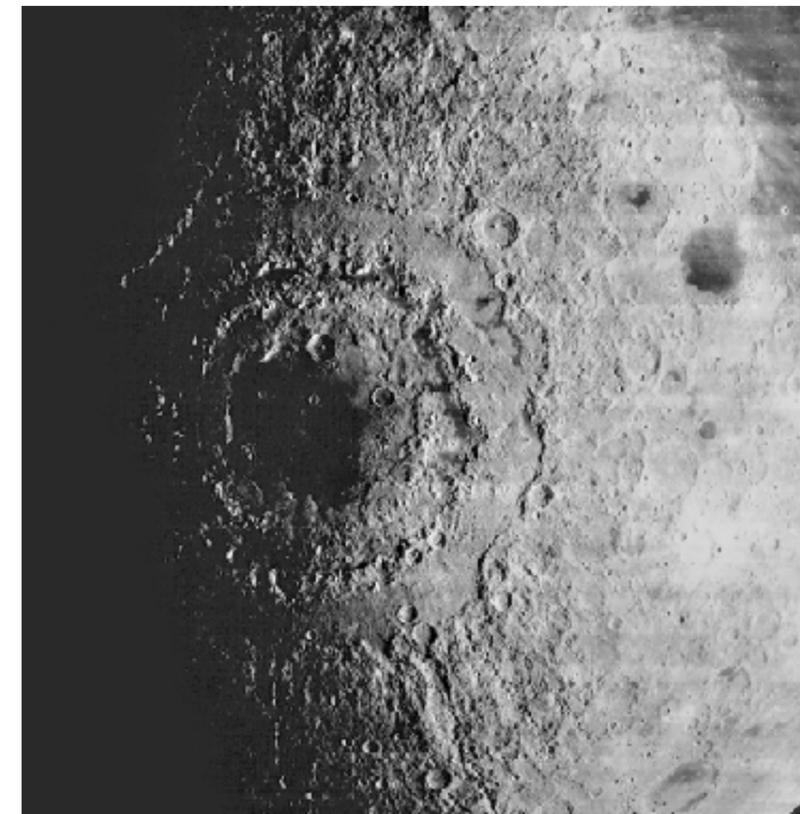
Moltke: ~1 km



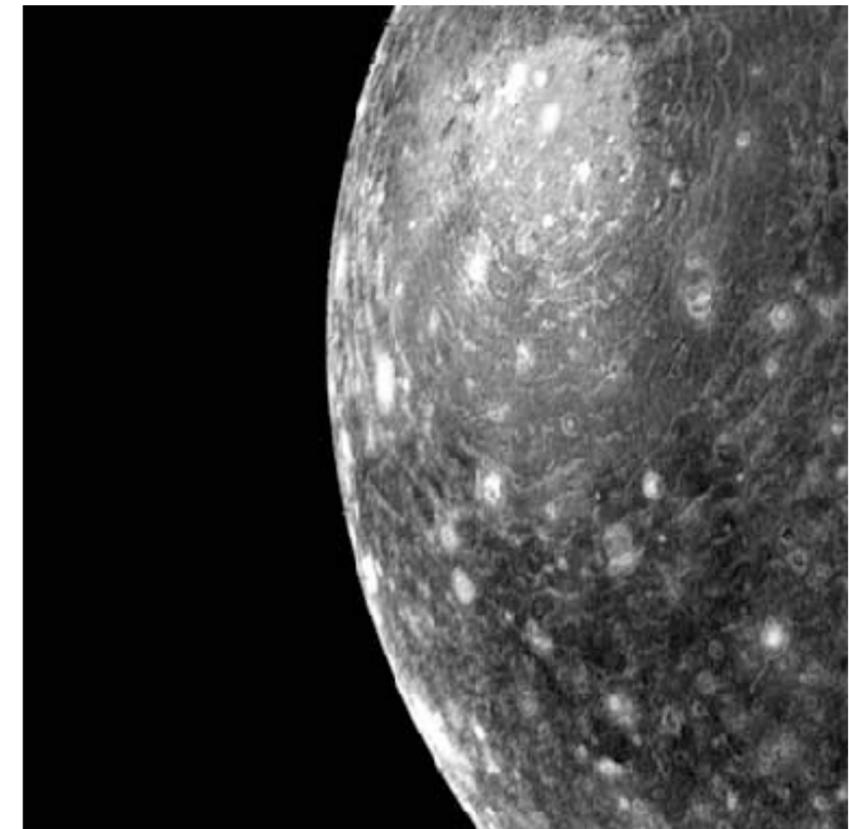
Euler: ~28 km

Multi-ring basins

- Rings surrounding crater (spaced by $\sqrt{2}$ factors)
- Transition diameter does not scale as inverse of gravitational acceleration: different processes at work



Moon



Callisto

Break

05:00

Impact Physics

- Projectile energy is all kinetic:

$$E = \frac{1}{2}mv^2 \approx 2R^3\rho v^2$$

- Very sensitive to size of object
- Minimum velocity of impact: escape velocity of the planet

$$v_{esc} = \sqrt{\frac{2GM}{R}}$$

- Maximum velocity: object hitting head-on after falling from infinity (from the Sun)
 - For example, a long-period comet



Order of Magnitude: Energy of Impact

• Vis-viva equation: $v = \sqrt{GM_{\odot} \left(\frac{2}{r} - \frac{1}{a} \right)}$

- 1 kiloton of TNT = 4.2×10^{12} J
 - Trinity test: 21 kilotons
 - Tzar Bomba: 50,000 kilotons
- Suppose an asteroid (made of rock) the size of our building (about 40 m diameter) were to impact the Earth. How much energy would the impact release if:
 - 1) the asteroid hits at escape velocity? (in kilotons of TNT)
 - 2) the asteroid is a semi-major axis of 100 AU comet that hits the Earth head-on? (in kilotons of TNT) Ignore the extra boost from Earth's gravity for this one.



Order of Magnitude: Energy of Impact

- 1) the asteroid hits at escape velocity?
- Density of water is 1 g/cc, density of rock is 3 g/cc = 3000 kg / cubic meter

• Escape velocity is: $v_{esc} = \sqrt{\frac{2GM_E}{R_E}}$ and energy of impact is $E = \frac{1}{2}mv^2 = 2R^3\rho v^2$

• Putting these together, $E = 4R^3\rho\frac{GM_E}{R_E}$

• Plugging in numbers: $E = 4(40m)^3(3000\frac{kg}{m^3})\frac{(7x10^{-11})(6x10^{24}kg)}{(6x10^6m)}$

$$= (3x4x64x7x\frac{6}{6})x(10^3x10^3x10^{-11}x10^{24}x10^{-6}) = (10000)x(10^{13}) = 10^{17}J$$

Order of Magnitude: Energy of Impact

- Converting 10^{17} J to kilotons of TNT:

$$E = 10^{17} J \frac{1 \text{ kt TNT}}{4 \times 10^{12} J} = 3 \times 10^4 \text{ kt TNT} \quad \text{about half the Tsar Bomba}$$

- 2) the asteroid is a semi-major axis of 100 AU comet that hits the Earth head-on? (in kilotons of TNT)

- Plugging into the vis-viva equation:

$$v = \sqrt{GM_{\odot} \left(\frac{2}{r} - \frac{1}{a} \right)} = \sqrt{(7 \times 10^{-11})(2 \times 10^{30} \text{ kg}) \frac{1 \text{ AU}}{1.5 \times 10^{11} \text{ m}} \left(\frac{2}{1 \text{ AU}} - \frac{1}{100 \text{ AU}} \right)}$$

$$= \sqrt{(7 \times 10^{-11})(2 \times 10^{30} \text{ kg}) \frac{1 \text{ AU}}{1.5 \times 10^{11} \text{ m}} \left(\frac{2}{1 \text{ AU}} \right)} = \sqrt{\left(\frac{7 \times 2 \times 2}{1.5} \right) \times (10^{-11} \times 10^{30} \times 10^{-11})}$$

$$= \sqrt{\frac{28}{1.5} \times 10^8} = \sqrt{2 \times 10^9} = \sqrt{20 \times 10^8} = 4 \times 10^4 \text{ m/s} \quad \text{(about 40 km/s...close to escape velocity from the Sun!)}$$

Order of Magnitude: Energy of Impact

- And orbital velocity of the Earth:

$$v_{orb} = \sqrt{\frac{GM_{\odot}}{d_E}} = \sqrt{\frac{(7 \times 10^{-11}) \times (2 \times 10^{30} \text{ kg})}{(1.5 \times 10^{11} \text{ m})}} = \sqrt{\frac{14}{1.5} \times 10^8} = \sqrt{10 \times 10^8} = 3 \times 10^4 \text{ m/s}$$

In Earth's reference frame: $v_{impact} = 30 \text{ km/s} + 40 \text{ km/s} = 70 \text{ km/s}$

- There will also be a boost from Earth's gravity, but that will be negligible, so we'll ignore it:

$$E = 2(40 \text{ m})^3 \left(3000 \frac{\text{kg}}{\text{m}^3}\right) \left(7 \times 10^4 \frac{\text{m}}{\text{s}}\right)^2 = (2 \times 3 \times 64 \times 49) \times (10^3 \times 10^3 \times 10^8) = (2 \times 10^4) \times (10^{14}) = 2 \times 10^{18} \text{ J}$$

$$\text{• And converting to kilotons: } E = 2 \times 10^{18} \text{ J} \frac{1 \text{ kt TNT}}{4 \times 10^{12} \text{ J}} = 0.5 \times 10^6 \text{ kt TNT} = 5 \times 10^5 \text{ kt TNT} \quad \text{10 times the Tsar Bomba!}$$

Stages of Crater Formation

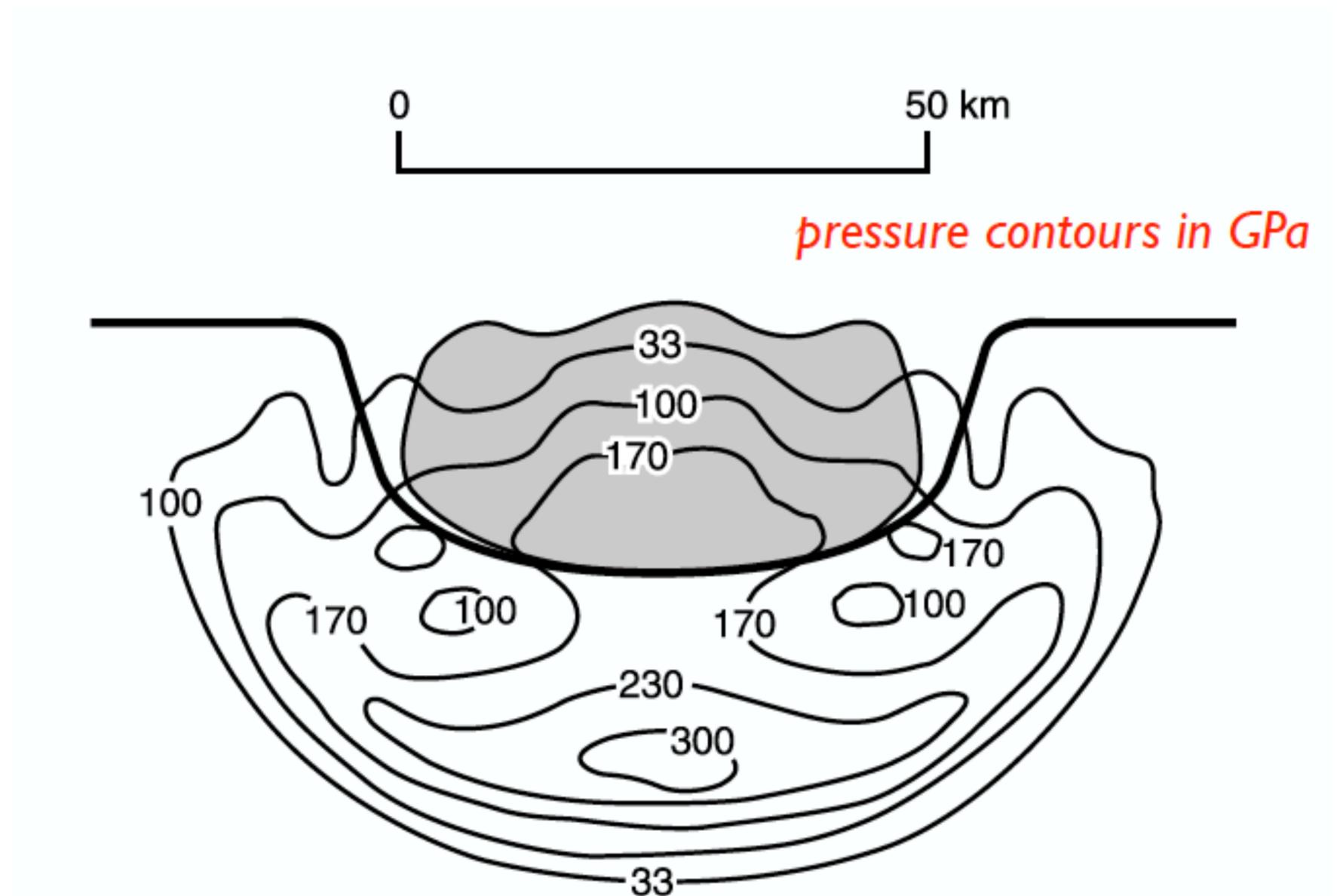
- 1) Contact and compression
- 2) Excavation
- 3) Modification
- Timescale is the time required for impactor to penetrate its own diameter into the target:

$$\tau = \frac{D_{impactor}}{v_{impactor}}$$



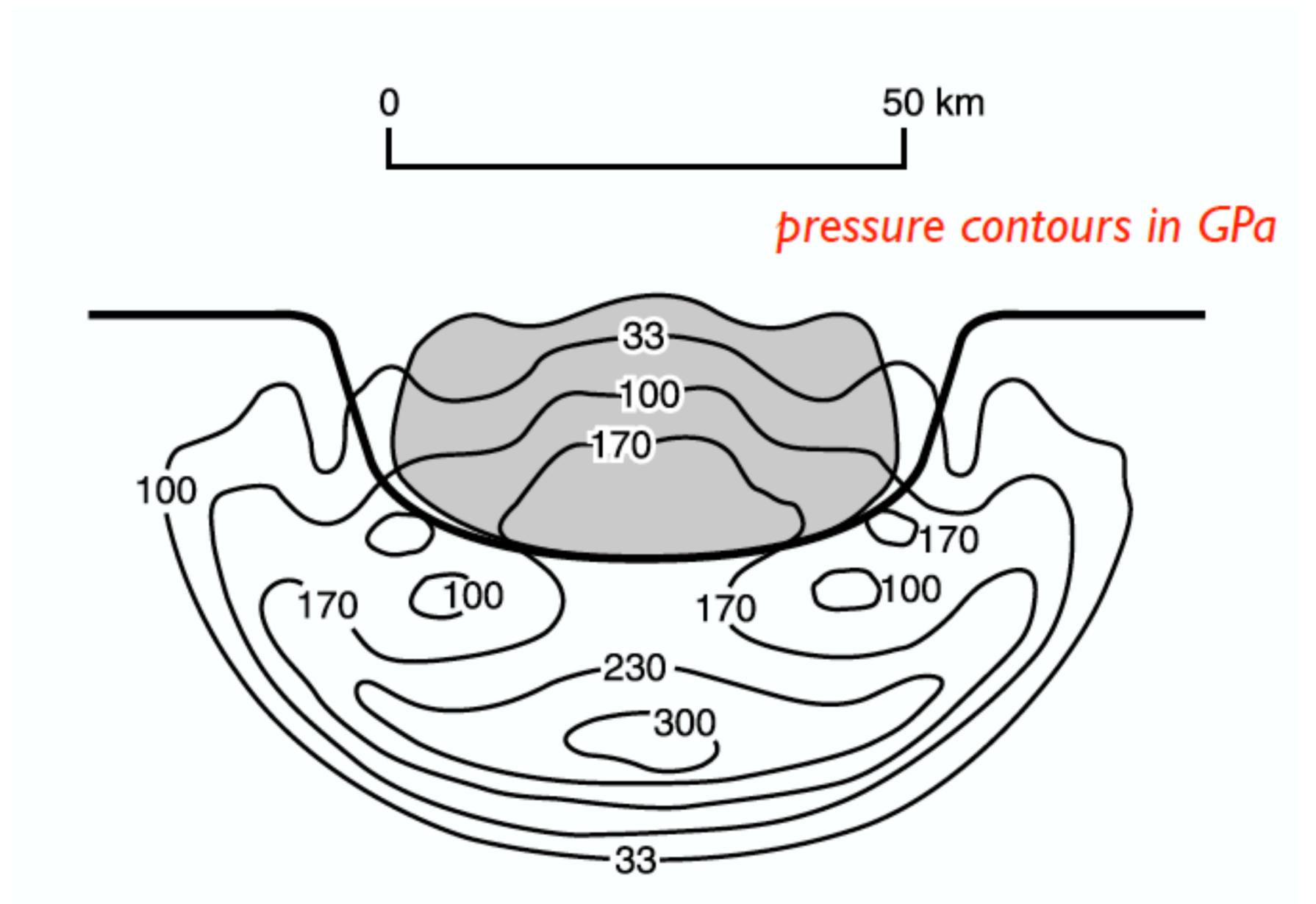
Contact and Compression

- Jetting: highest speed ejecta thrown out as impactor edge penetrates into target
- short-lived: persists for $\sim \frac{\tau}{2}$
 - jetted material can continue in flight for long time after that
- Jetting can eject up to 80% of impactor mass, and pressures that drive this jetting can reach hundreds of GPa



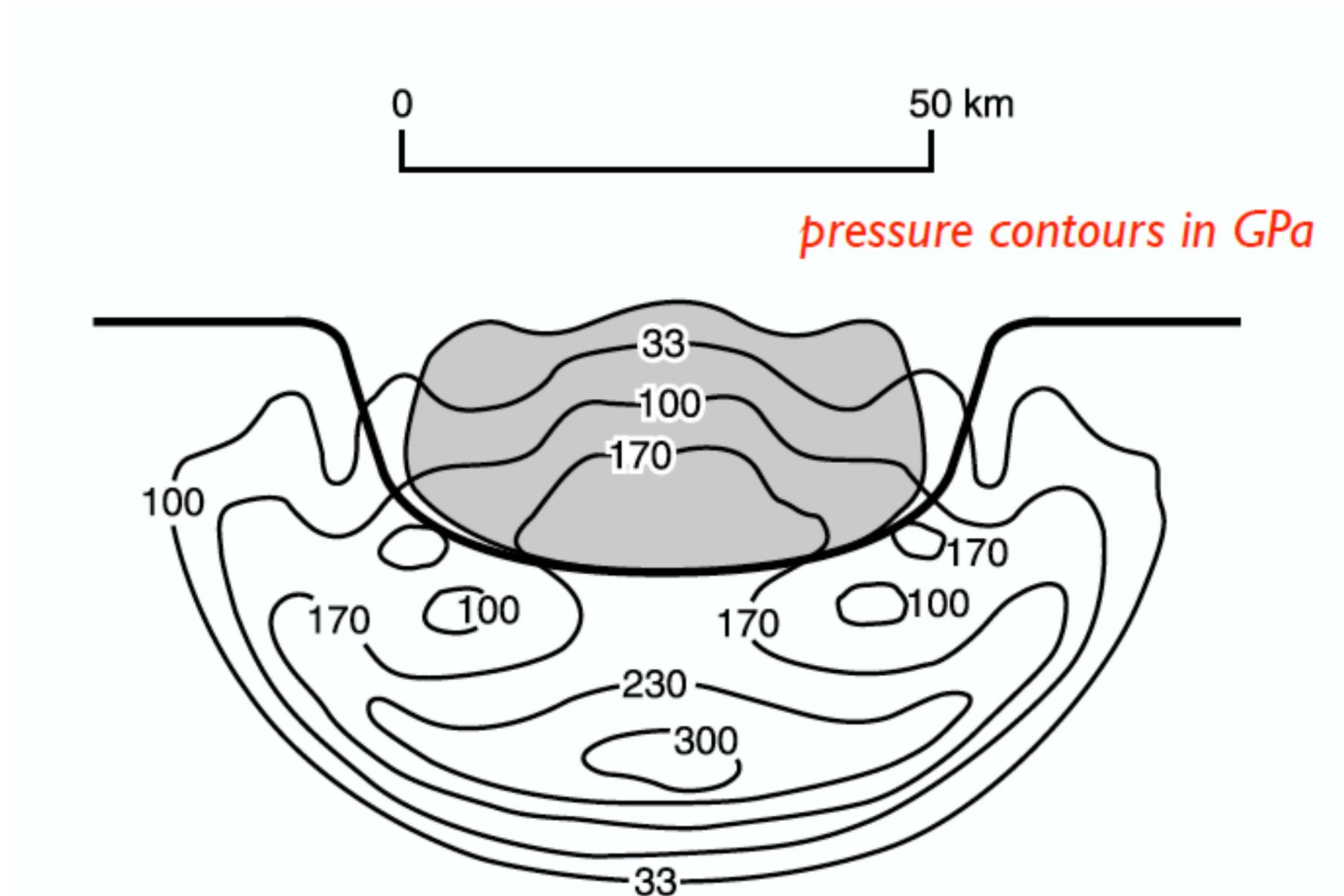
Compression and Shock

- Extreme pressures from impact produces shock waves that travel through both impactor and target
- Physics of shock involve conserving mass, momentum, and energy across the shock, as well as equation of state of material



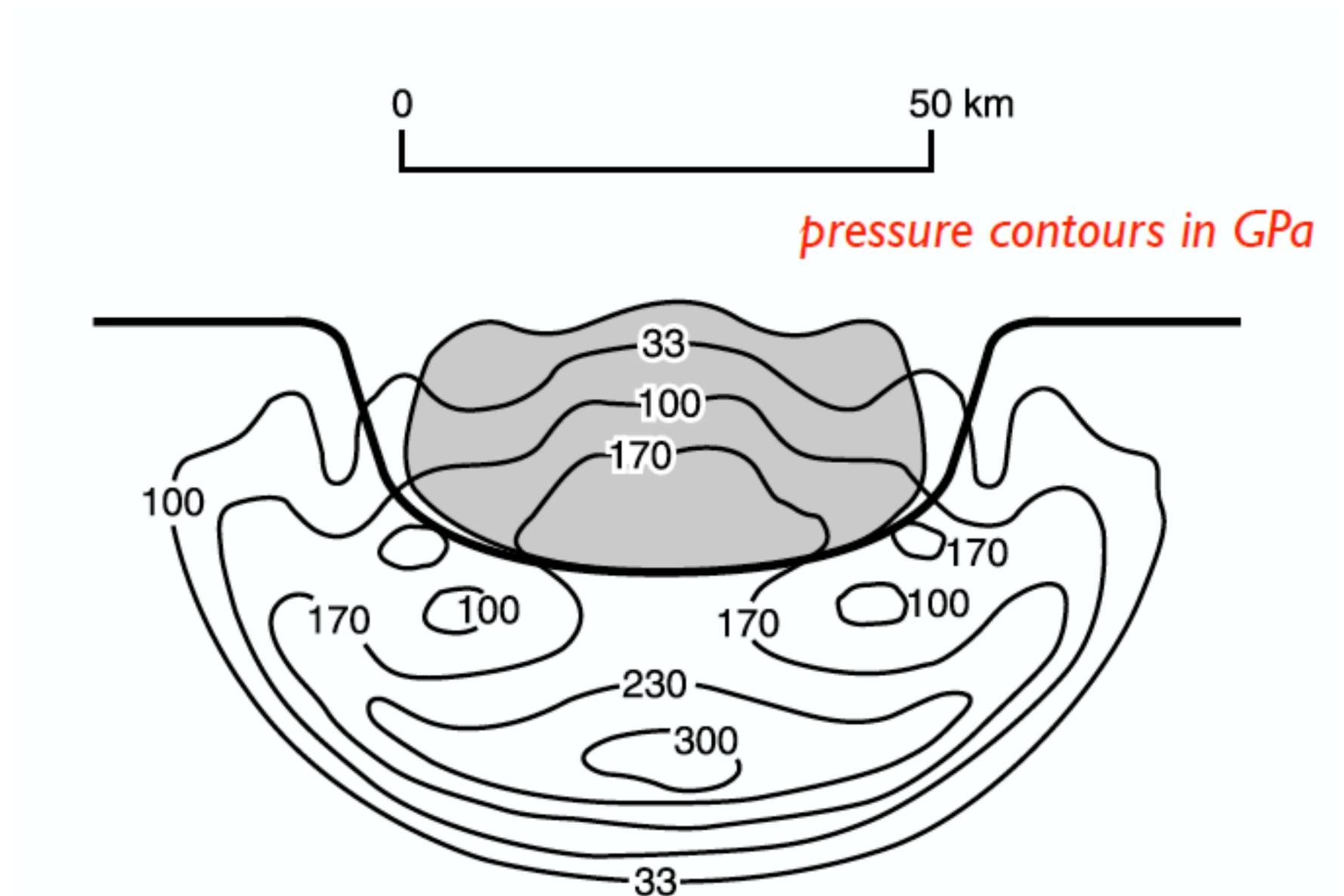
Crater Formation

- Impactors strike ground with speed much greater than sound speed of target rock
- Crater produced by intense shock waves and are generated at impact point and radiate outward at velocities of ~ 10 km/s
- As it expands outward, shock waves set large volumes of rock into motion, excavating crater



Shock Wave

- Speed of shock is similar to speed of impactor (very fast)
- Shock from impact location travels both down through target, and up through impactor
- When shock reaches top of impactor, pressure is released in a rarefaction wave: this is what vaporizes the impactor
- Total duration (impact, shock wave, rarefaction wave): $\sim 1.5\tau$

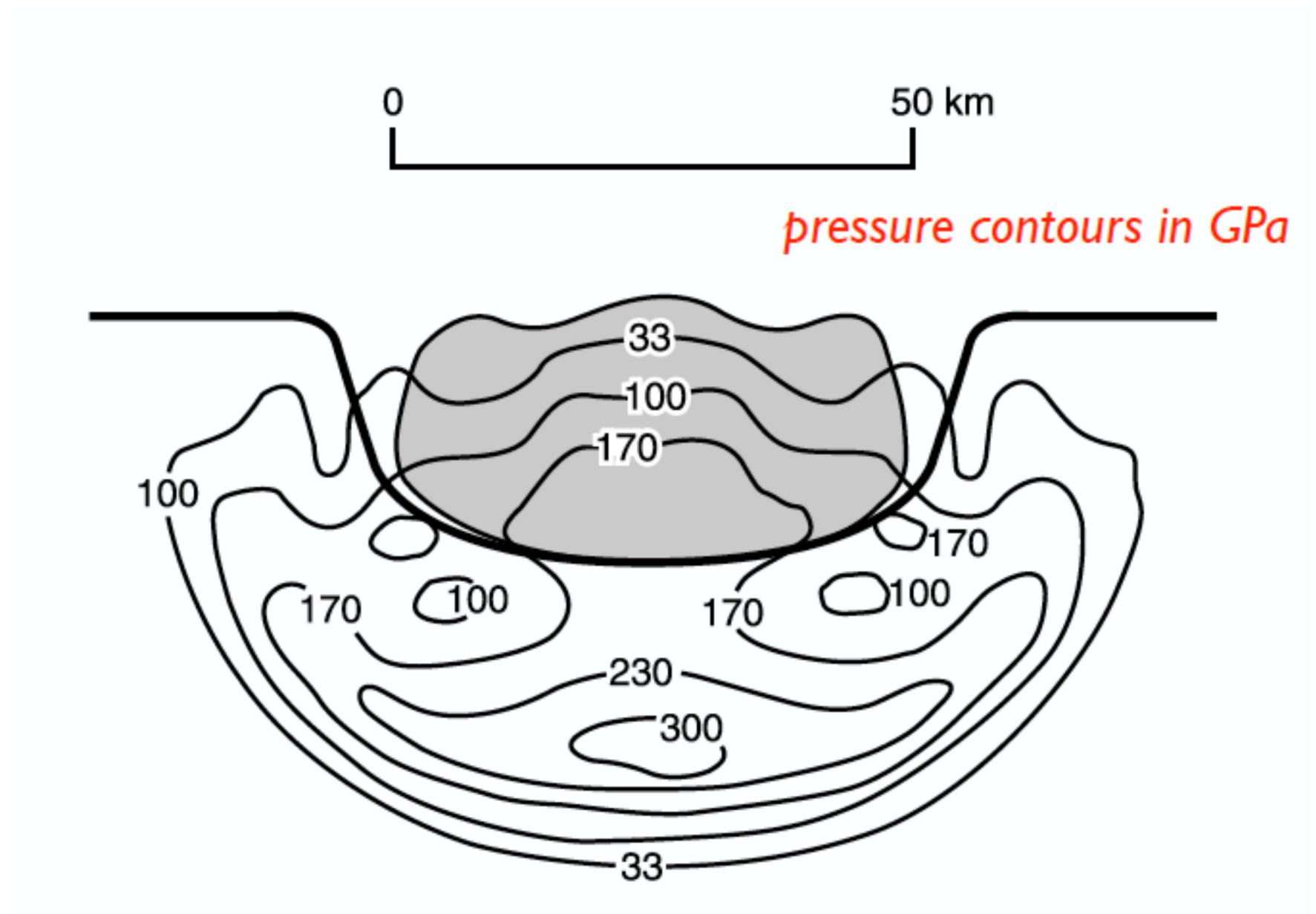


Response Card Question

- A 1 km impactor hits with a velocity of 10 km/s. What is the timescale τ ?
 - (A) — 100 seconds
 - (B) — 10 seconds
 - (C) — 1 second
 - (D) — 0.1 seconds
 - (E) — 0.01 seconds

Contact and Compression

- Shock wave (downward through target) loses energy rapidly:
 - Expanding shock front is covering a larger and larger area as it expands radially
 - Heat lost to target rocks through heating, deformation, acceleration



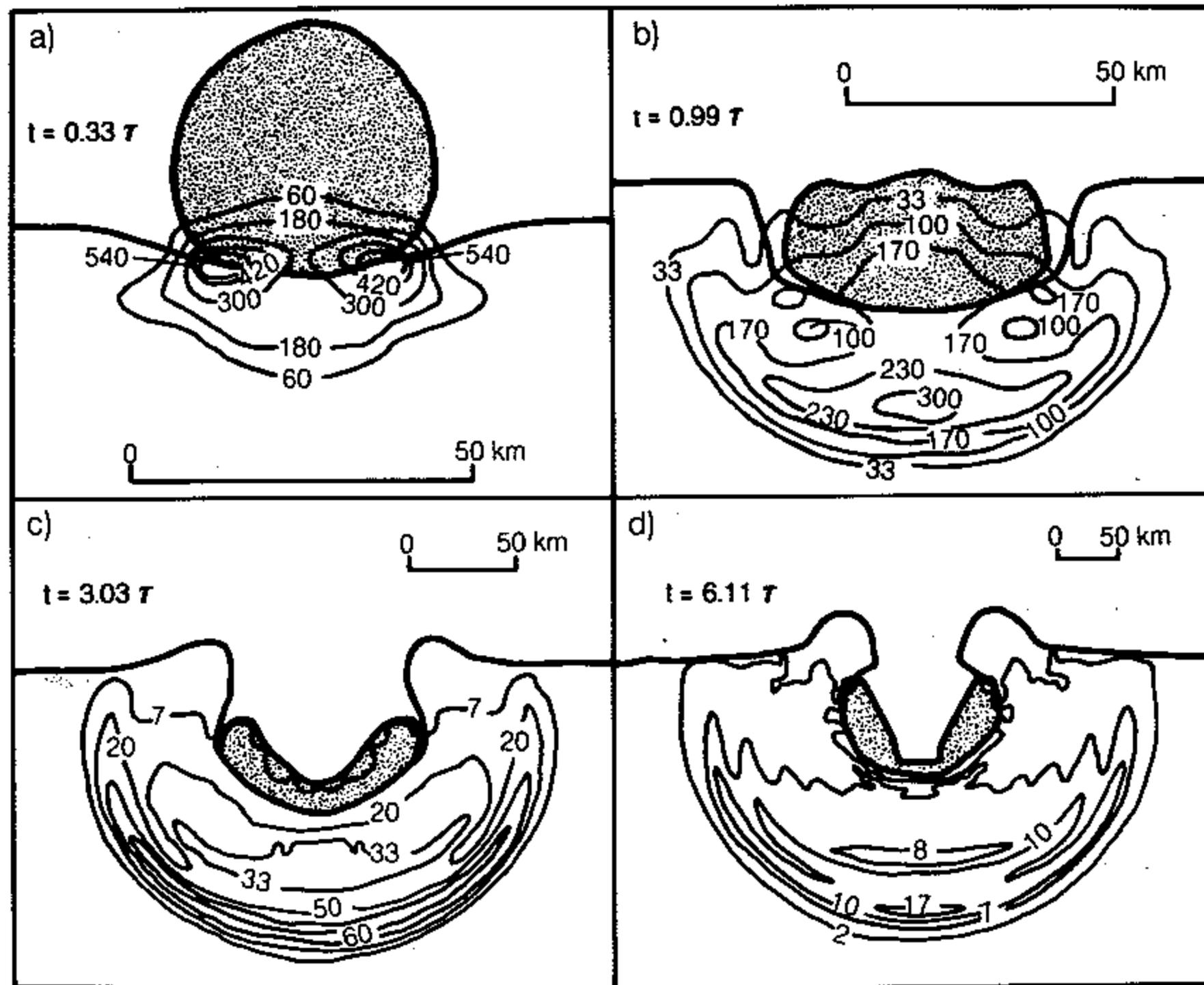


Fig. 4.1 Four snapshots are shown of the vertical impact of a 46.4-km diameter iron projectile on a gabbroic anorthosite target at 15 km/second. The first three frames illustrate different phases in the contact and compression stage and the last frame is a very early phase of the excavation stage. The contour values are pressures in GPa. Times shown are in units of τ , Equation 4.2.1. See the text for individual discussion of the frames. Do not overlook the changes in scale from one frame to the next. *After O'Keefe and Ahrens (1975).*

For next time

- Reading: de Pater & Lissaeuer Chaper 5, section 5.4.2.2-5.4.2.5
- Homework 2 will be due Wednesday, September 14 at 11:59pm