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

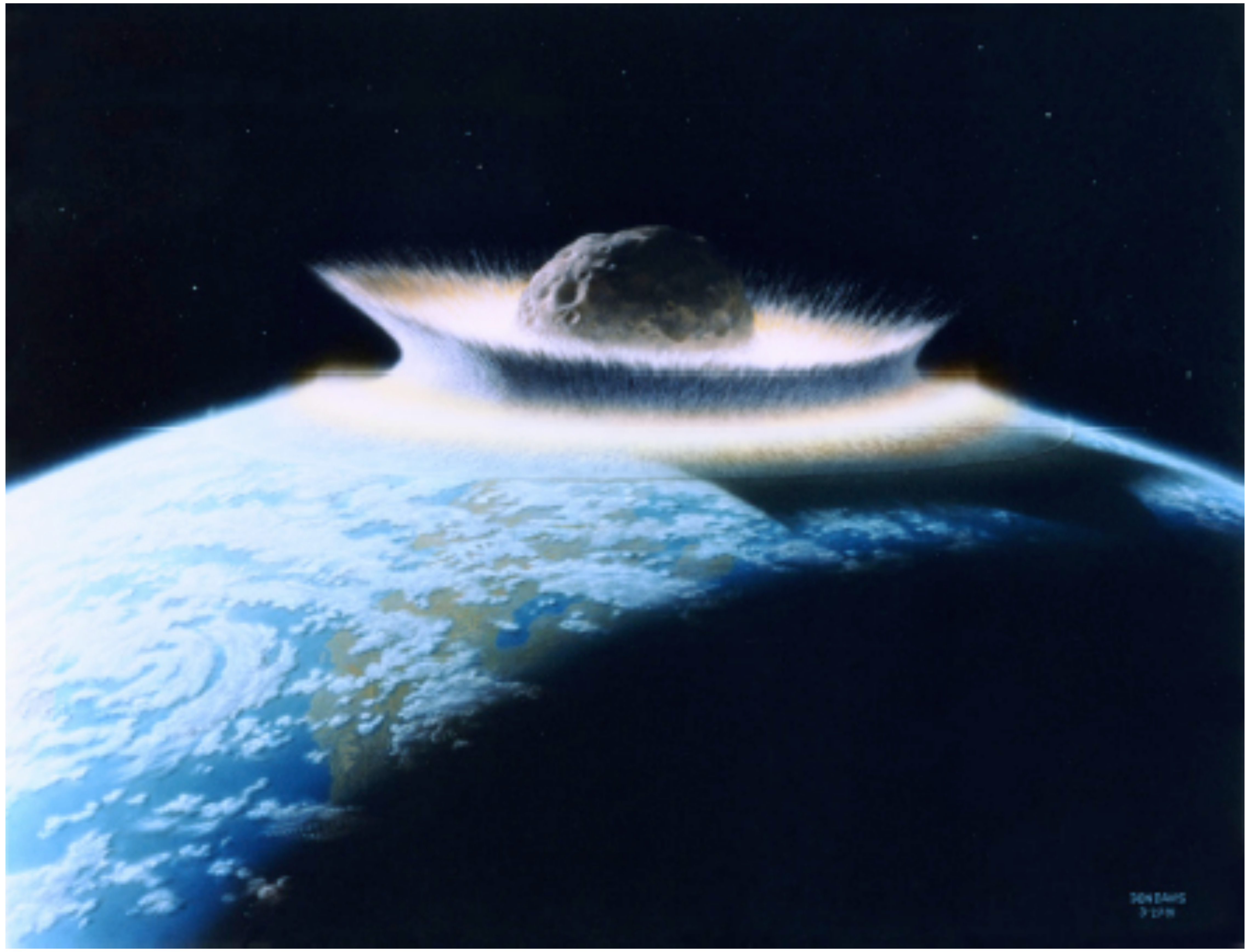
- The reason the Yarkovsky Effect is less important for larger asteroids is:
  - (A) — Large asteroids don't rotate
  - (B) — Surface area scales as R^2, volume as R^3
  - (C) — Large asteroids have a very different albedo from small asteroids
  - (D) — The day/night temperature difference on large asteroids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



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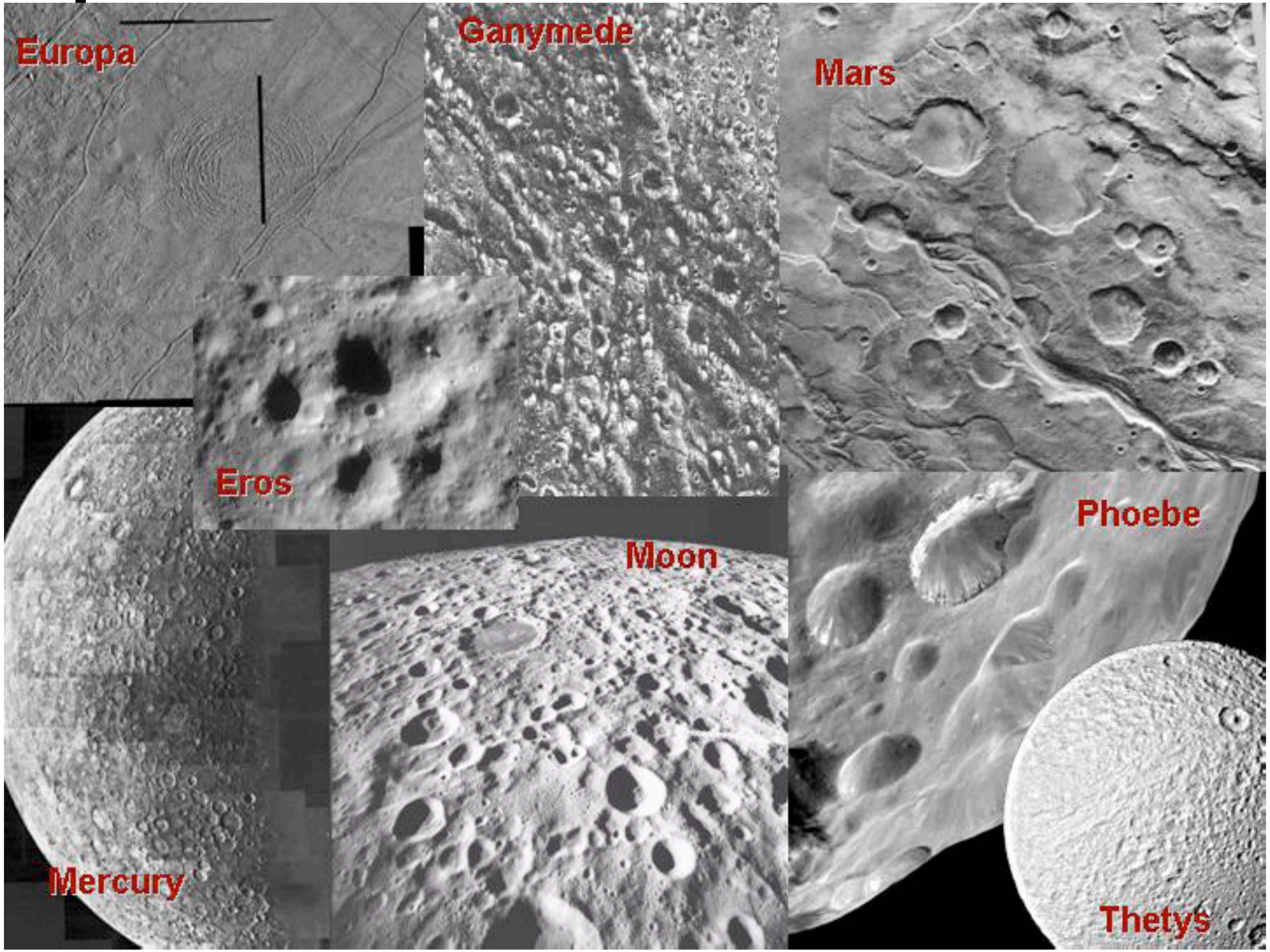
Impact Craters



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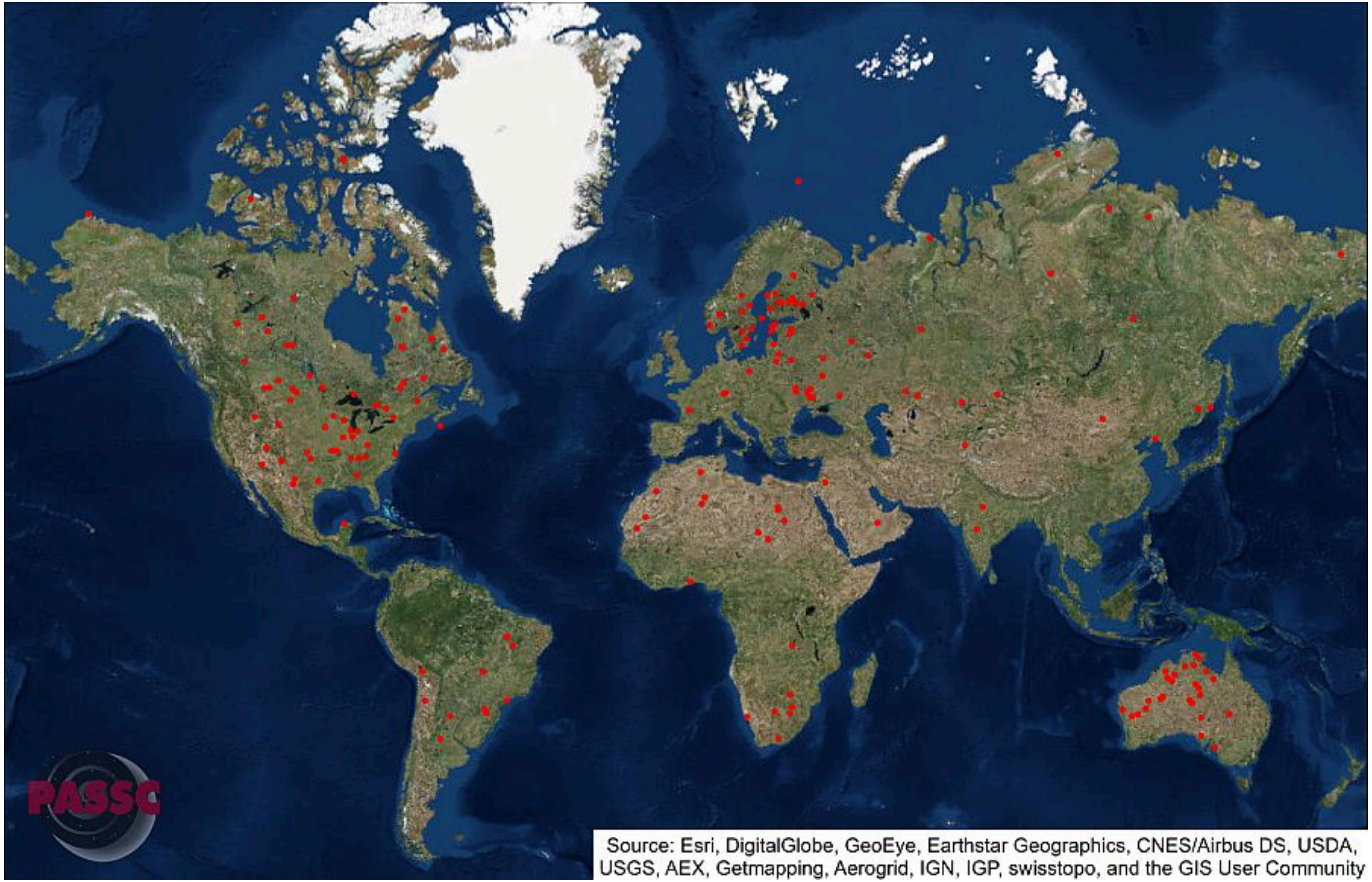
Impact Craters



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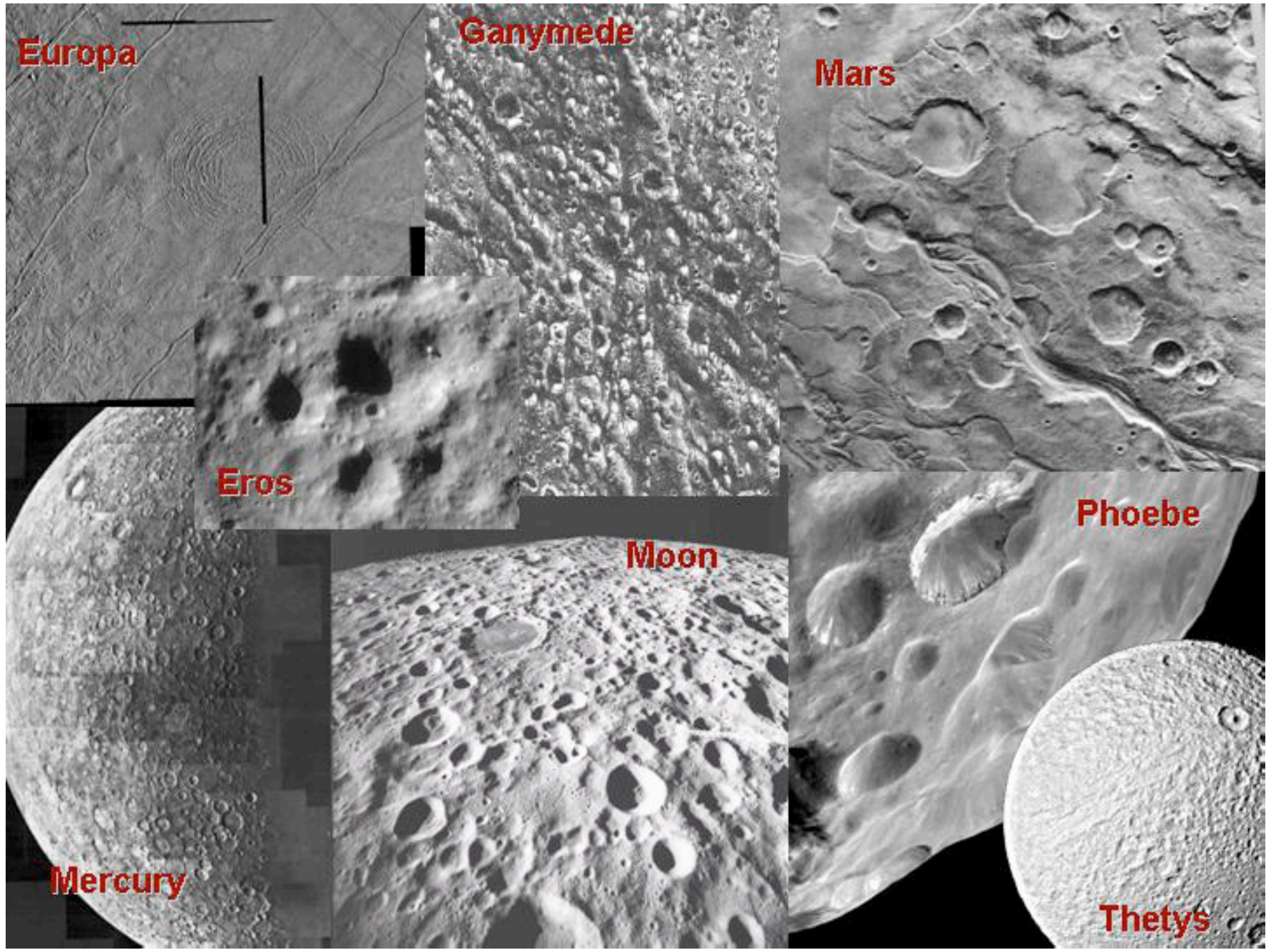
Impact Events

- 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)



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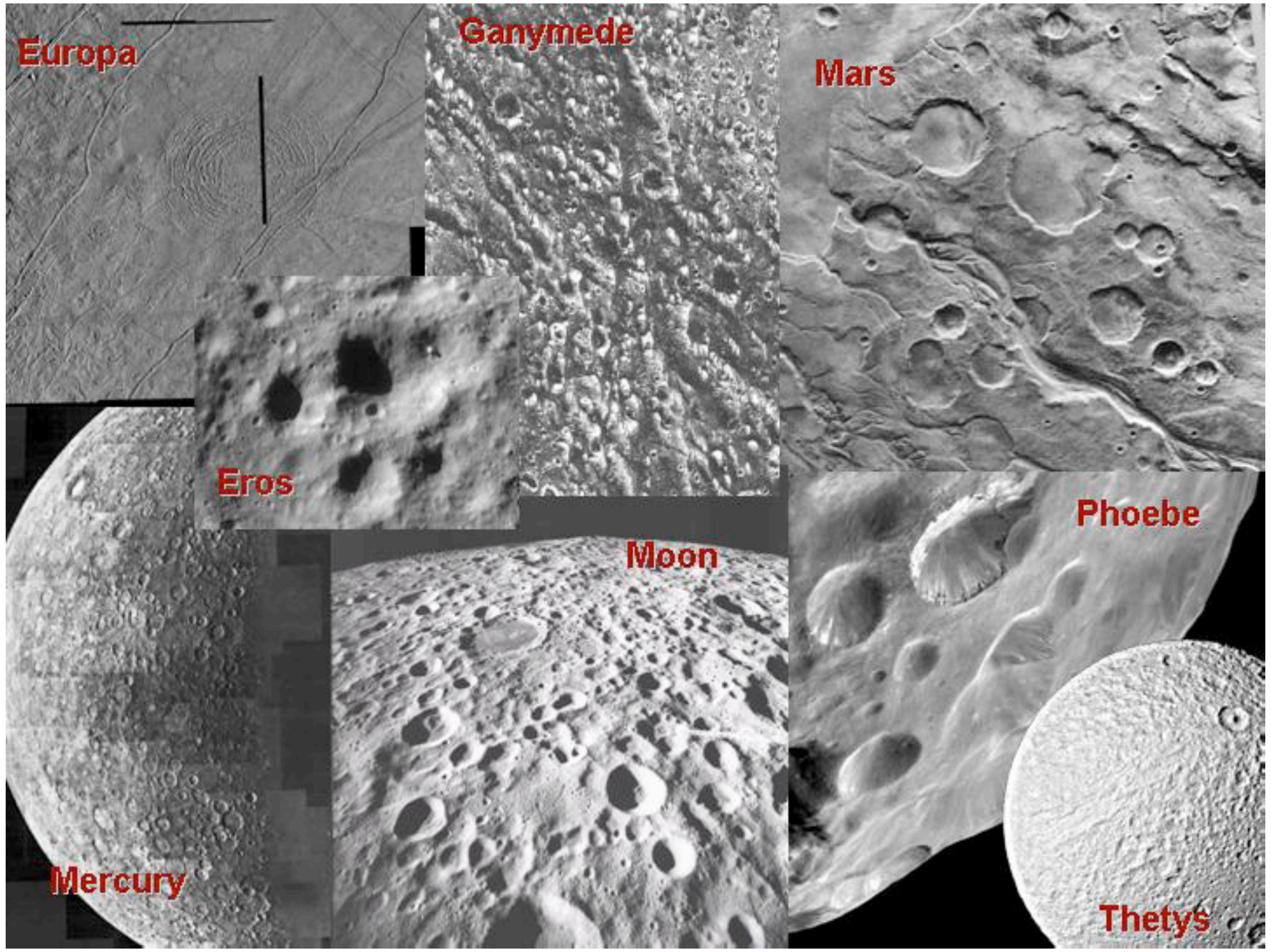
Scientific Value of Impacts

- 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



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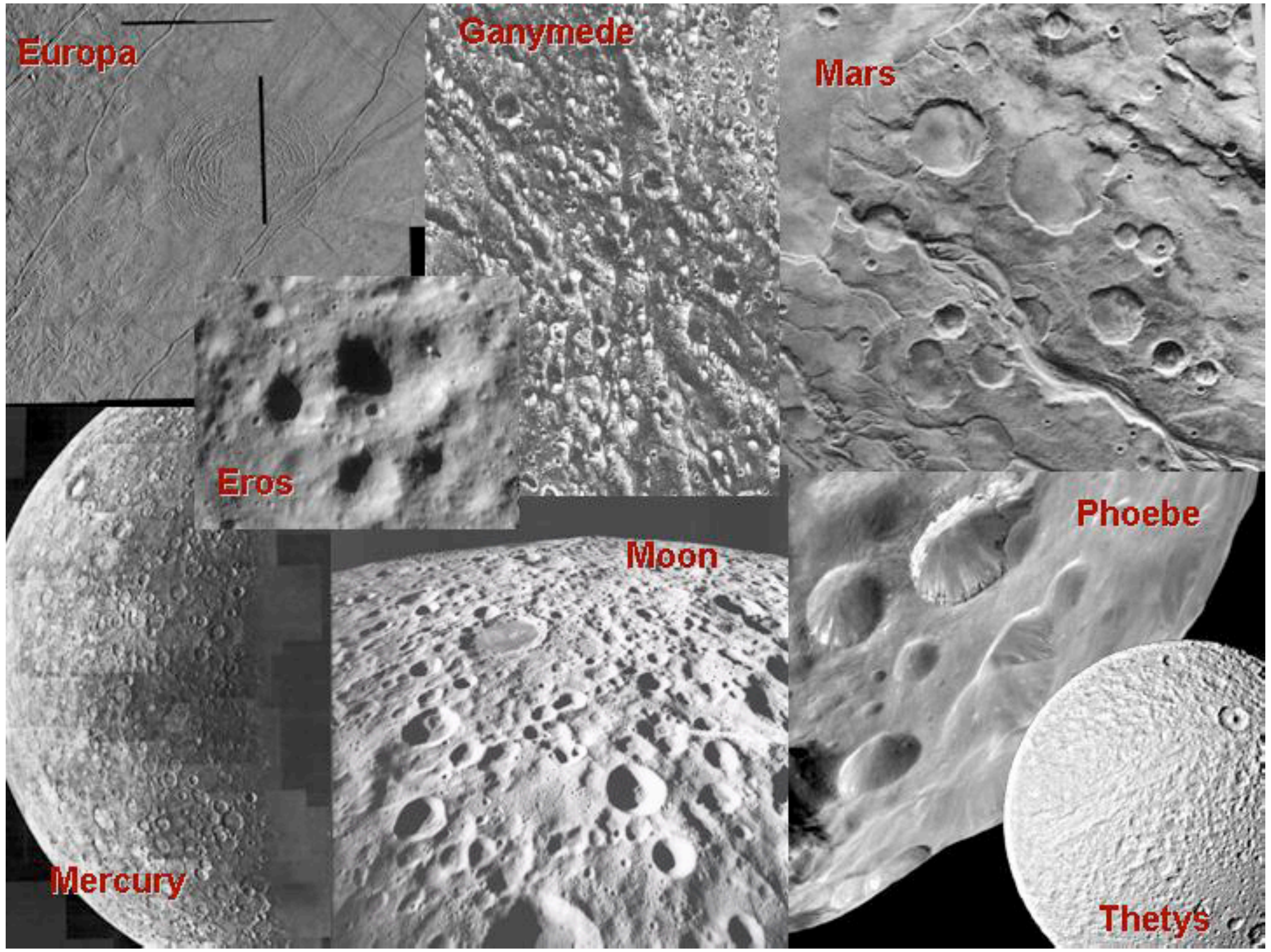
History of Crater Study

- 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



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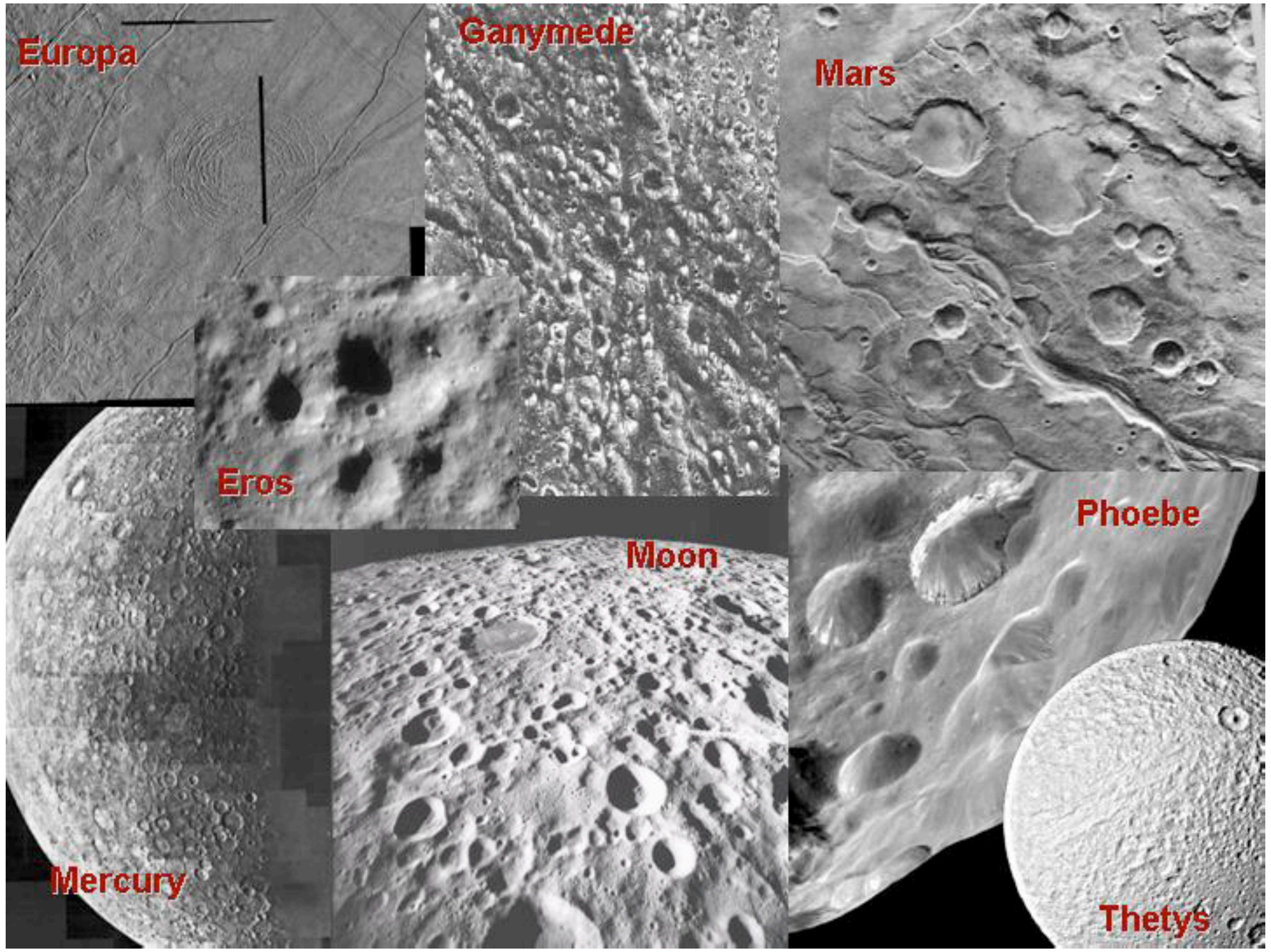
Types of Craters

- 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)



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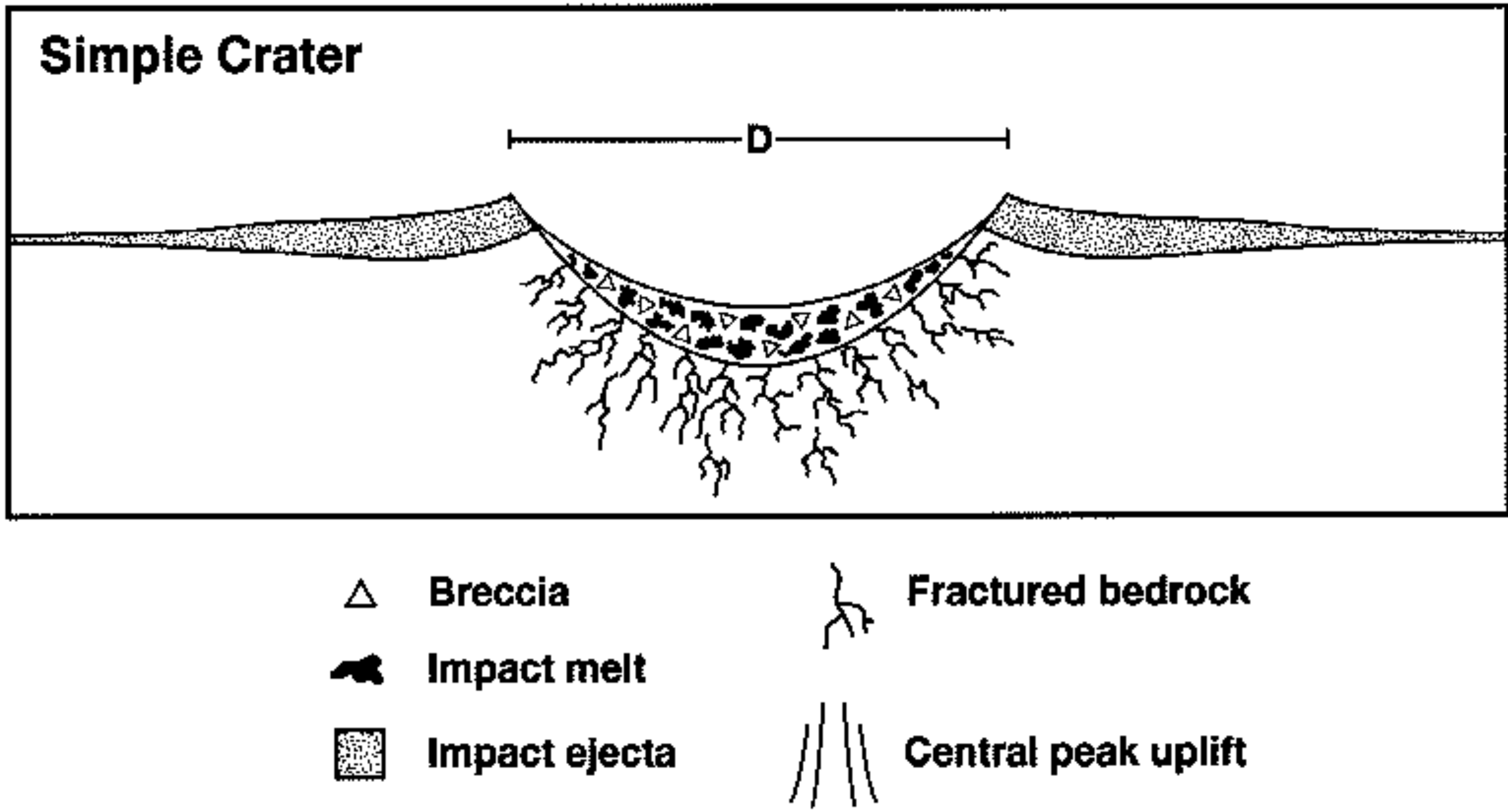
Simple Craters

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



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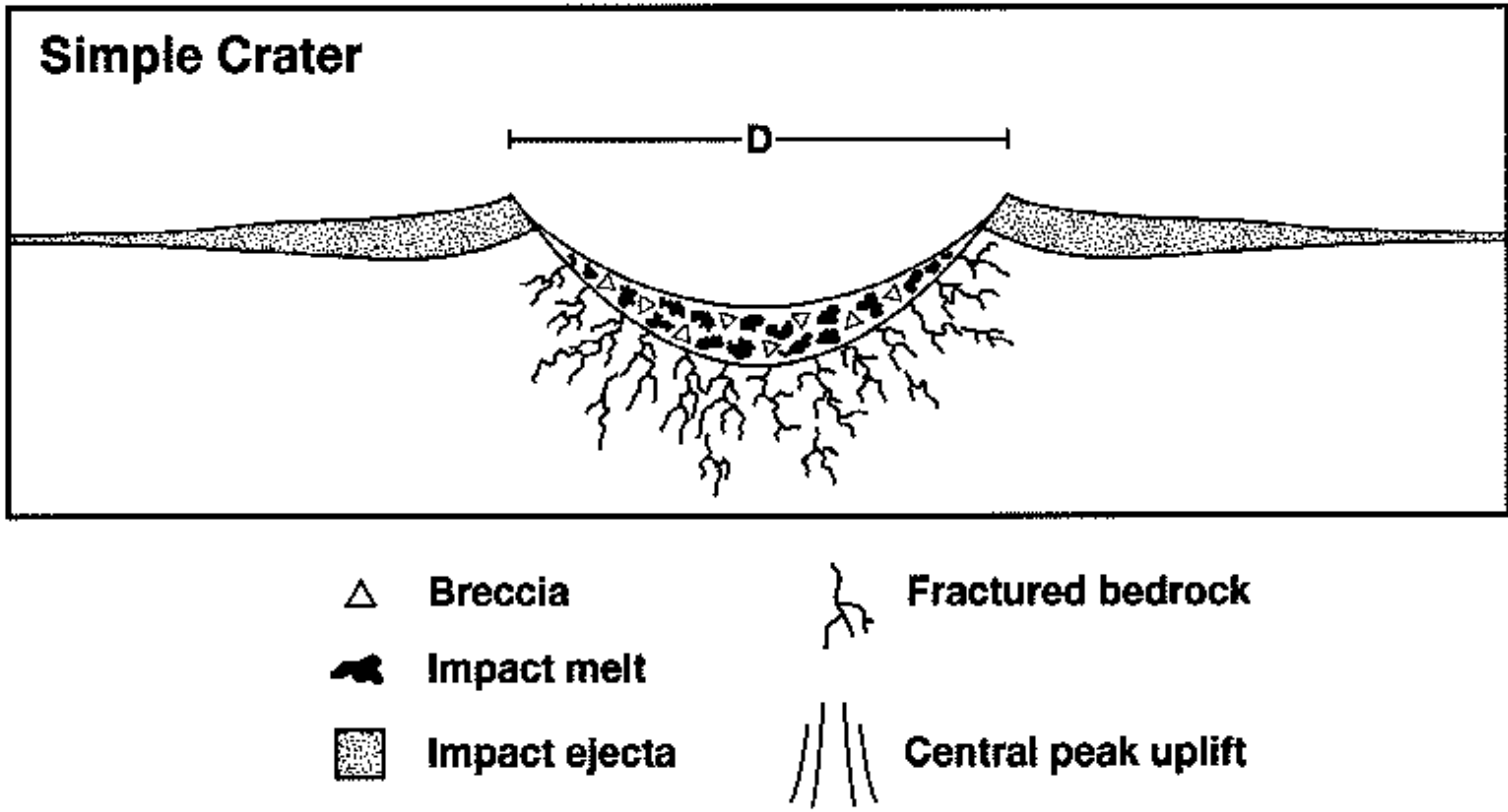
Simple Craters

- Ratio of depth to diameter about 0.2
- Rim height (above unperturbed, pre-impact surface) about 0.04 x 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



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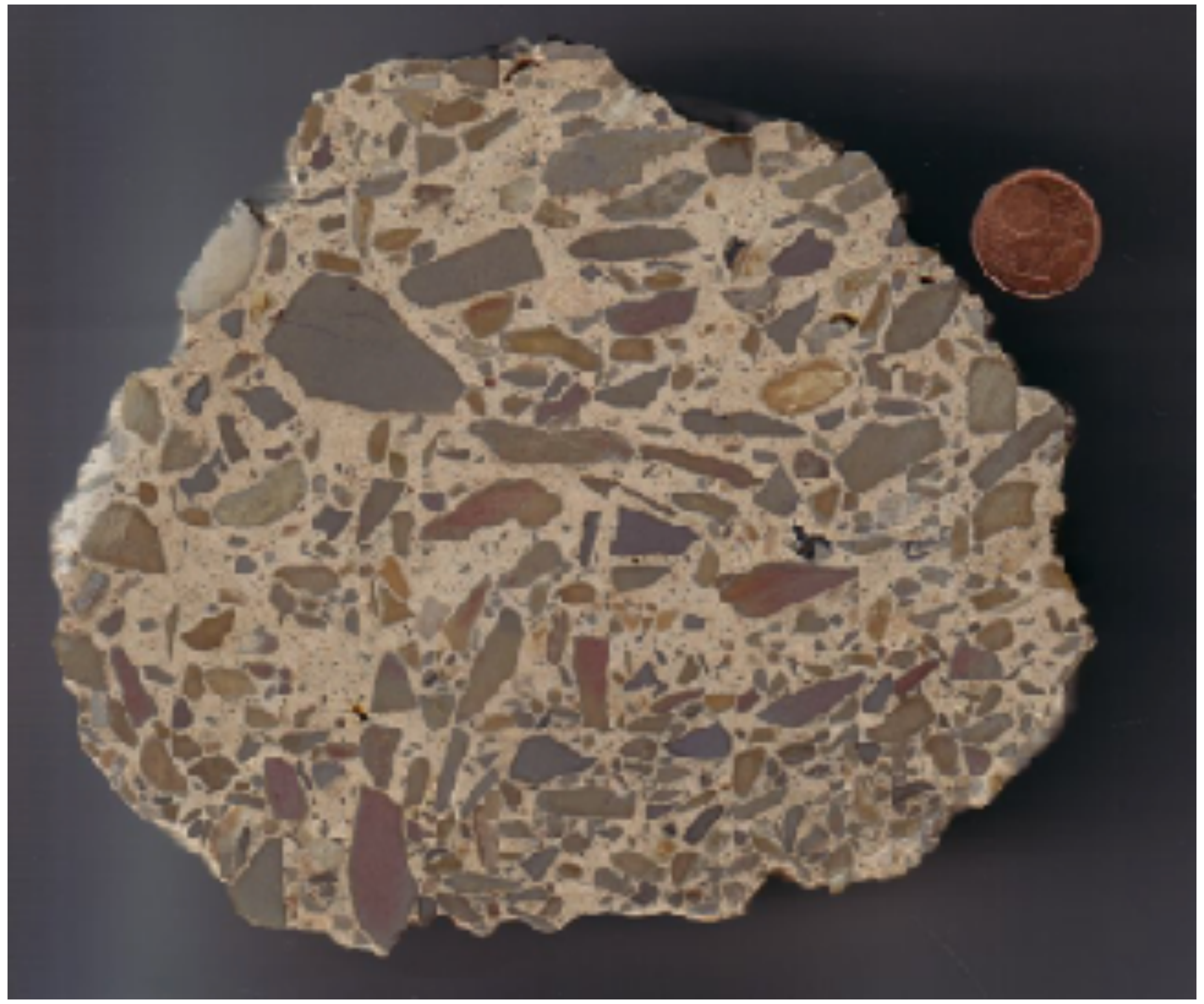
Breccia

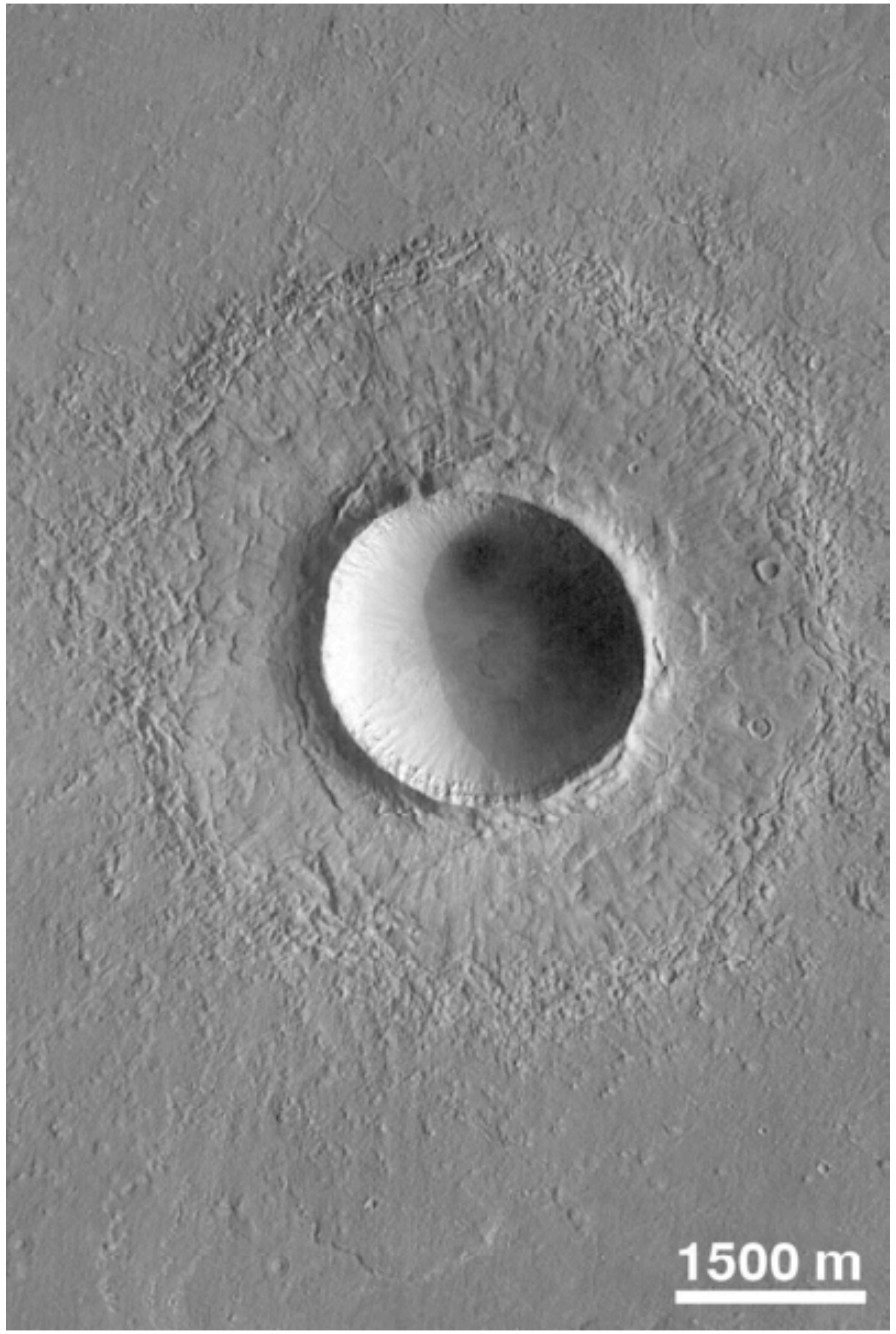
- Created during impacts
- Sedimentary rock composed of large (>2 mm) angular fragments that are cemented together
- Angular fragments suggest they have not been transported far from their source
- Matrix (the stuff in between the angular fragments) that cements it together is fine-grained silt



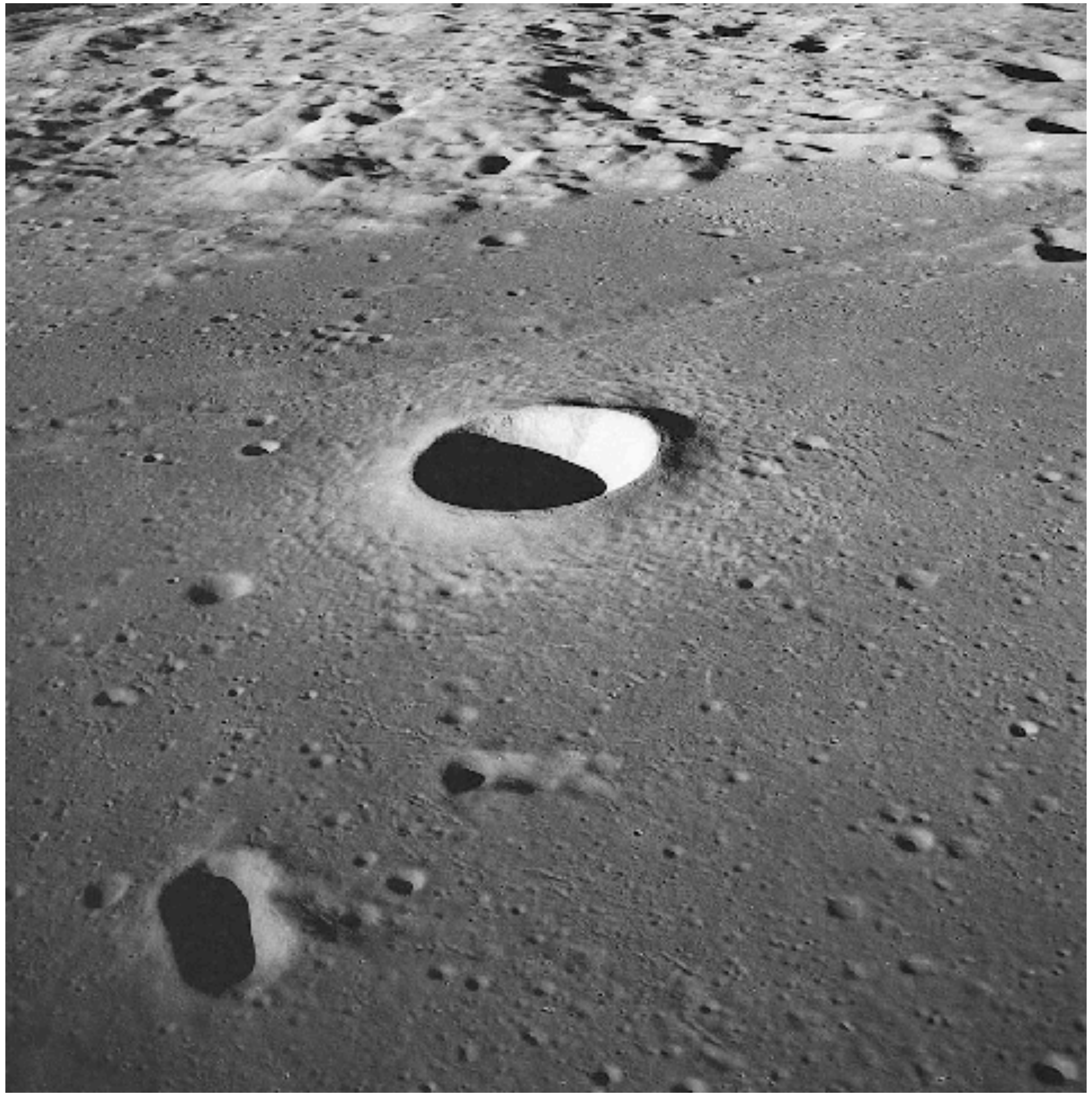
impact-structures.com

Titus Canyon, Death Valley

Simple Craters

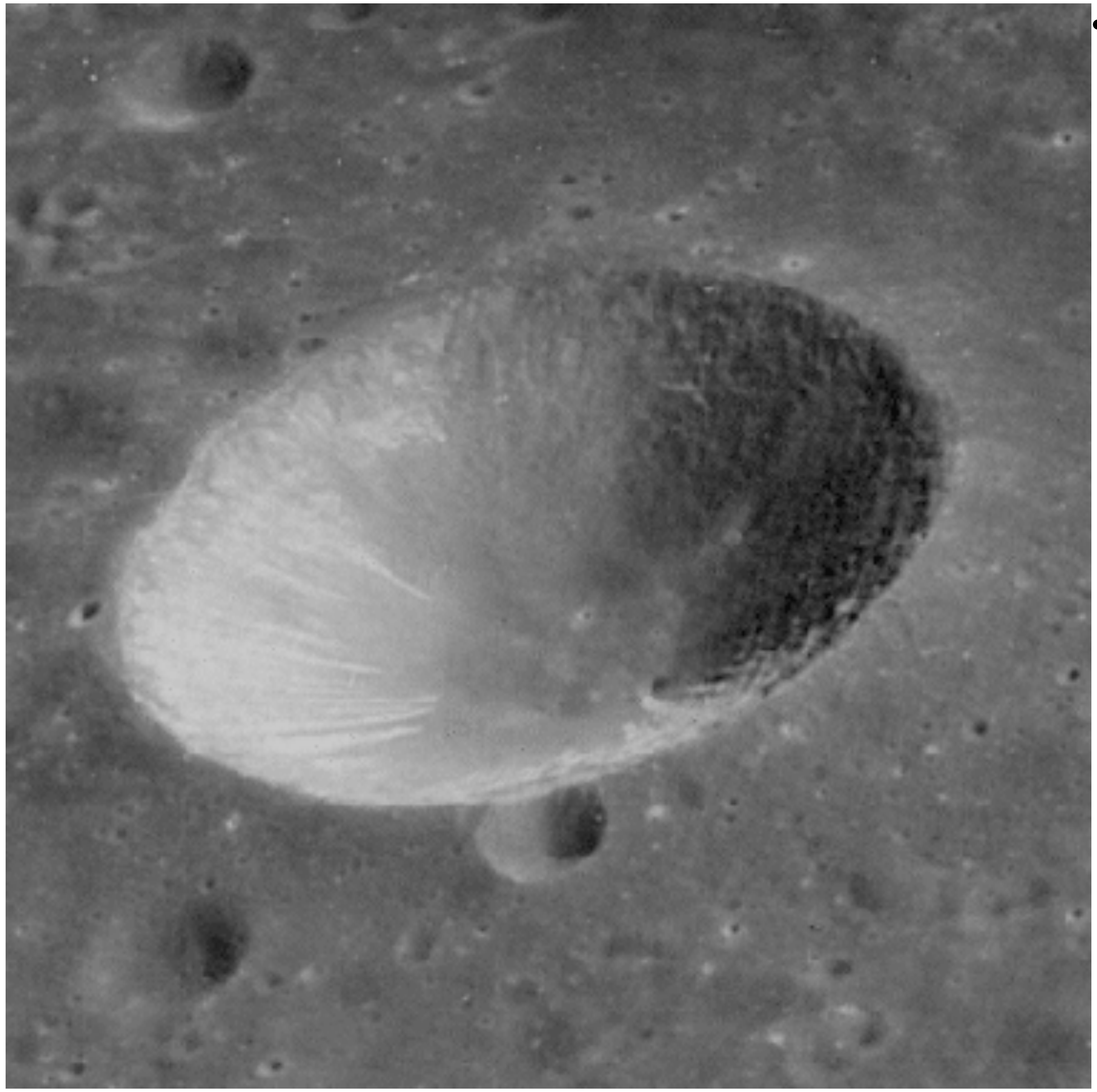


Mars



Moon

Simple Craters



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

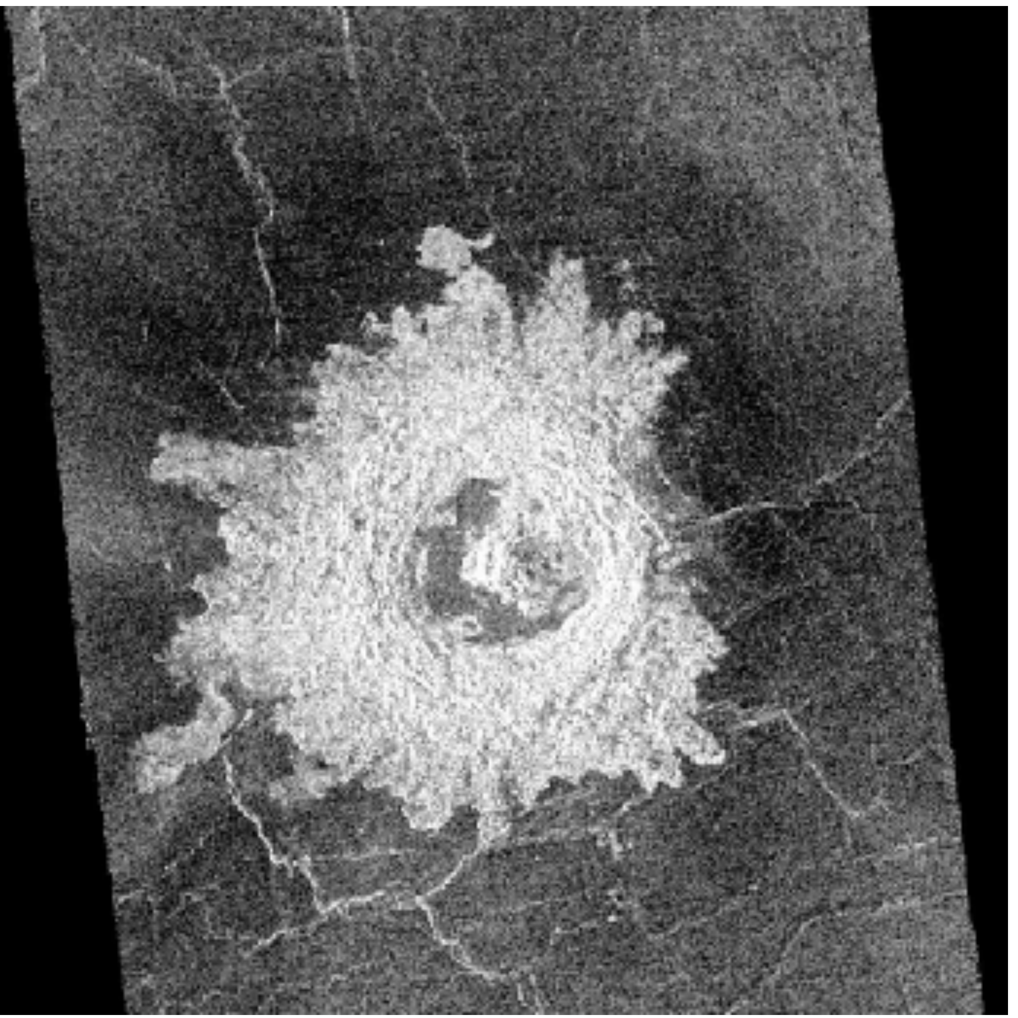
- Meteor Crater, AZ
  - D ~ 1100 m
  - depth ~ 150 m (at time of formation)
  - rim height ~ 65 m (at time of formation)

Complex Craters

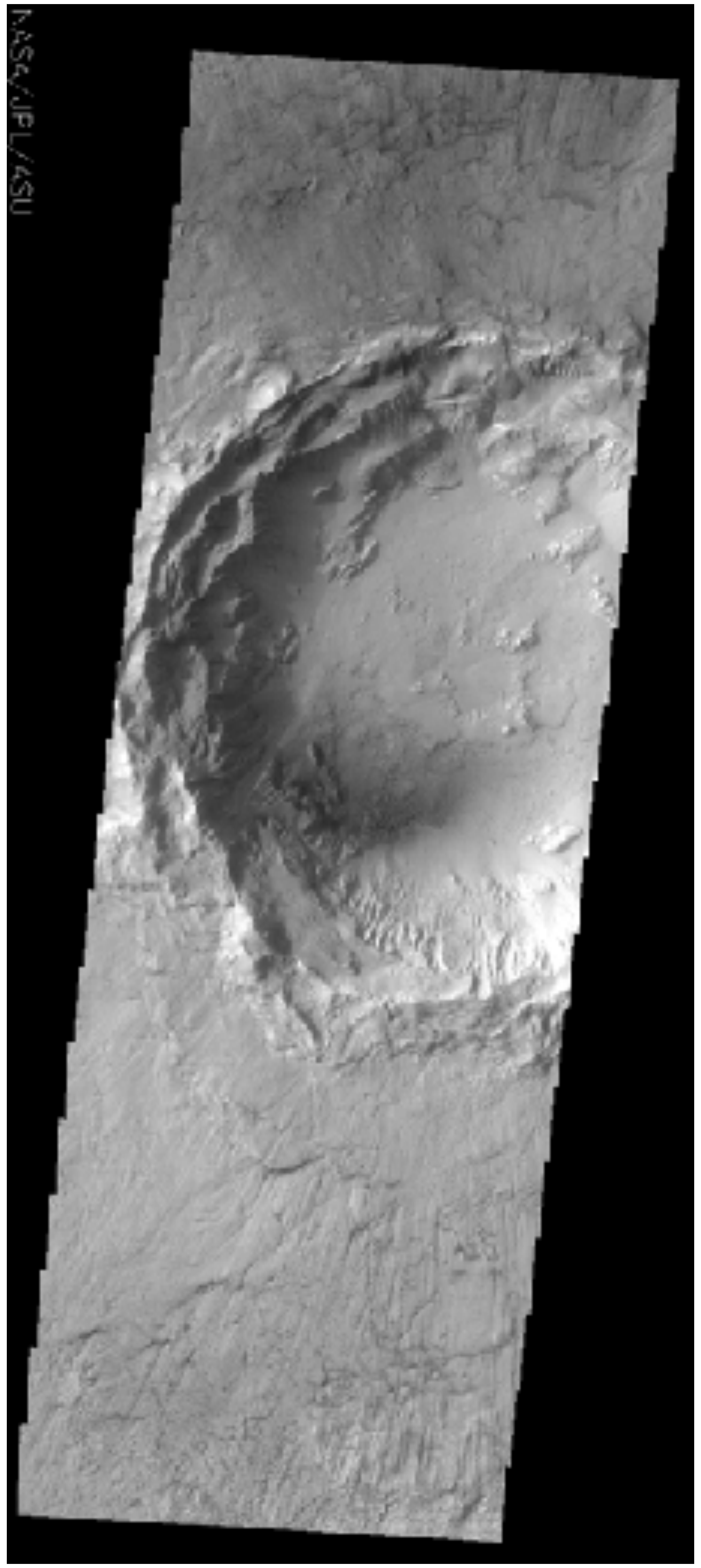
- Central peak composed of uplifted material from below crater center
  - Central peak is the major structural difference between complex craters and simple craters
- Depth-to-diameter ratio decreases
- More flat-bottomed structure
- Land slides (slumping) near crater rim
- More melting of surface material

Complex Craters

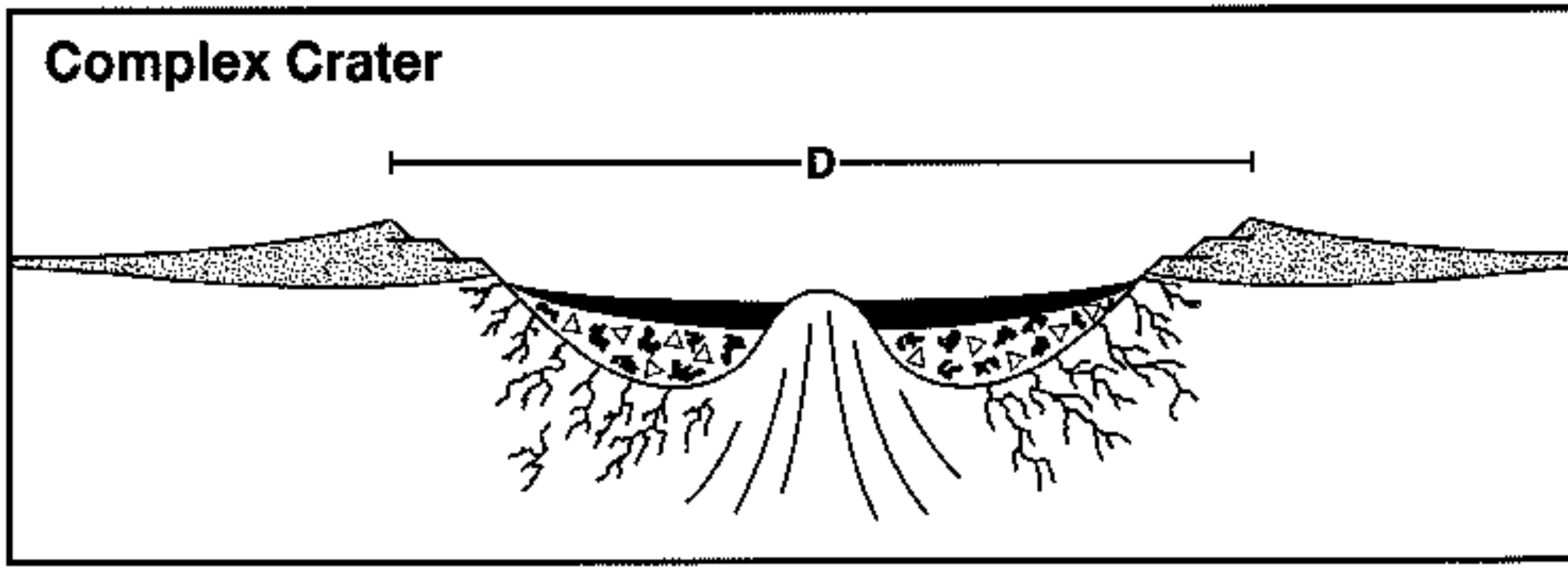
Moon



Venus



Mars

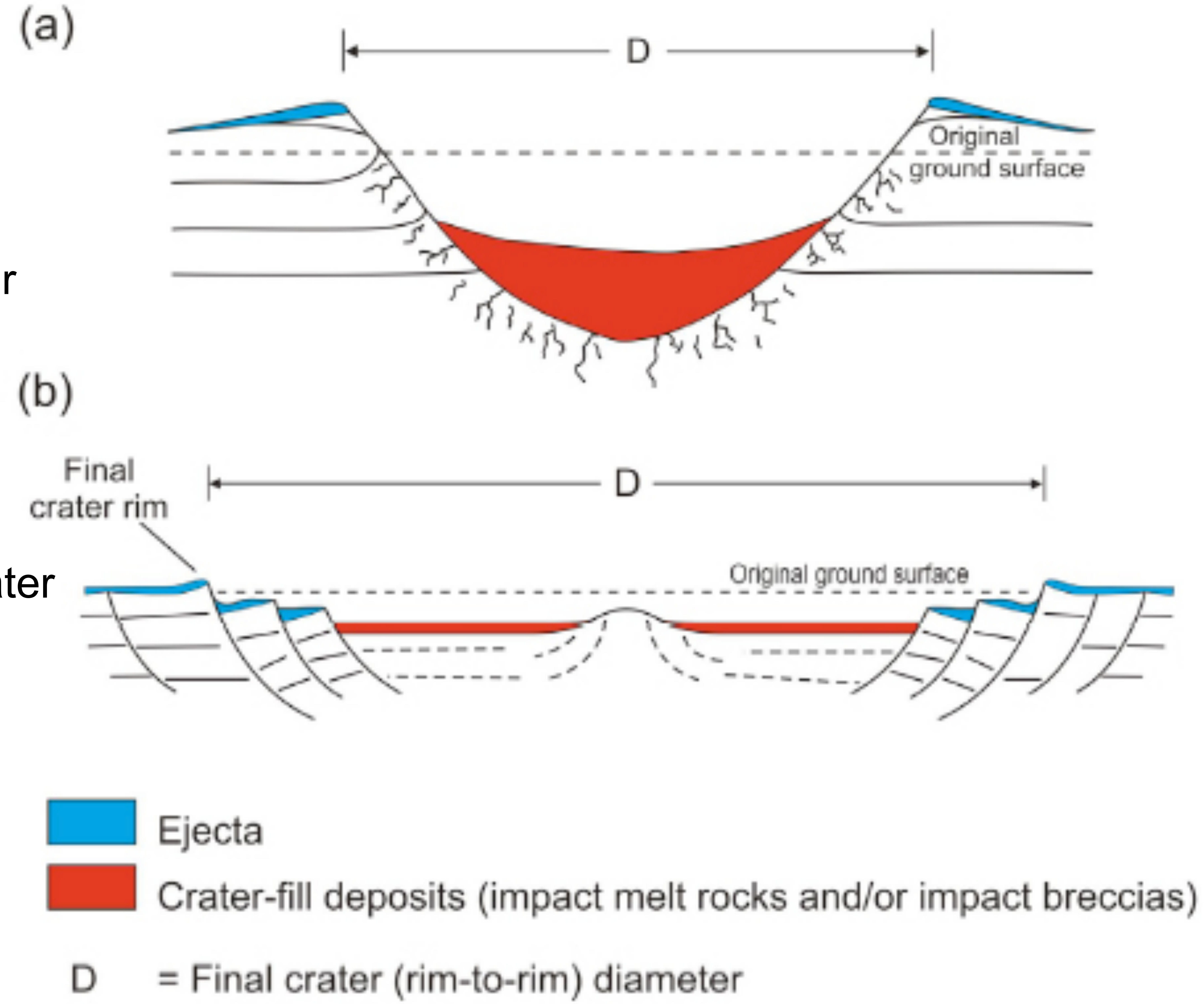


Earth

Complex Craters

Simple Crater

Complex Crater



Complex Craters

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

Craters are point-source explosions

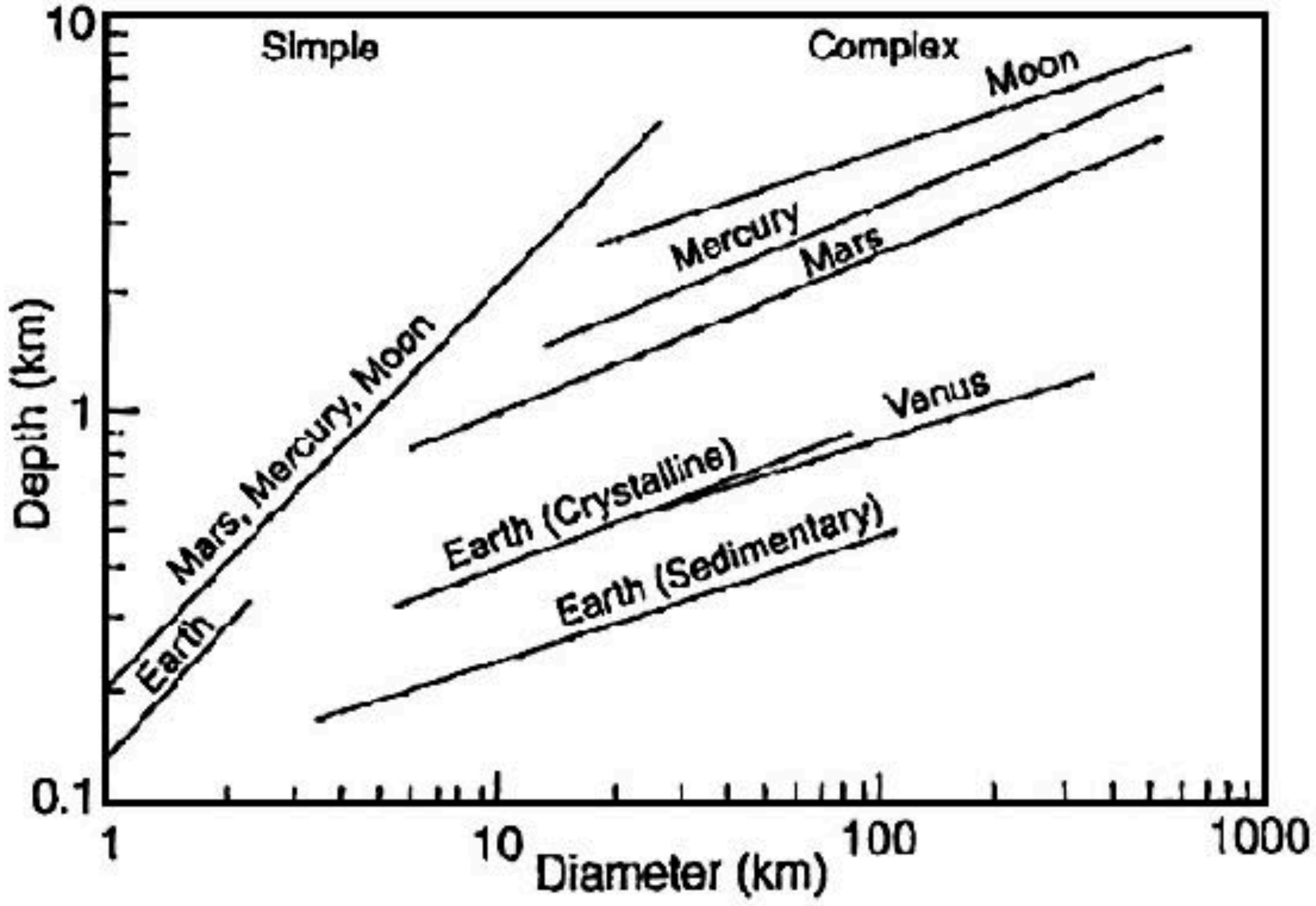
- Fully realized in 1940s and 1950s after nuclear weapon tests
- Crater depends on impactor's kinetic energy: NOT JUST SIZE
- Impactor is MUCH smaller than the crater it produces (Meteor Crater impactor was ~50 m diameter)
- Oblique (not head-on) impacts still make circular craters, unless impact angle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

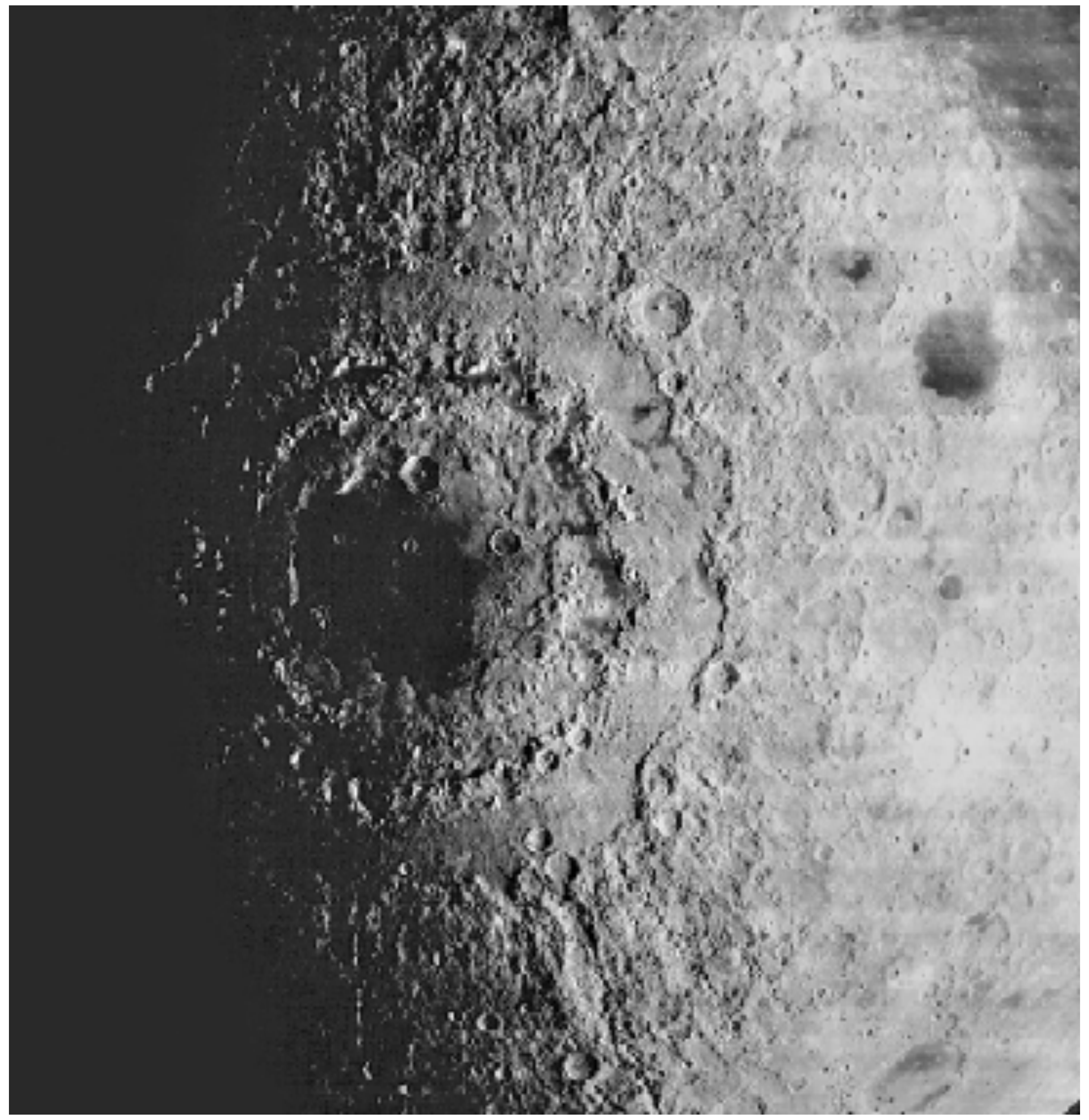
Target	Transition Diameter (km)	g (m/s/s)
Moon	20-25	1.6
Mars	6	3.7
Mercury	13	3.8
Earth	3	9.8

Moltke: ~1 km

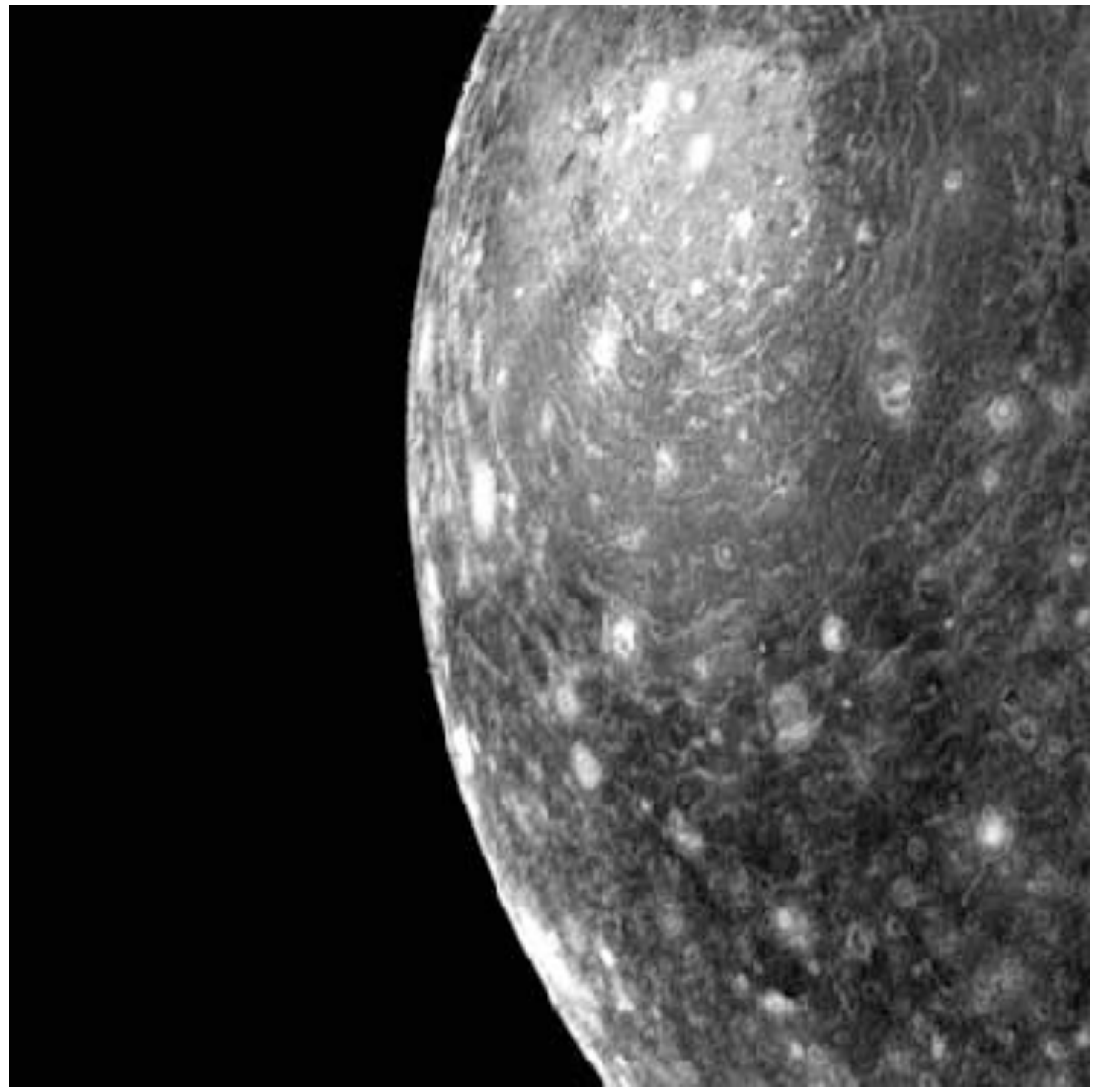
Euler: ~28 km

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

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 = $4.2\text{x}10^{12}$ 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 kiltons of TNT:

$$E = 10^{17}J\frac{1ktTNT}{4x10^{12}J} = 3x10^{4}ktTNT$$ 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:

$$v = \sqrt{GM_{\odot}\left(\frac{2}{r} - \frac{1}{a}\right)} = \sqrt{(7x10^{-11})(2x10^{30}kg)\frac{1AU}{1.5x10^{11}m}\left(\frac{2}{1AU} - \frac{1}{100AU}\right)}$$

$$= \sqrt{(7x10^{-11})(2x10^{30}kg)\frac{1AU}{1.5x10^{11}m}\left(\frac{2}{1AU}\right)} = \sqrt{(\frac{7x2x2}{1.5})x(10^{-11}x10^{30}x10^{-11})}$$

$$= \sqrt{\frac{28}{1.5}x10^{8}} = \sqrt{2x10^{9}} = \sqrt{20x10^{8}} = 4x10^{4}m/s$$ (about 40 km/s…close to escape velocity from the Sun!)

Order of Magnitude: Energy of Impact

- And orbital velocity of the Earth:

$$v_{orb} = \sqrt{\frac{GM_\odot}{d_E}} = \sqrt{\frac{(7x10^{-11})x(2x10^{30}kg)}{(1.5x10^{11}m)}} = \sqrt{\frac{14}{1.5}x10^8} = \sqrt{10x10^8} = 3x10^4 m/s$$

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

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

- $$E = 2(40m)^3(3000\frac{kg}{m^3})(7x10^4\frac{m}{s})^2 = (2x3x64x49)x(10^3x10^3x10^8) = (2x10^4)x(10^{14}) = 2x10^{18}J$$

- And converting to kilotons: $E = 2x10^{18}J\frac{1ktTNT}{4x10^{12}J} = 0.5x10^6ktTNT = 5x10^5ktTNT$ 10 times the Tsar Bomba!

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