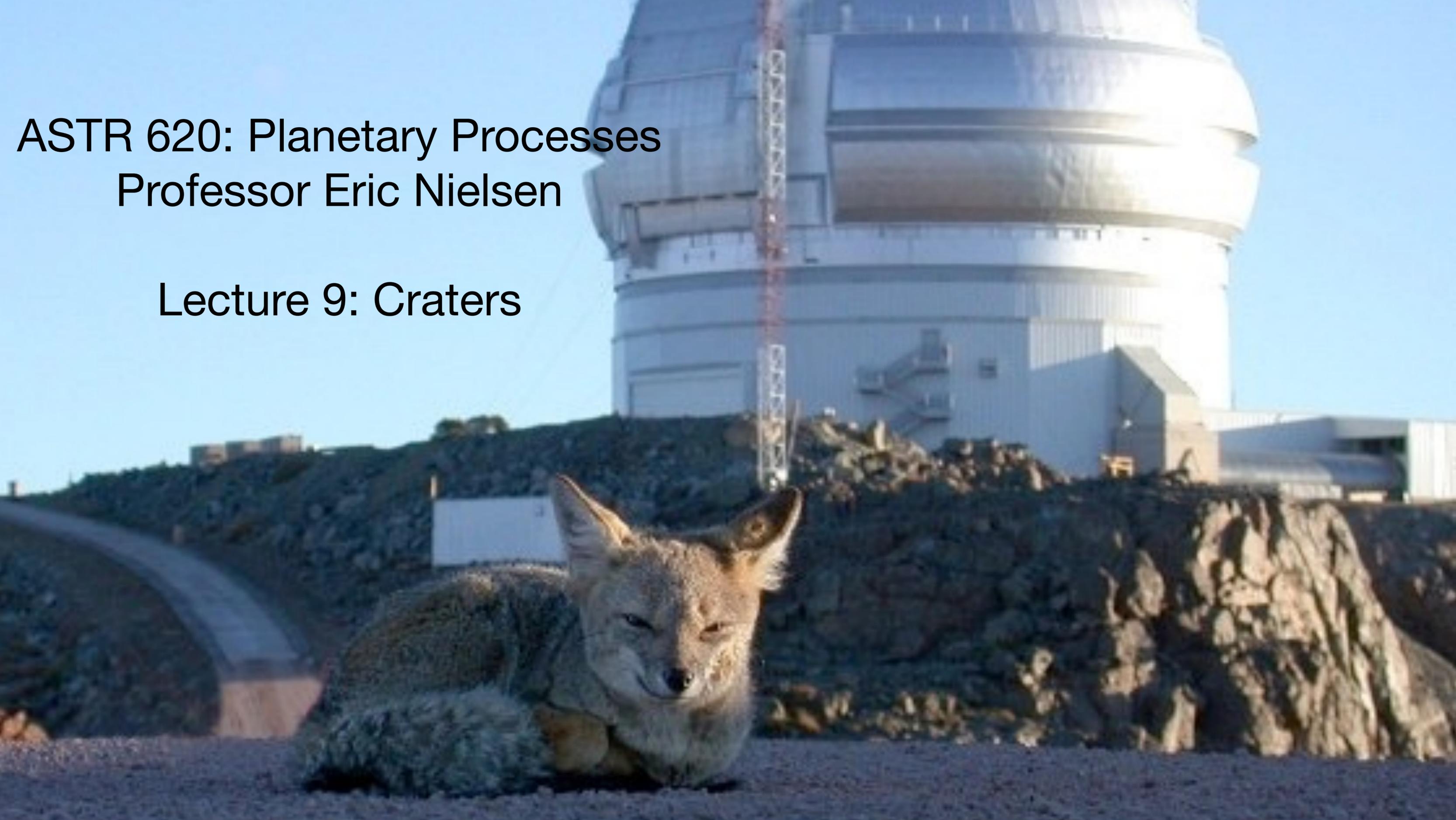


ASTR 620: Planetary Processes
Professor Eric Nielsen

Lecture 9: 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
- Reminder on homework: working together (discussing problems, checking answers) is encouraged, but you should each do your own calculations

Review of the last class

- A 100 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

Review of the last class

- A transient crater forms:
 - (A) — Before the contact and compression stage
 - (B) — After the contact and compression stage but before the excavation stage
 - (C) — After the excavation stage but before the modification stage
 - (D) — After the modification stage

Review of the last class

- Compared to the final crater, the transient crater is:
 - (A) — Deeper, wider, with a shorter rim
 - (B) — Deeper, less wide, with a shorter rim
 - (C) — Shallower, less wide, with a shorter rim
 - (D) — Deeper, wider, with a taller rim
 - (E) — Deeper, less wide, with a taller rim

Review of the last class

- The shock wave that results from an impact:
 - (A) — Is about the same as the sound speed in rock, and much less than the impact velocity
 - (B) — Is about the same as the sound speed in rock, and much greater than the impact velocity
 - (C) — Is about the same as the impact velocity, and much less than the sound speed in rock
 - (D) — Is about the same as the impact velocity, and much greater than the sound speed in rock

Review of the last class

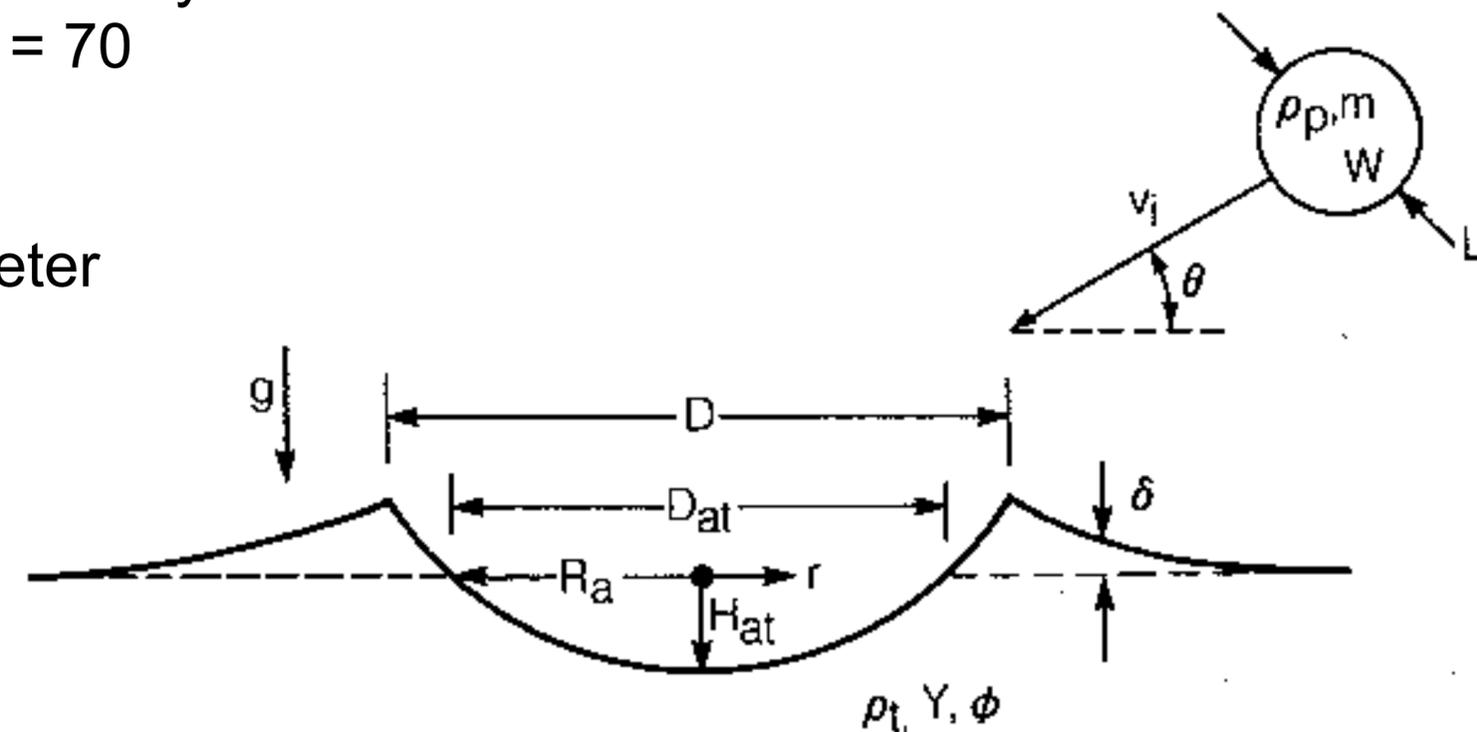
- Which of these craters will have the largest diameter?
 - (A) — Denser impactor, Denser target material, higher surface gravity, larger impactor radius
 - (B) — Denser impactor, less dense target material, higher surface gravity, larger impactor radius
 - (C) — Denser impactor, less dense target material, lower surface gravity, larger impactor radius
 - (D) — Less dense impactor, less dense target material, lower surface gravity, larger impactor radius
 - (E) — Less dense impactor, denser target material, higher surface gravity, smaller impactor radius

Impact Velocities

$$D \approx 2 \rho_m^{0.11} \rho_p^{-\frac{1}{3}} g_p^{-0.22} R^{0.13} E_K^{0.22} (\sin \theta)^{\frac{1}{3}} \quad (\text{everything in mks units})$$

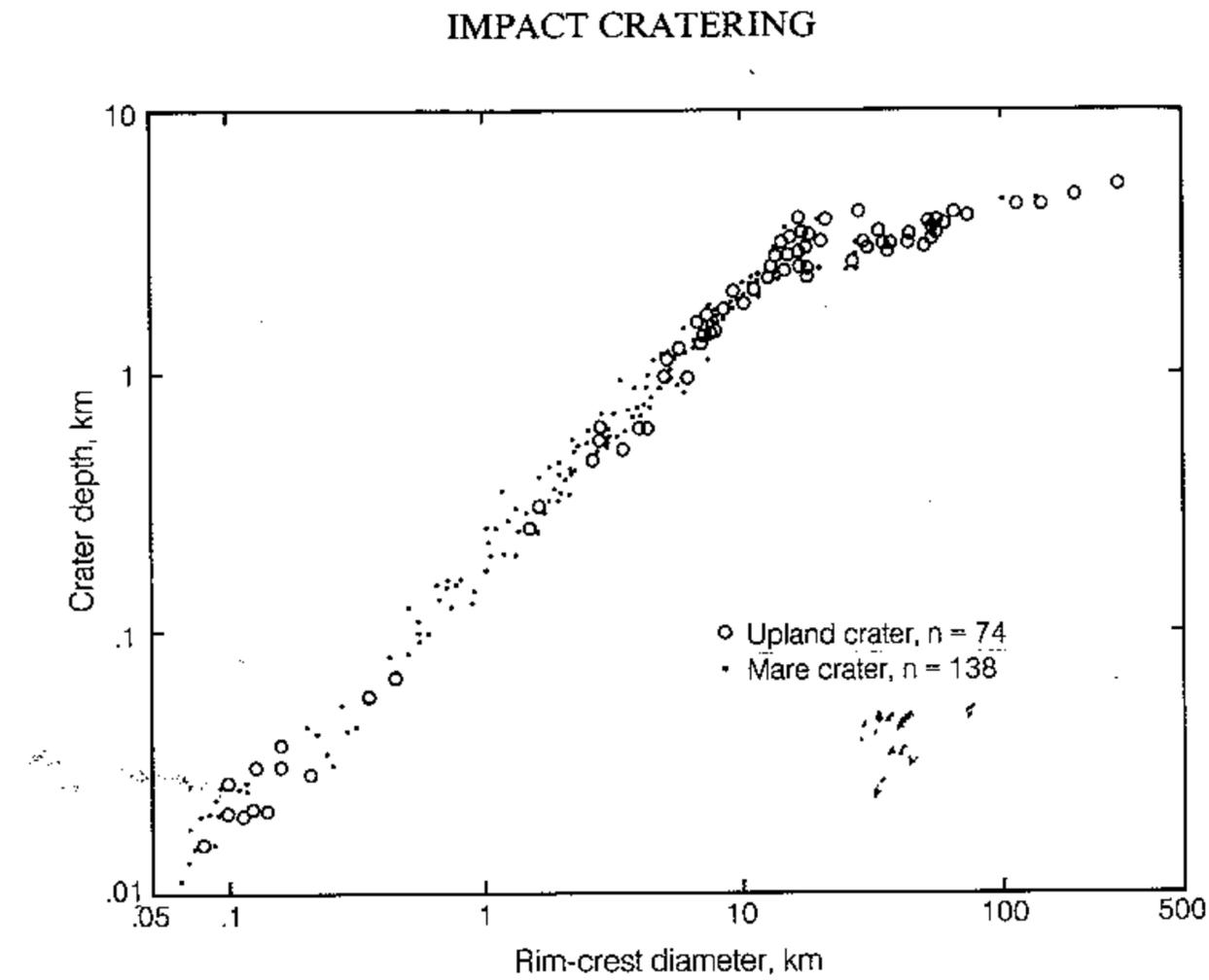
- Impact velocity:
- minimum: Earth's escape velocity (11 km/s)
- maximum: Head-on collision with an object traveling at escape velocity (from the Sun) at 1 AU: 40 km/s (total velocity of impact: 40+30 = 70 km/s)
- Craters on Earth tend to be ~10x larger than the impactor diameter

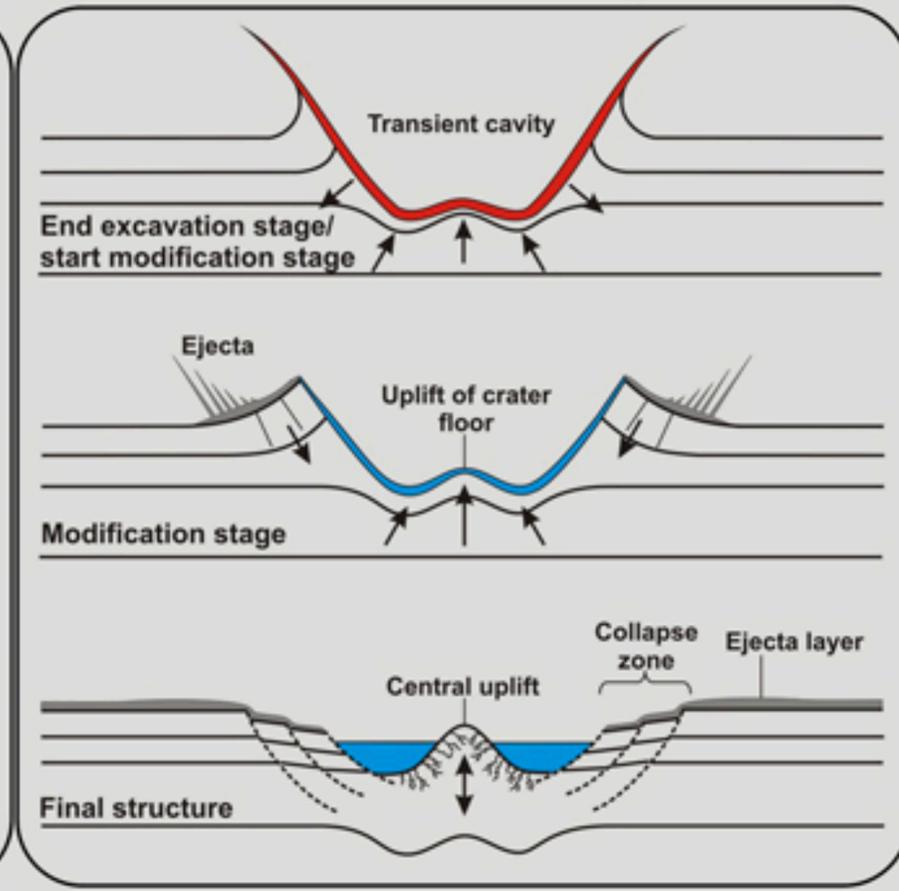
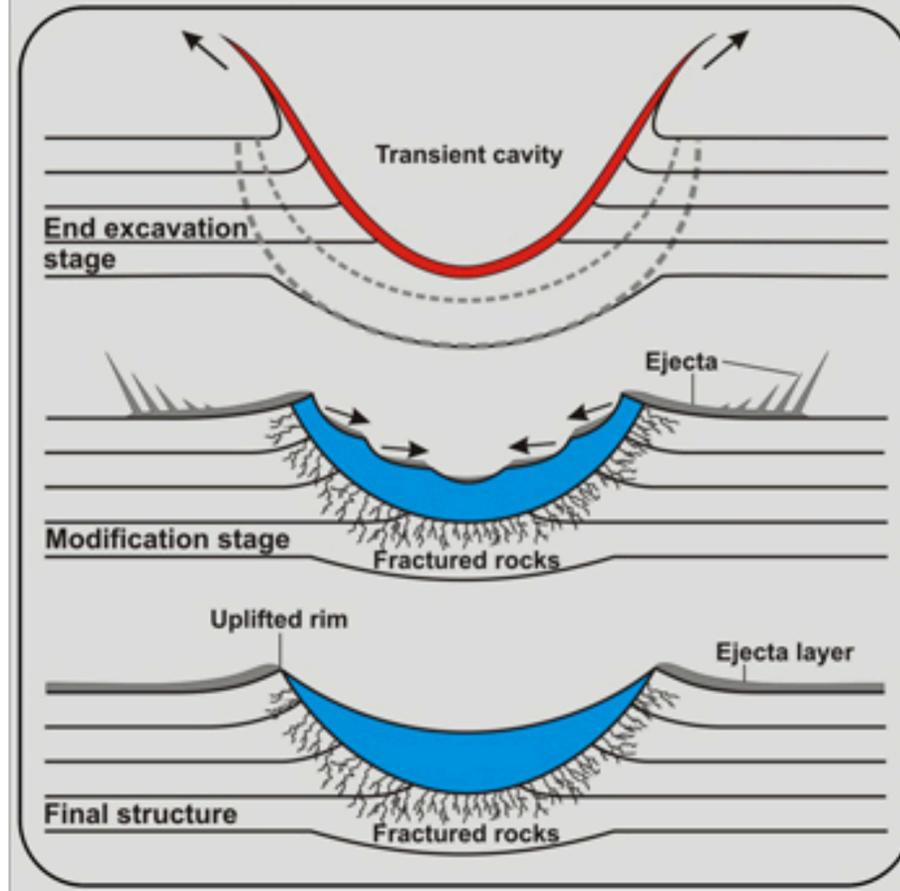
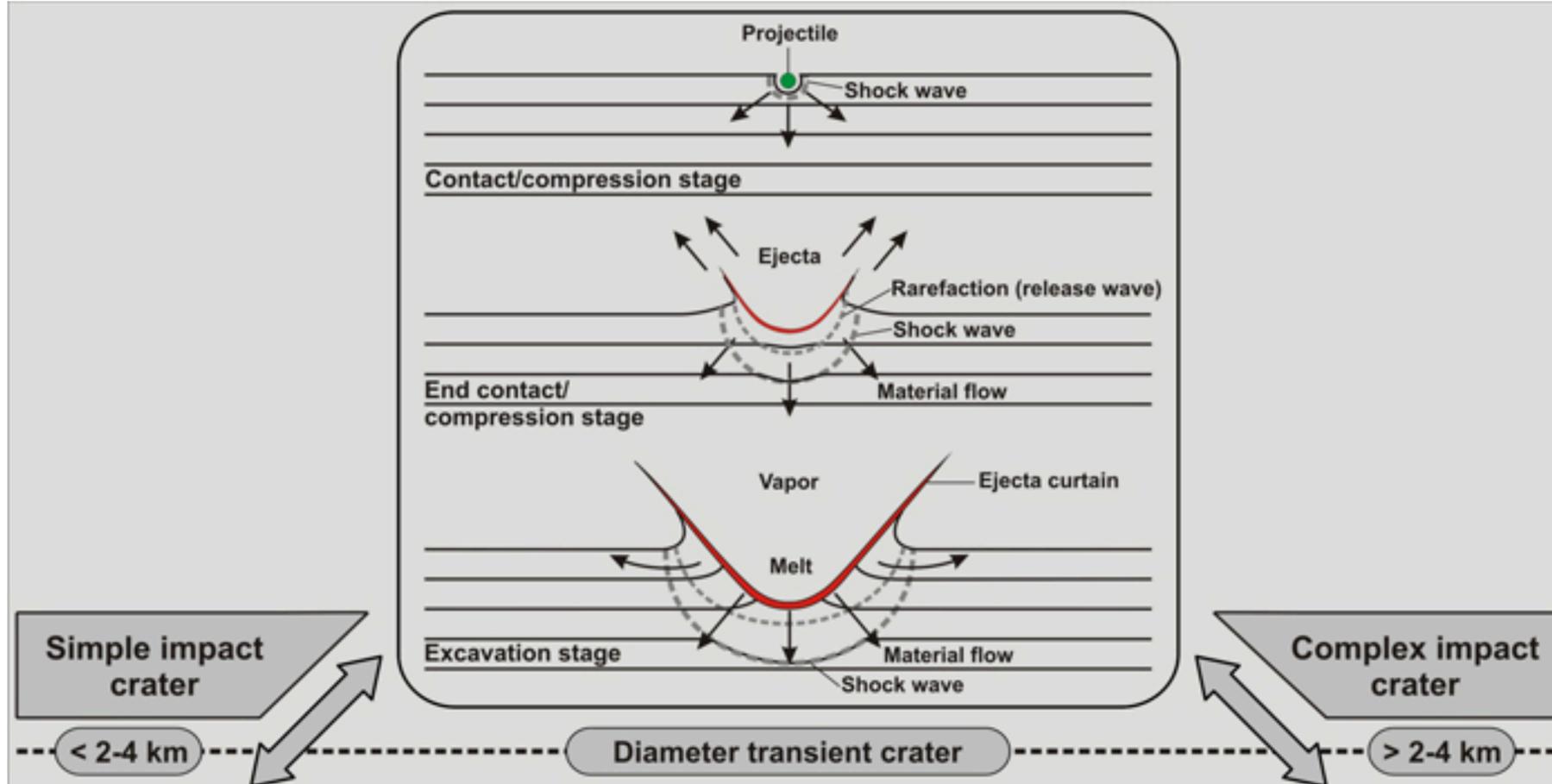
SCALING OF CRATER DIMENSIONS



Simple/Complex Transition

- All craters start as transient, semi-hemispheric cavities
- Simple craters are in “strength regime,” most material is pushed downward and size of crater is limited by strength of rock
- Complex Craters are in “gravity regime,” size of crater is limited by gravity
- Transition radius depends on material strength, density of material, and gravity





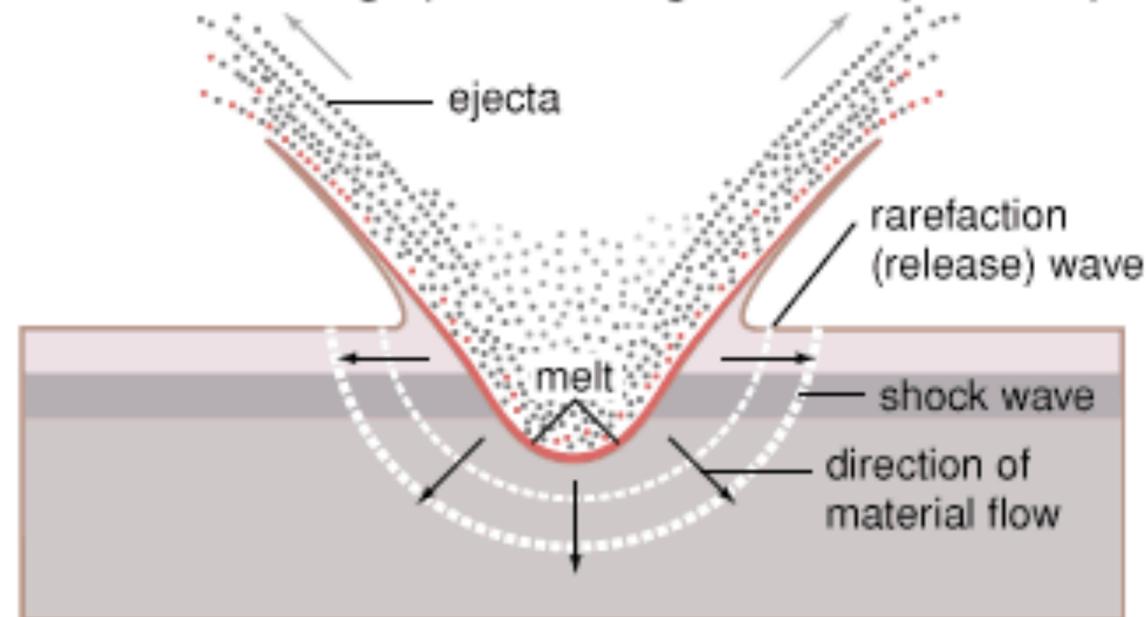
Complex Craters

- Central peak in Complex Craters results from upward penetration of sub-crater materials
- Likely related to some kind of fluidization and “sloshing” of material in the larger, faster, higher energy impacts
- Peak height depends on crater diameter:

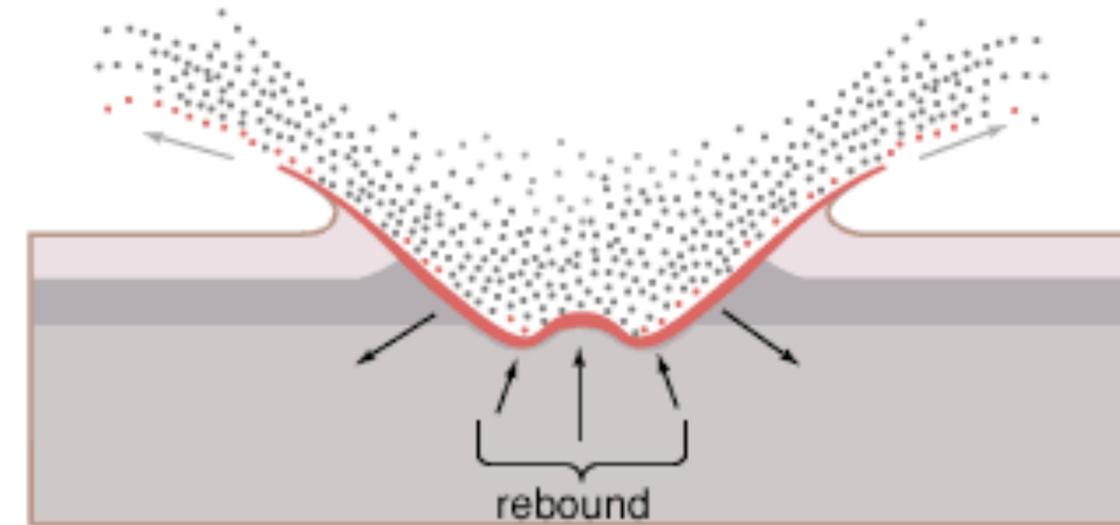
$$h \approx 0.06D^{1.1}$$

Formation of a complex impact crater

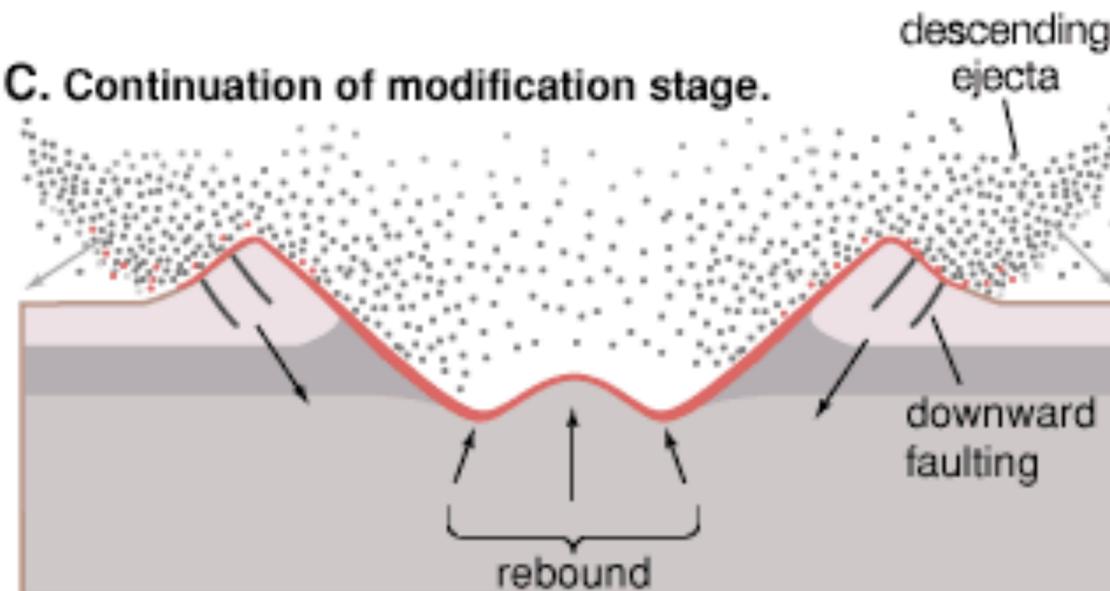
A. Excavation stage (the sole stage for a simple crater).



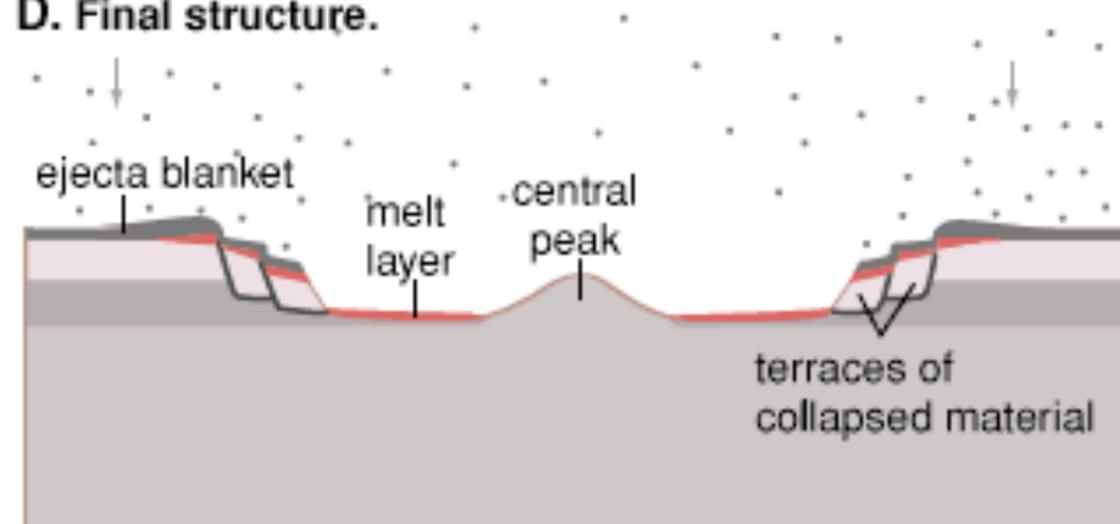
B. End of excavation stage; start of modification stage.



C. Continuation of modification stage.

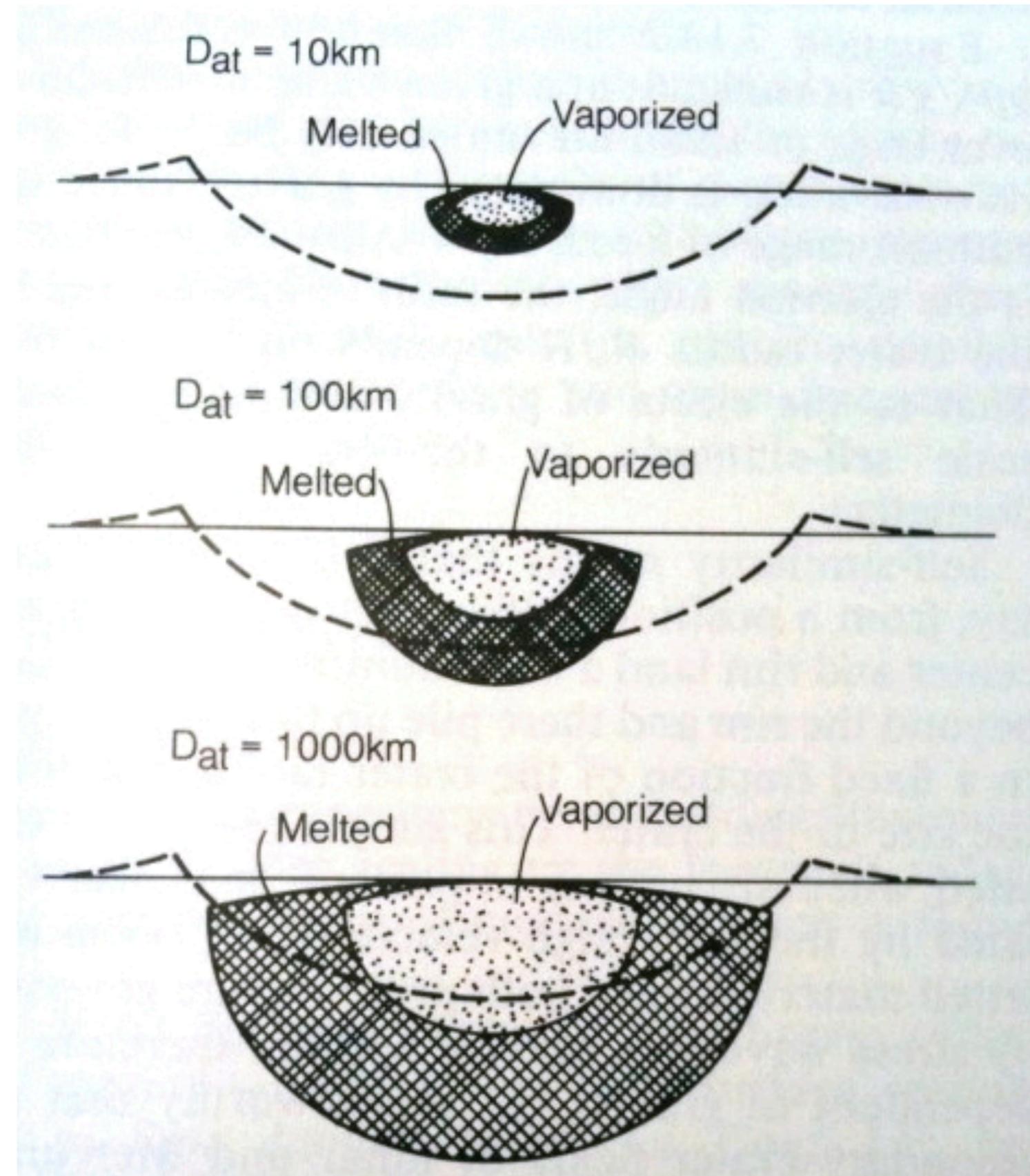


D. Final structure.



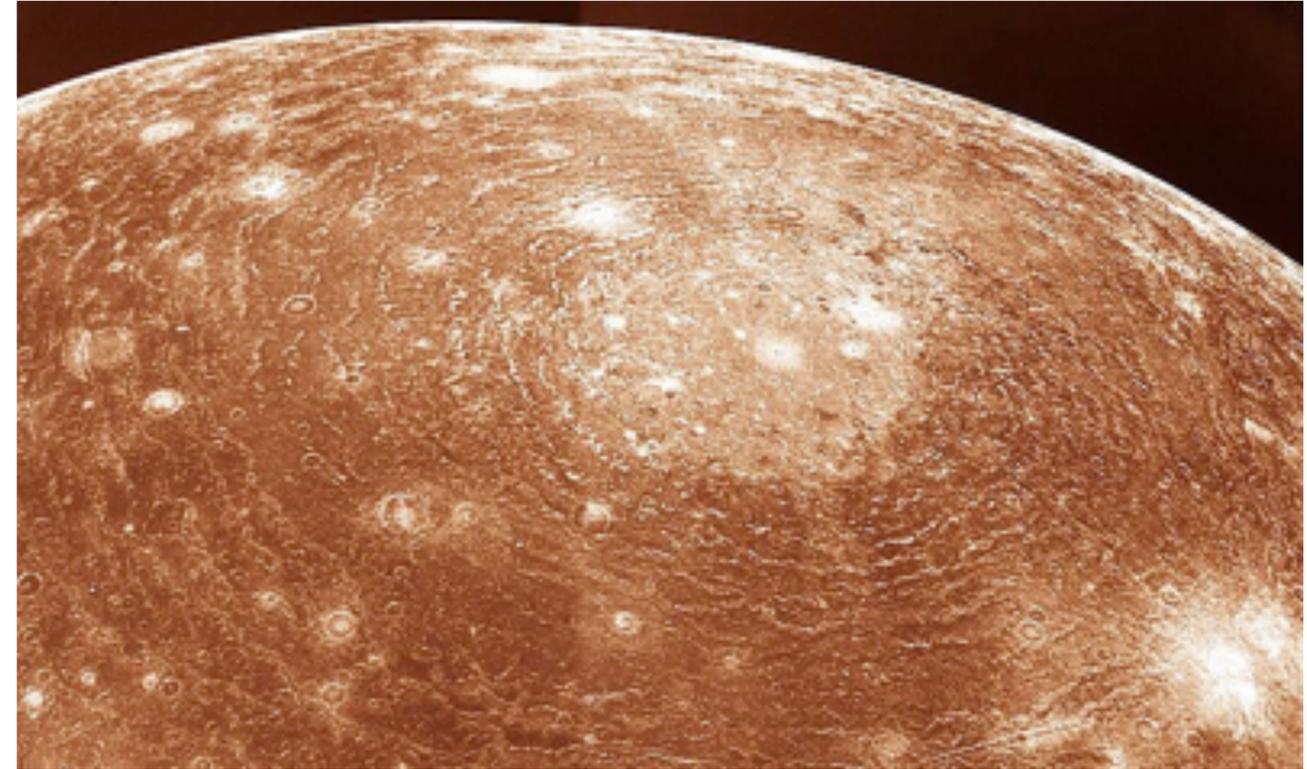
Melt and Vapor

- 6-10x more material is melted than vaporized
- Melt and vapor are small components of ejecta from small craters
- For larger craters, the amount of melt+vapor can be about the volume of the crater

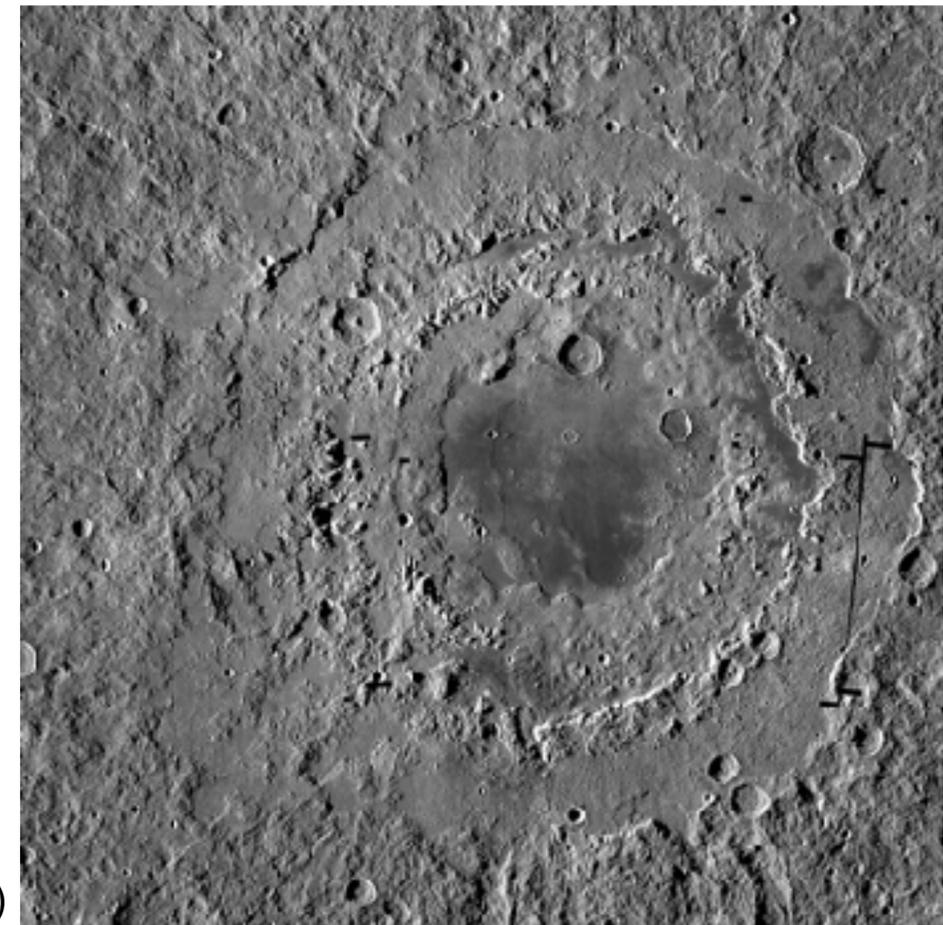


Multiring Basins

- Result of impactors with the largest energies
- Formation process still not well understood
- Ring Tectonic theory is the most wide accepted:
 - ring fractures develop outside of original crater
 - related to thickness of lithosphere (uppermost layer of a planet's crust), and viscosity of fluid mantle



Callisto (wikipedia)



Moon (cseligman.com)

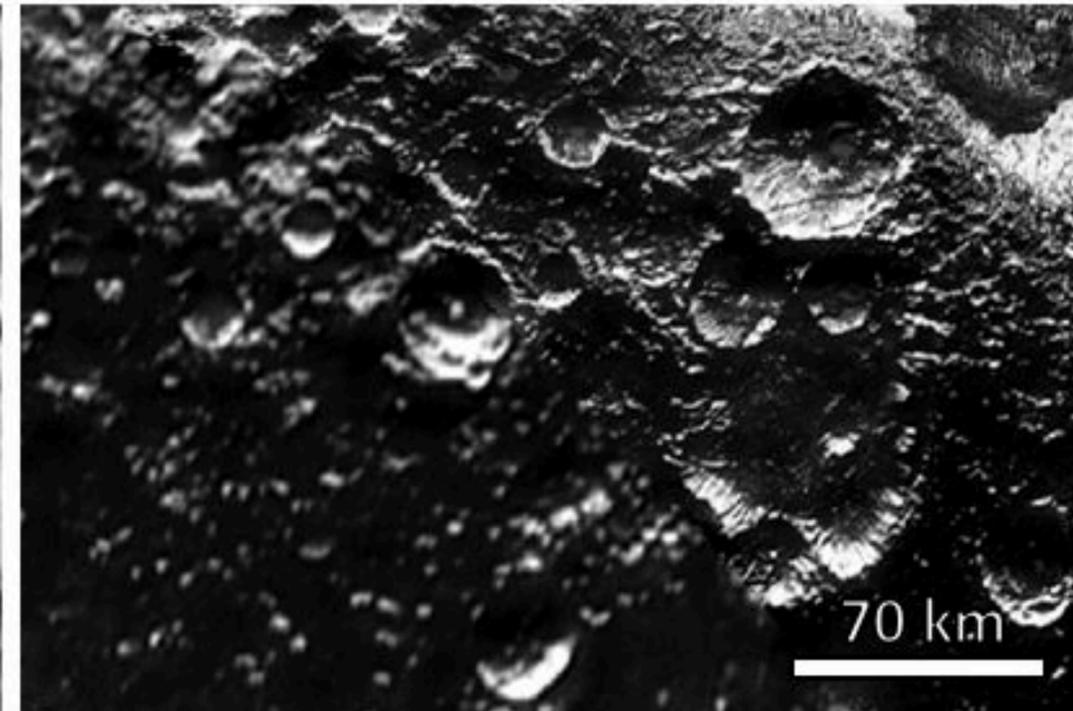
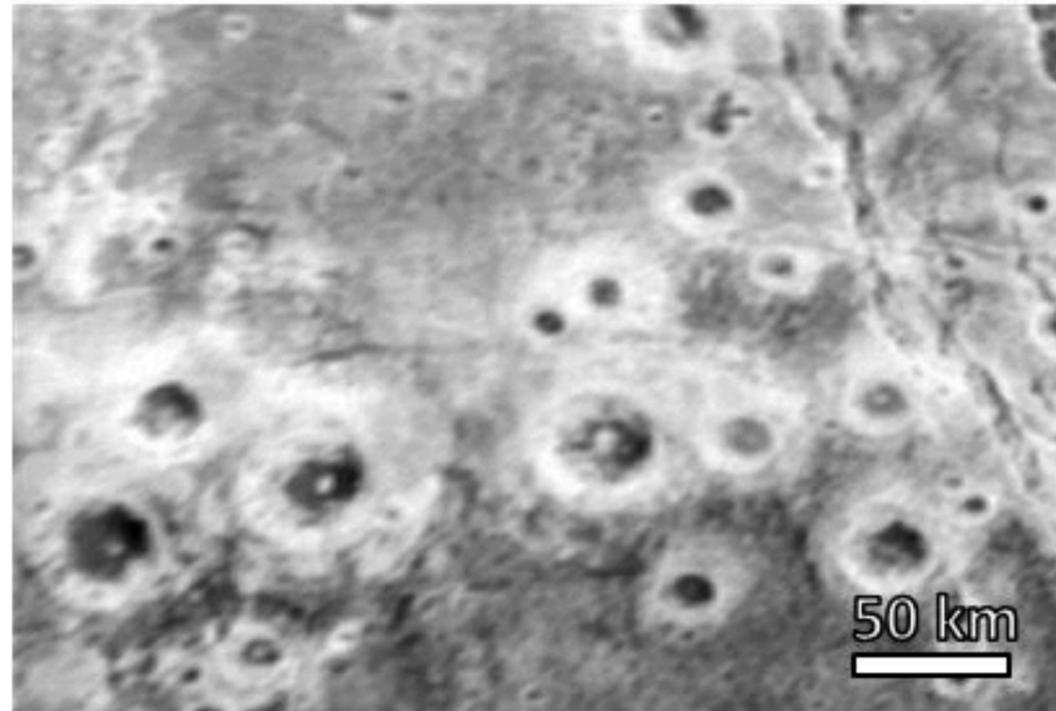
Sun Overhead

- Fewer Shadows
- More dark/bright contrasts

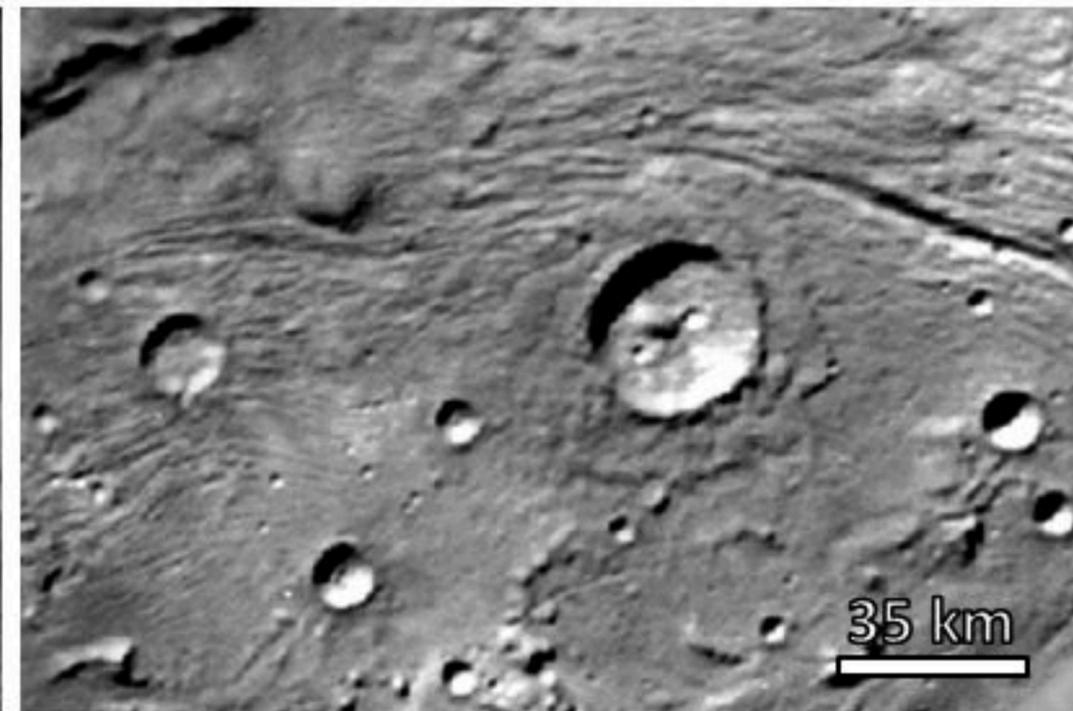
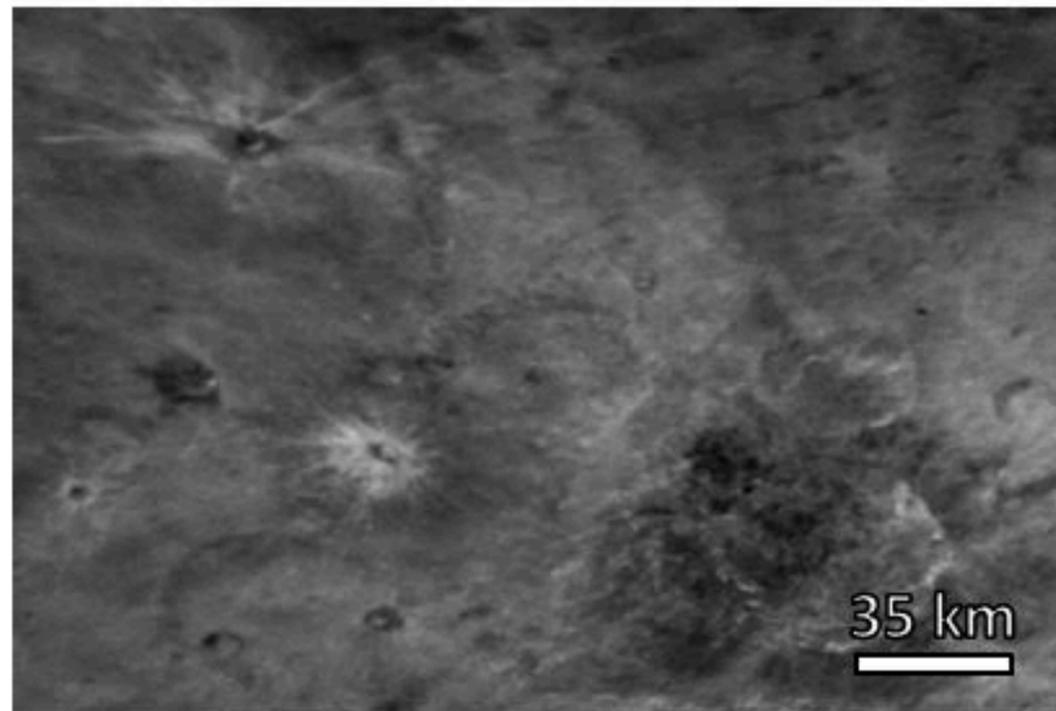
Sun at an Angle

- More Shadows
- Fewer dark/bright contrasts

Pluto

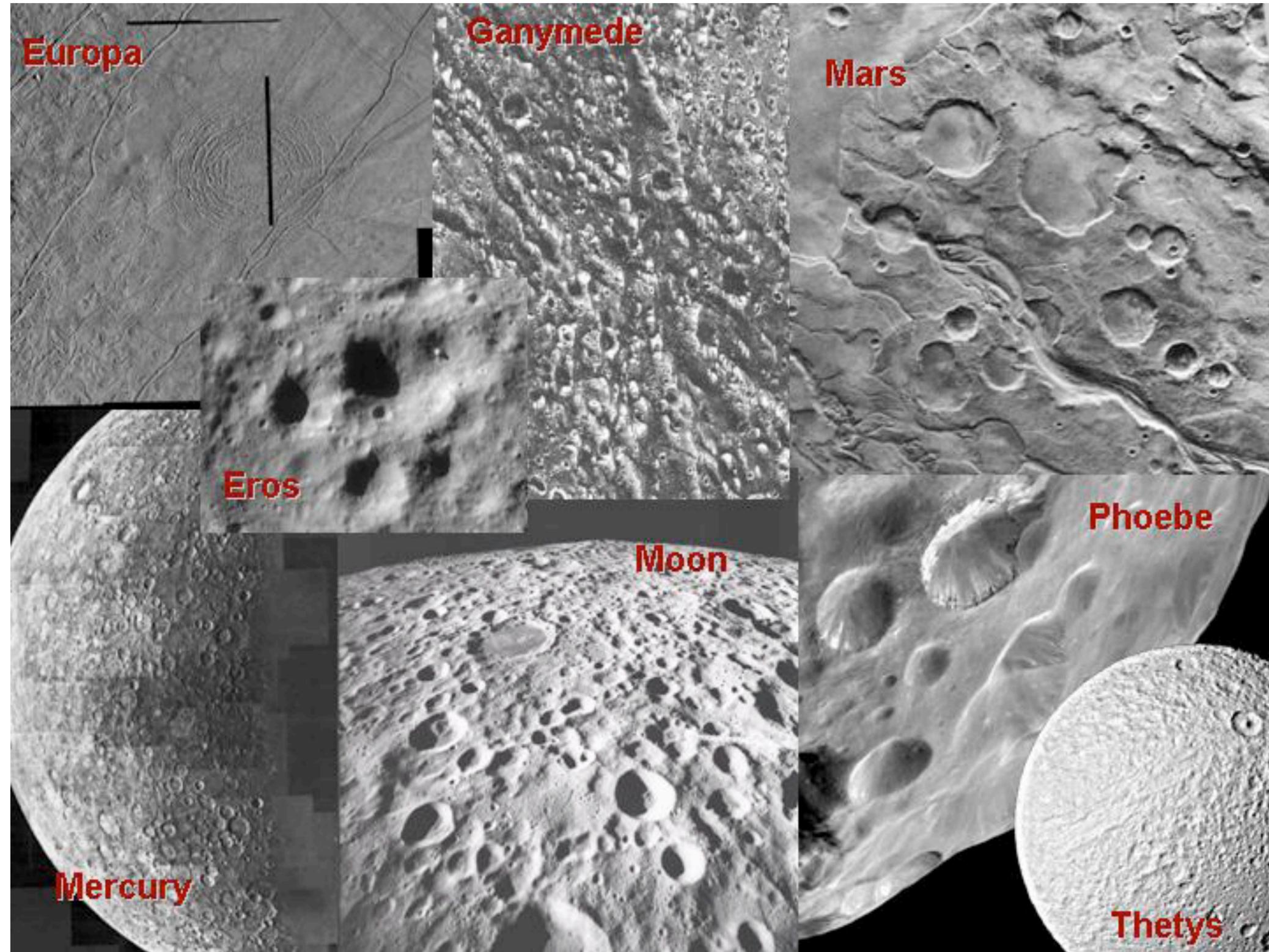


Charon



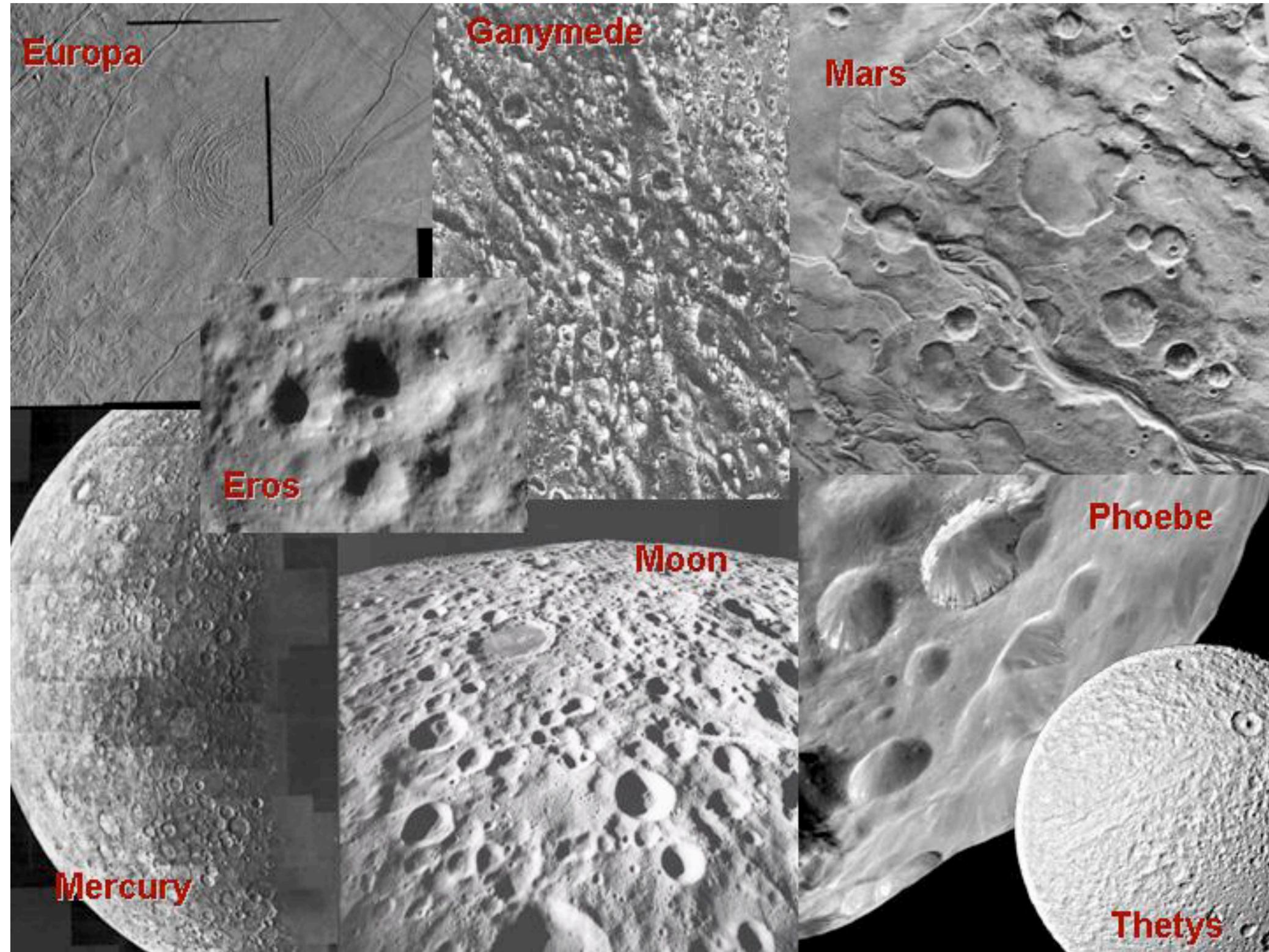
Cratering Statistics

- Current crater population, along with an estimate of rate of crater formation, gives information about the resurfacing history of an (airless) object
- absolute age is difficult (don't know precise size or temporal history of impactors)
 - but can get relative age



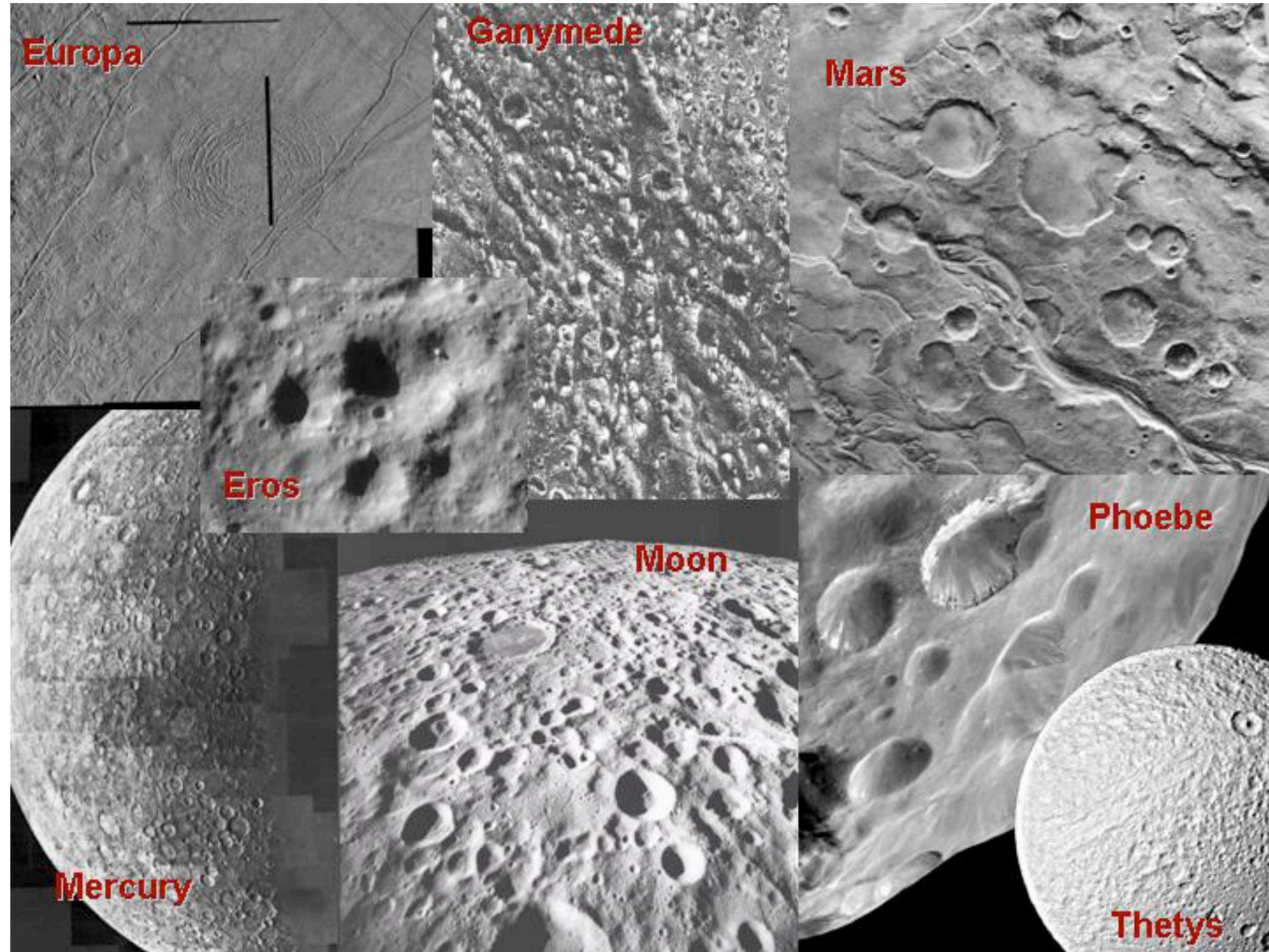
Cratering Statistics

- Older surfaces have more craters
- Small craters are more frequent than large craters
- Crater count techniques developed for lunar maria
 - telescope work established relative ages
 - Apollo samples provided absolute calibration



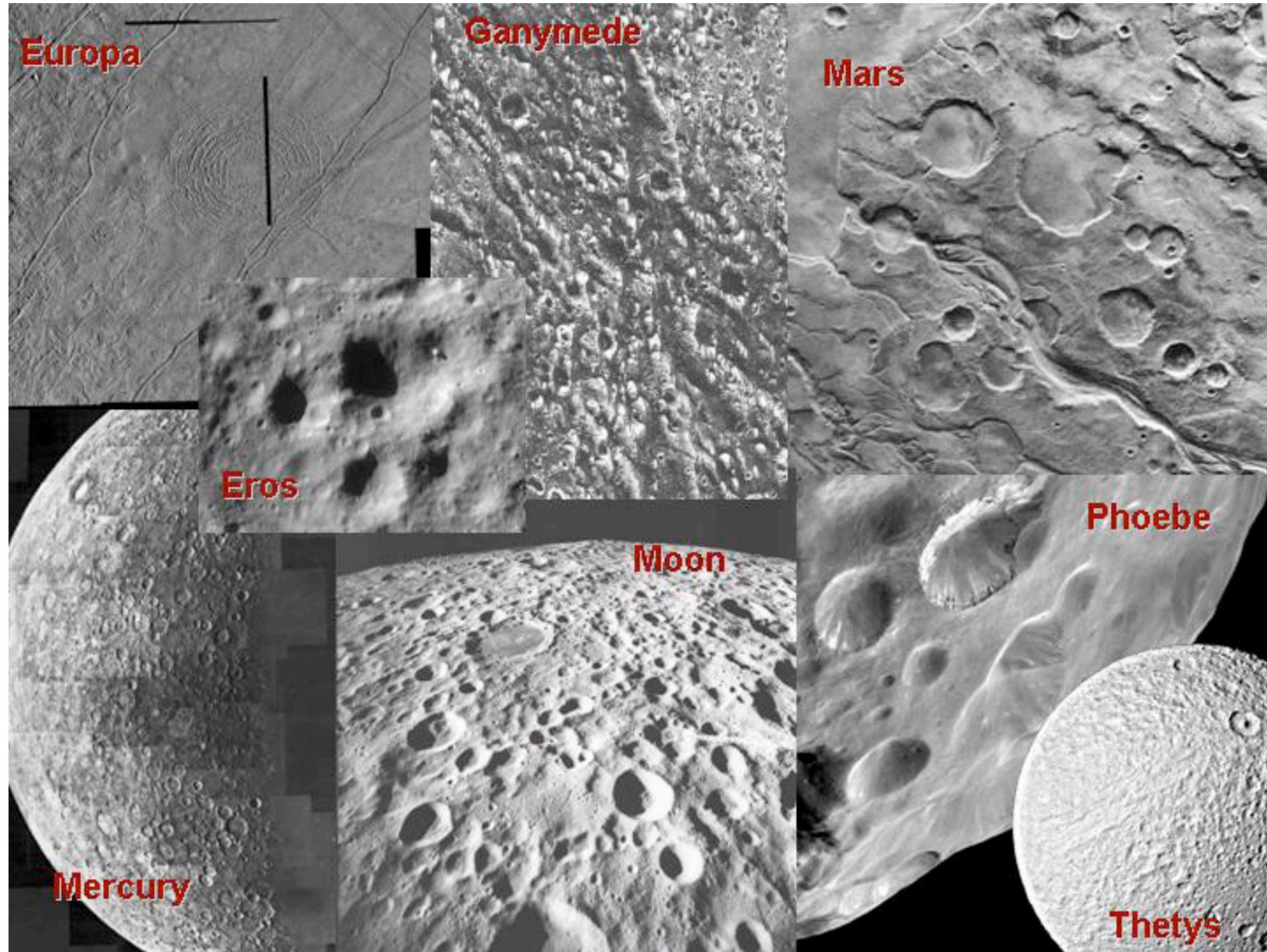
Cratering Statistics

- Can relate crater count to surface age if:
 - impact rate is constant
 - Landscape is far from equilibrium (new craters don't erase old craters)
 - Target area all has one age
 - You have enough craters (need fairly old or large areas)



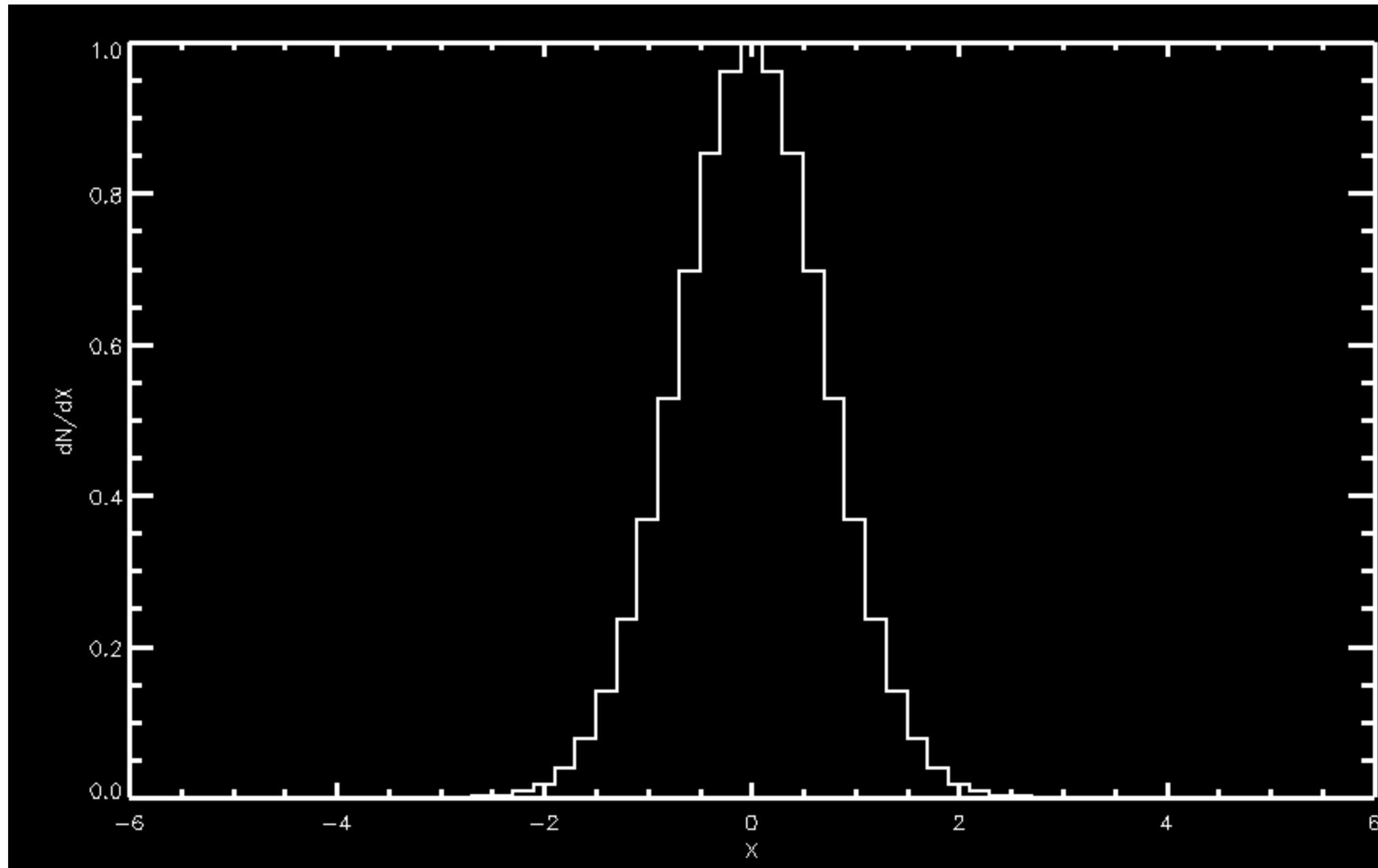
Cratering Counts

- Select an area that is thought to have had a homogenous geologic history
- count craters within that area
 - Measure: number of craters of a certain diameter per unit area
- This assumes cratering is a random process: no significant to exact location of a crater within a given area



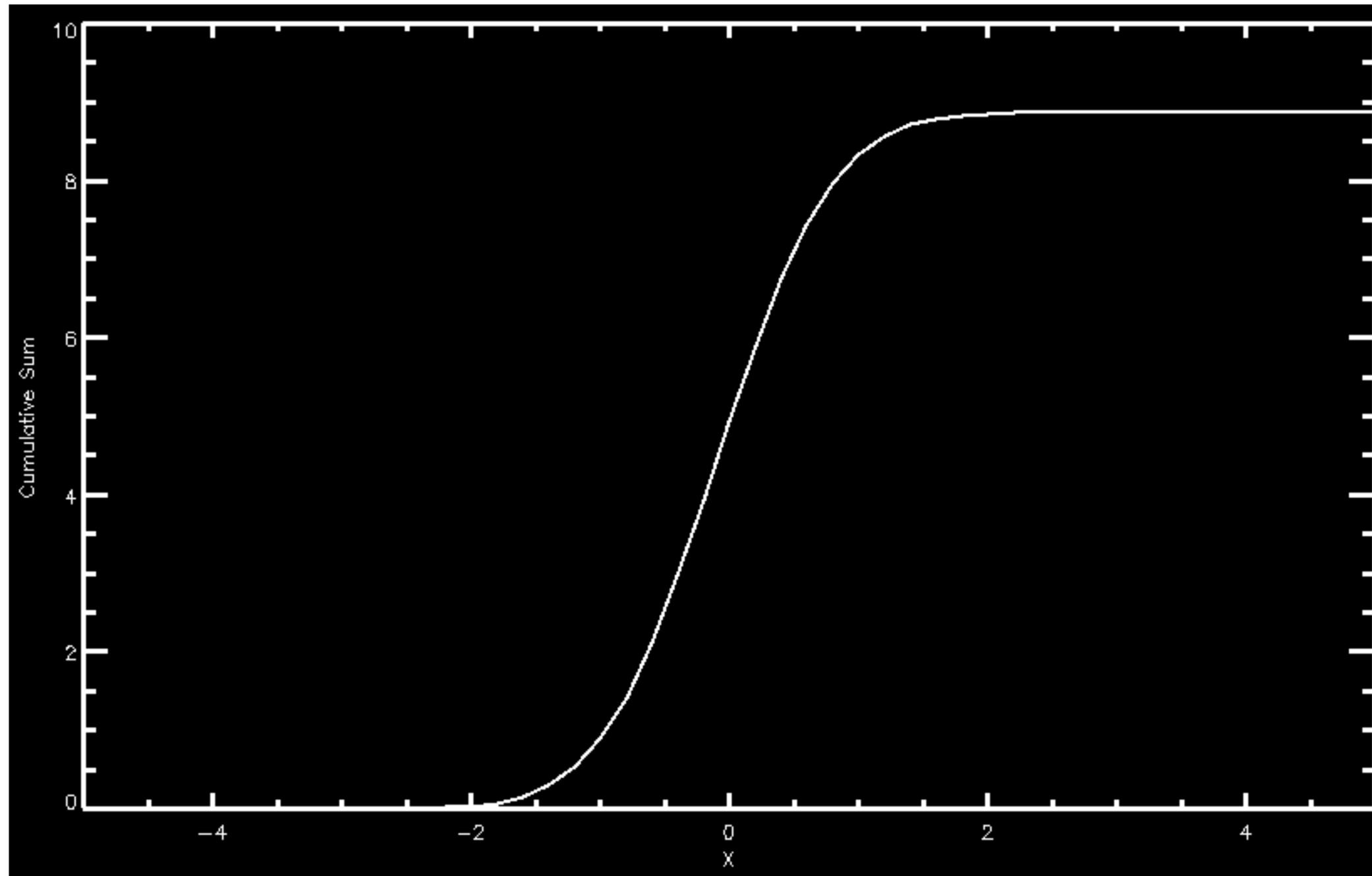
Cumulative Distributions

- A histogram of some parameter (X , say) can be thought of a differential measurement:
 - Number of occurrences (dN) per bin of size dX
- An integral of a histogram then gives the number (N) between two endpoints



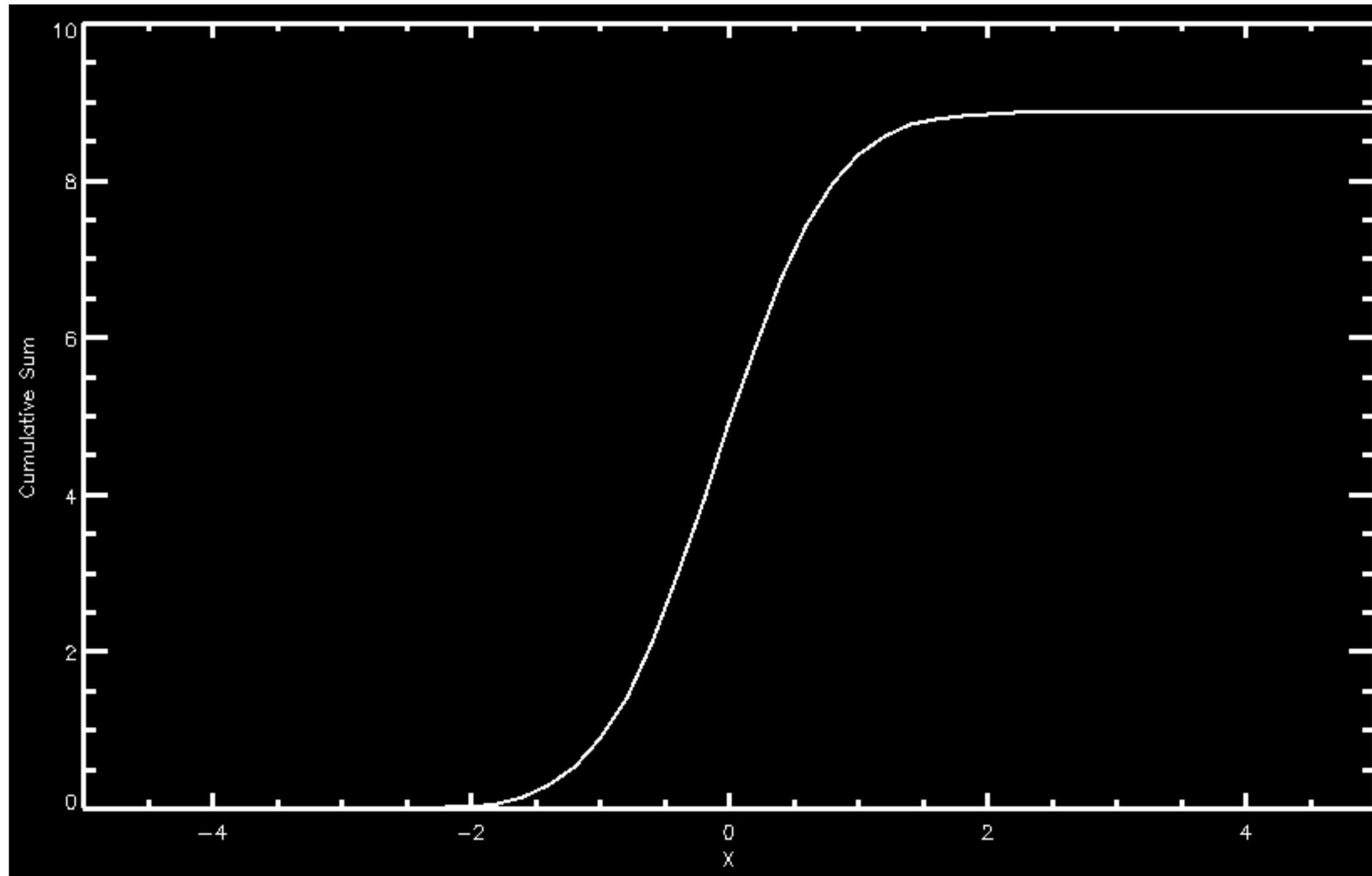
Cumulative Distributions

- A cumulative distribution is the integral of a histogram, often from negative infinity to some value X
 - Number of occurrences for values less than or equal to X
 - Unlike histograms, cumulative distributions don't require an arbitrary choice of bin size

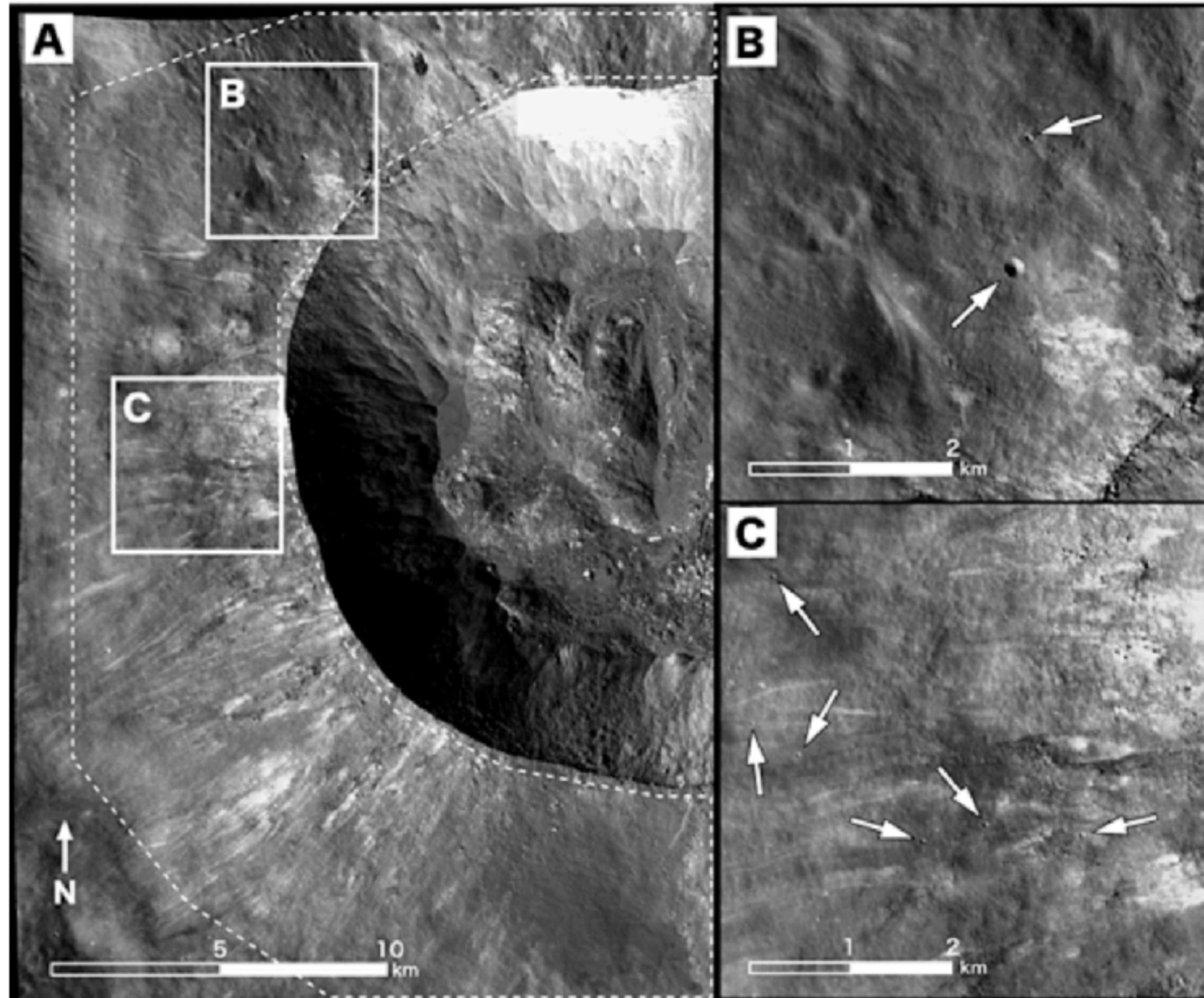


Cumulative Distributions

- Crater counts use crater diameter as the parameter (X), and integrate in the opposite direction:
 - Number of craters with a diameter greater than or equal to X
 - (the resolution of your images sets a lower limit on crater diameter you can determine, but you should always see the biggest craters)

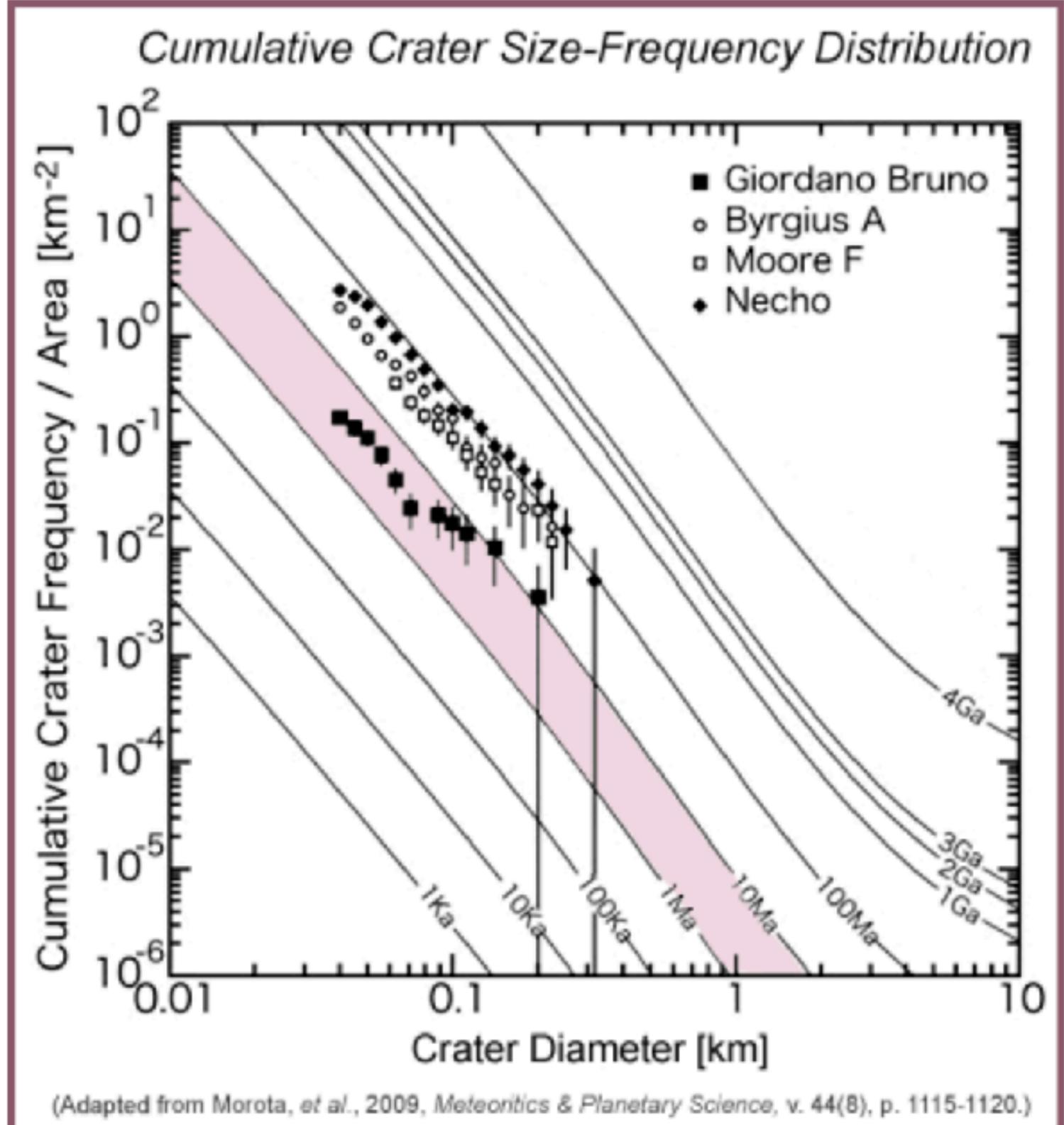


Lunar Crater Giordano Bruno



(From Morota, *et al.*, 2009, *Meteoritics & Planetary Science*, v. 44(8), p. 1115-1120.)

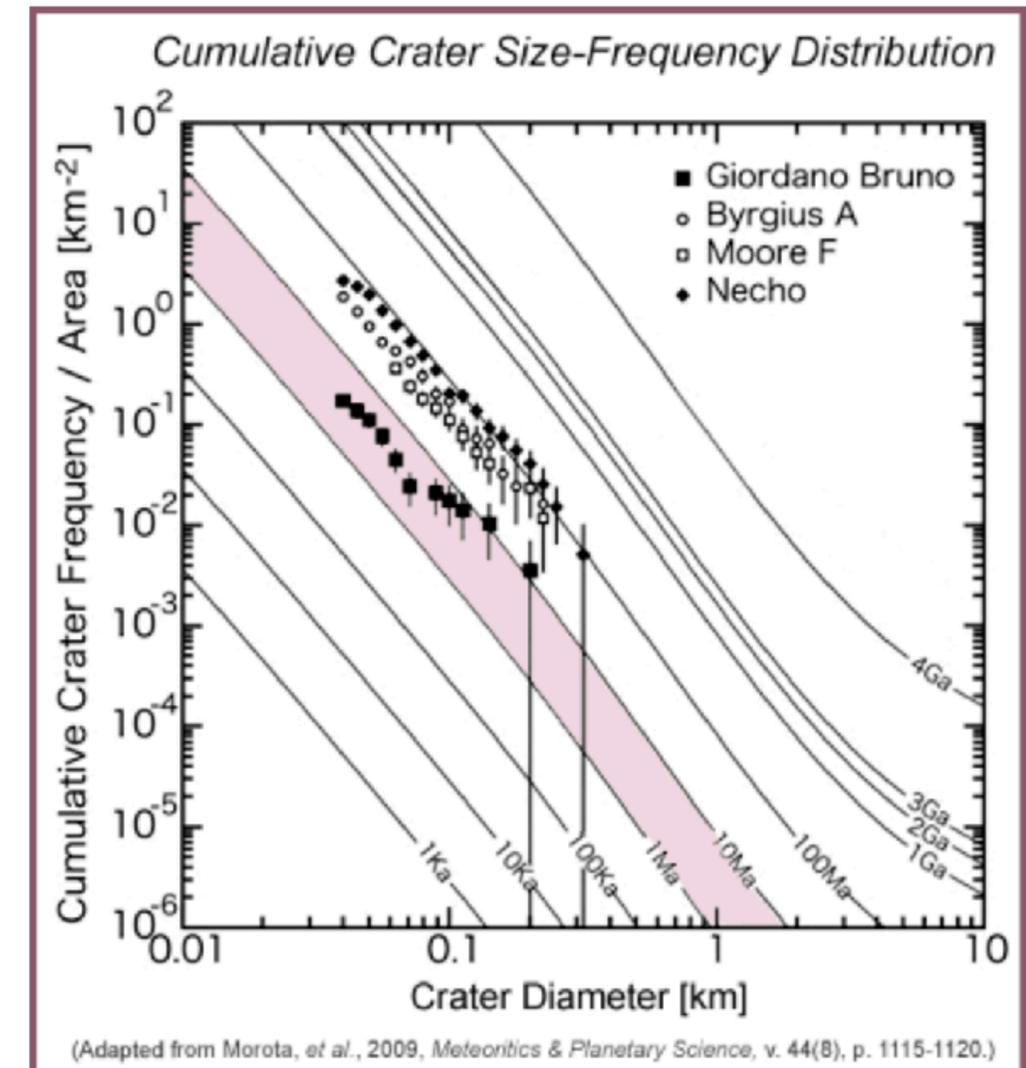
Acquired by the Terrain Camera on SELENE (Kaguya), these images are among the four terabytes of TC data released so far by JAXA. Spatial resolution is 10 meters/pixel. Morota and coauthors measured the size-frequency distribution of craters in the area bordered by the white, dashed line. Images B and C are close-ups of regions of interest with arrows pointing to craters larger than 40-meters in diameter.



Cumulative size-frequency distributions of craters on the continuous ejecta of Giordano Bruno and three other young craters for comparison. Frequencies of craters per unit area are plotted against crater diameters and used with chronology models to derive the age of the surface. If a medieval formation hypothesis were correct, then the crater-size distribution for Giordano Bruno would plot on an isochron (line of equal age) of 1 Ka (one thousand years). Instead, we see that the crater-size distribution points plot between 1 to 10 million years.

Order of Magnitude: Lunar Craters

- If all craters on the Moon follow the distribution like the distribution around the Necho crater:
- (1) How many craters bigger than a diameter of 80m are there on the Moon?
- (2) What fraction of the Lunar surface is covered with craters larger than 80m?



Cumulative size-frequency distributions of craters on the continuous ejecta of Giordano Bruno and three other young craters for comparison. Frequencies of craters per unit area are plotted against crater diameters and used with chronology models to derive the age of the surface. If a medieval formation hypothesis were correct, then the crater-size distribution for Giordano Bruno would plot on an isochron (line of equal age) of 1 Ka (one thousand years). Instead, we see that the crater-size distribution points plot between 1 to 10 million years.

Order of Magnitude: Lunar Craters

- (1) How many craters bigger than a diameter of 80m are there on the Moon?
- The cumulative histogram at 80m diameter is about 1 crater per square kilometer
- Ok, how many square kilometers are there on the Moon?
- We need to know the radius of the Moon. The Moon has similar density to the Earth, but has 1% of the mass.

$$M_M = \frac{4}{3}\pi R_M \rho_M \quad M_E = \frac{4}{3}\pi R_E \rho_E \quad \frac{M_M}{M_E} = \frac{R_M^3}{R_E^3}$$

$$R_M = R_E \left(\frac{M_M}{M_E} \right)^{\frac{1}{3}} = (6000km)(10^{-2})^{\frac{1}{3}} = (6000km)(10 \times 10^{-3})^{\frac{1}{3}} = (6000km)(2 \times 10^{-1}) = 1200km$$

- Surface area of the Moon is $A = 4\pi R^2 = (12)(1200km)^2 = (12)(144 \times 10^4 km^2) = 2000 \times 10^4 km^2 = 2 \times 10^7 km^2$
- 1 crater bigger than 80 m per square kilometer, so 20 million craters!

Order of Magnitude: Lunar Craters

- (2) What fraction of the Lunar surface is covered with craters larger than 80m?
- We can solve this over a single square kilometer, it has one crater (equal to or larger than 80 m), so we just need the fraction of the 1 square kilometer area this crater takes up.
- There are more small craters than large craters, so something near the small end of the range (80m - infinity) is good. This is order-of-magnitude, so let's say a diameter of 100m

$$\frac{A_{crater}}{A_{square}} = \frac{\pi R^2}{1km^2} = \frac{\pi(50m)^2}{10^6m^2} = \frac{3 \times 2500m^2}{10^6m^2} = \frac{8000}{10^6} = 8 \times 10^{-3} = 0.008 \quad \text{about 1\%}$$

Break

05:00

Lunar Crater Counts

- Empirically, from the Moon:

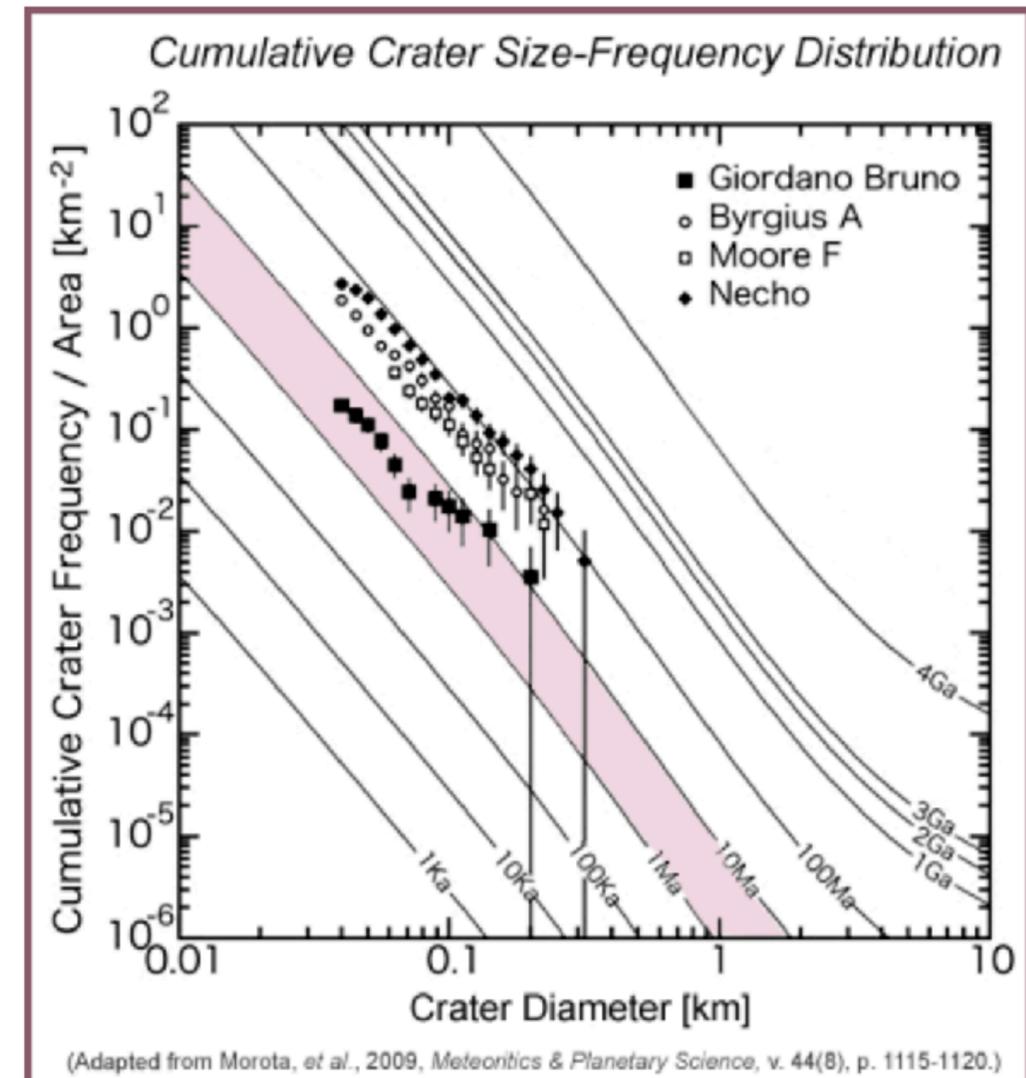
$$N_{cum} = cD^{-b}$$

- b is 1.8 for most craters on the Moon with diameters between 4 km to a few 100 km

- Special case when b=2:

- D^{-2} has units of 1/area
- N_{cum} has units of 1/area
- So c is dimensionless

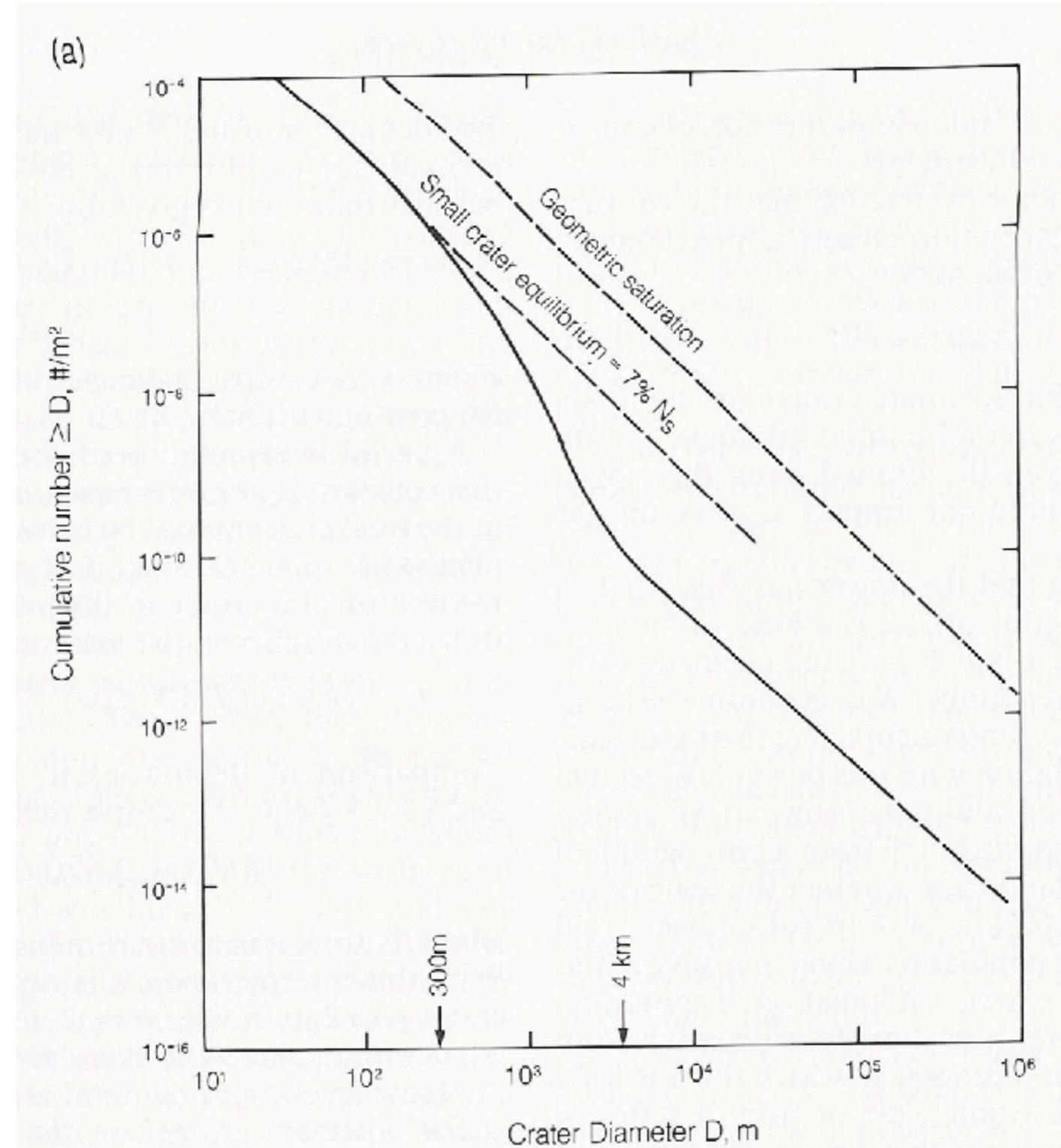
- Cumulative distribution becomes the same at all resolutions: you get the same answer even if you don't have a scale bar on the image.



Cumulative size-frequency distributions of craters on the continuous ejecta of Giordano Bruno and three other young craters for comparison. Frequencies of craters per unit area are plotted against crater diameters and used with chronology models to derive the age of the surface. If a medieval formation hypothesis were correct, then the crater-size distribution for Giordano Bruno would plot on an isochron (line of equal age) of 1 Ka (one thousand years). Instead, we see that the crater-size distribution points plot between 1 to 10 million years.

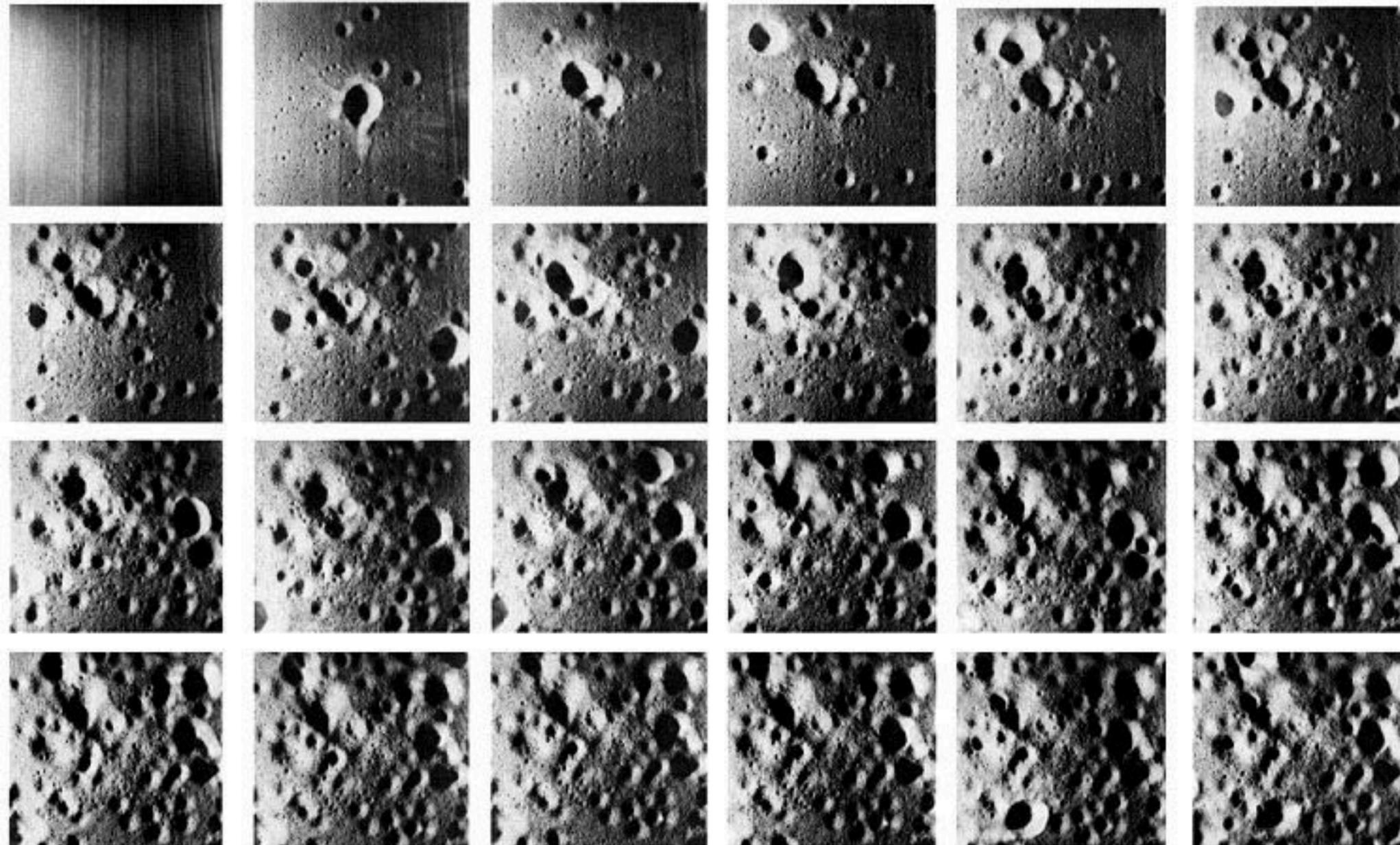
Lunar Crater Counts

- 3 distinct regions of the lunar crater cumulative distribution:
 - $D < 300\text{m}$: population is in equilibrium (each new crater destroys an older crater) and proportion to D^{-2}
 - $300\text{m} < D < 4\text{ km}$: $D^{-3.4}$
 - $D > 4\text{km}$: $D^{-1.8}$



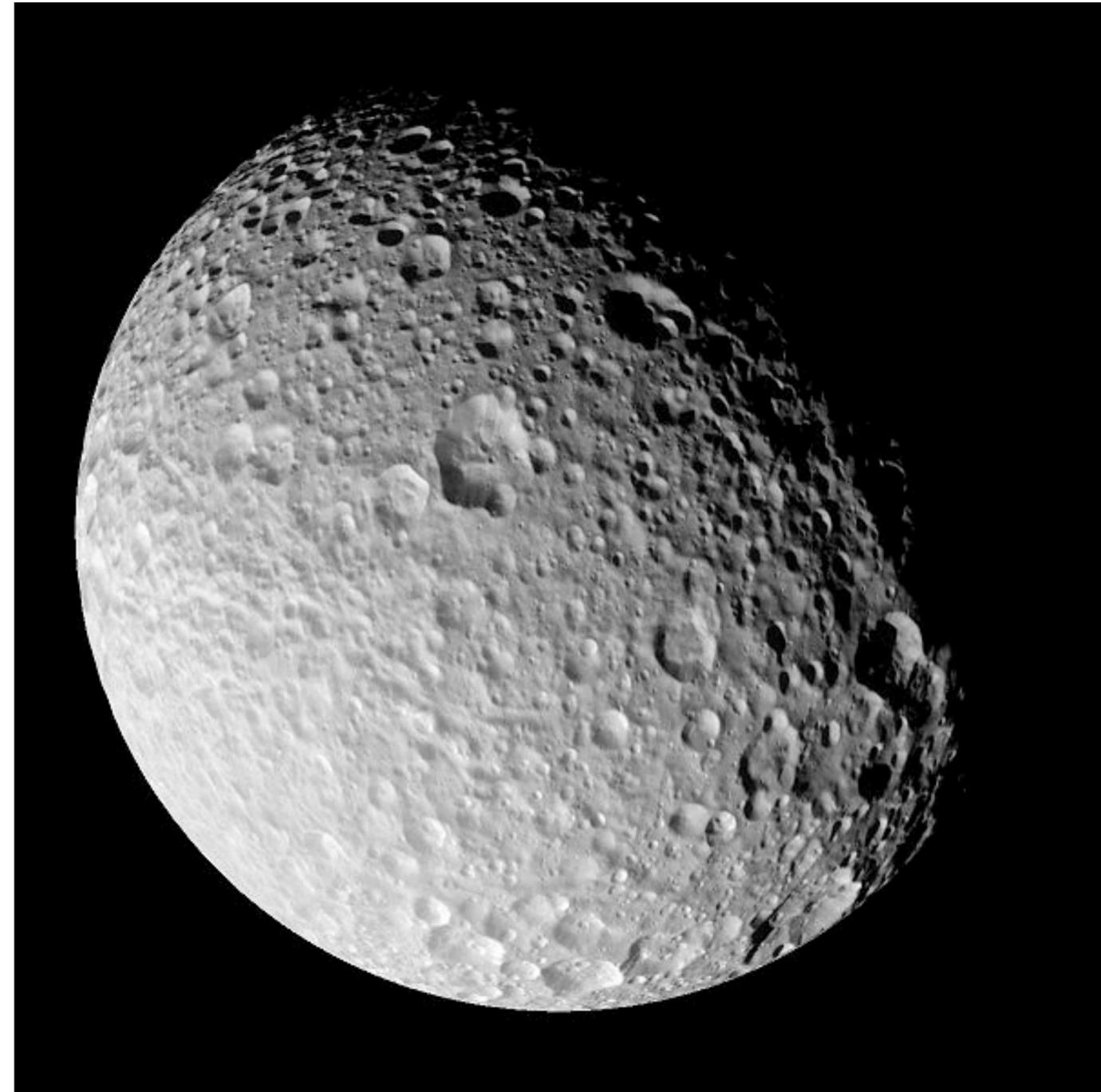
Equilibrium

- Equilibrium: on average, each new crater destroys 1 old crater (steady-state distribution)
- When a surface is in equilibrium no more age information is added
- Number of craters stops increasing
- One of the assumptions of crater dating is that the number of craters increases linearly over time



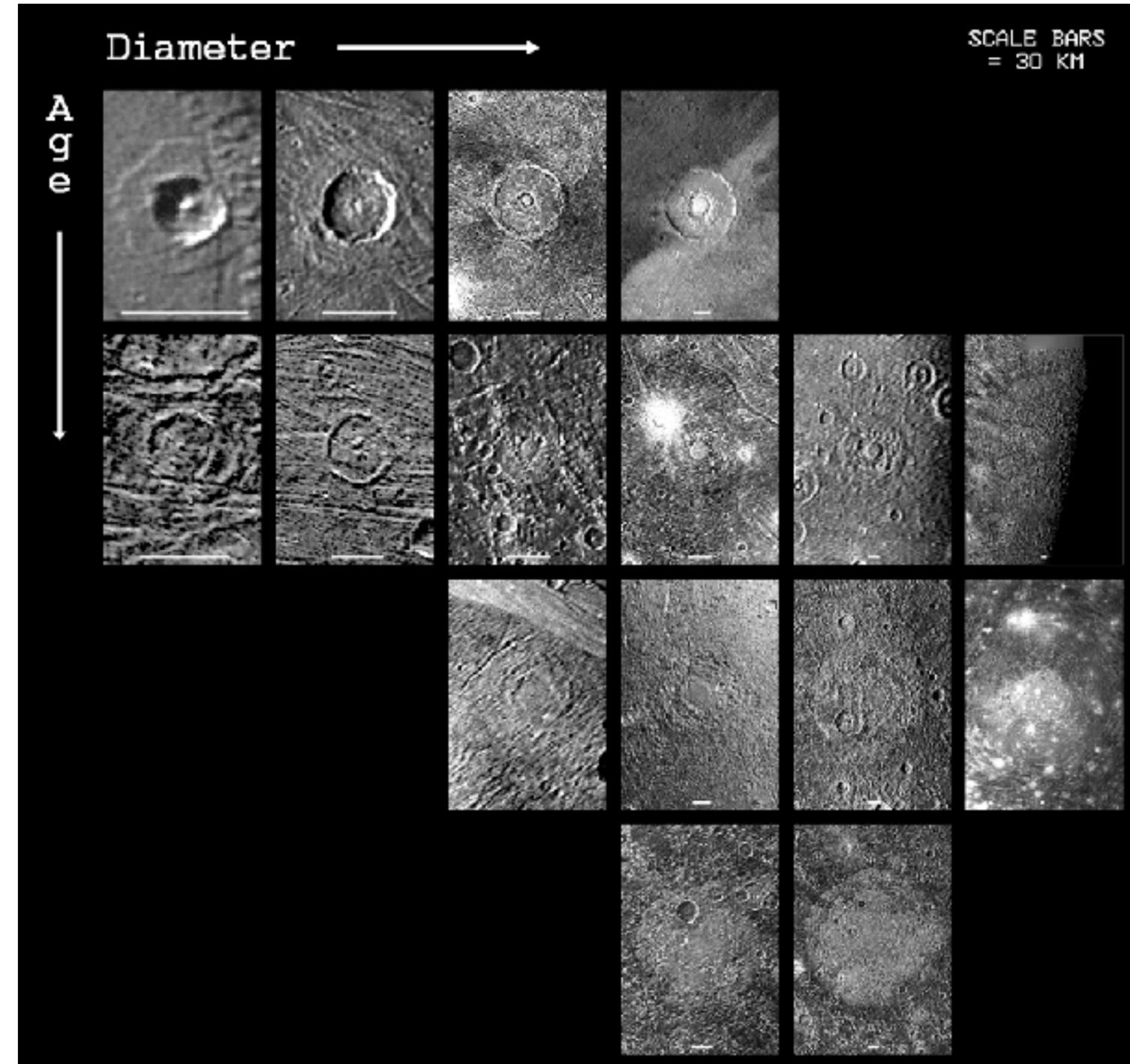
Geometric Saturation

- The theoretical limit where every patch of surface area has a crater on it
- No surface ever reaches the geometrical saturation limit, equilibrium is reached long beforehand
 - Equilibrium is a few percent of the geometric saturation limit
 - Mimas (an extreme case) reaches 13% of geometric saturation



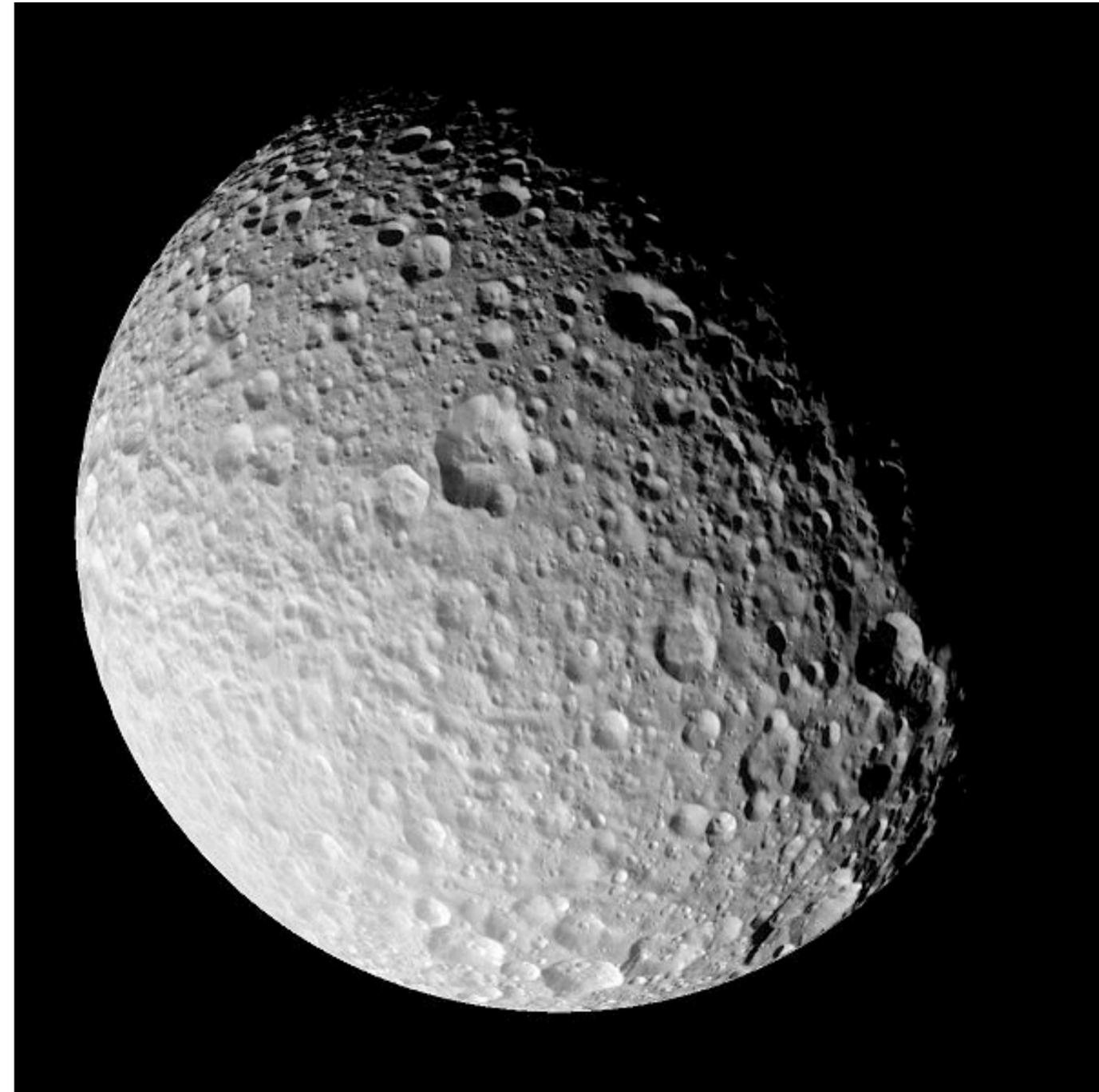
Cratering on an icy body

- Not as straightforward to do crater counts on icy bodies
- Viscous relaxation of ice can erase evidence of past cratering history
- Timescales for elastic deformation:
 - rock: Myrs
 - ice: minutes



Impactor Fluxes

- Crater population on surface is ultimately controlled by the flux of meteoroids hitting it
- Relationship between flux and crater population is not direct because final crater size is a function of:
 - velocity of impact
 - angle of impact
 - composition of target
 - composition of projectile
 - post-impact collapse
 - resurfacing
 - ...



Atmospheric Interactions

- An atmosphere limits the size of projectiles that can penetrate the atmosphere and reach the surface
- Thicker atmosphere means smaller asteroids slow down significantly before getting to the surface
- Earth: Rocky meteors must be at least 60cm in diameter to reach the surface and make a crater
- Mars: 0.9cm



Atmospheric Interactions

- Large impactors that travel at hypersonic speeds induce a shock in the gas ahead of them
- This subjects the leading face of the meteor to high average pressures
- If this pressure is greater than the tensile strength of the meteor it will fracture and disrupt



Stony Meteors and Earth

- 1-10 m: break up in atmosphere, fragments aerobraked, fall at terminal velocity, recovered in many pieces
- 10-100m: continue at high speed to deeper in atmosphere, disrupted by ram pressure of atmosphere
- >100m: reach surface after colliding with total amount of gas that is less than their own mass.
- Tunguska impactor was a stony bolide ~6m in diameter, disrupted ~5-10 km above the surface



Breakup and Crater Morphology

ATMOSPHERIC INTERACTIONS

209

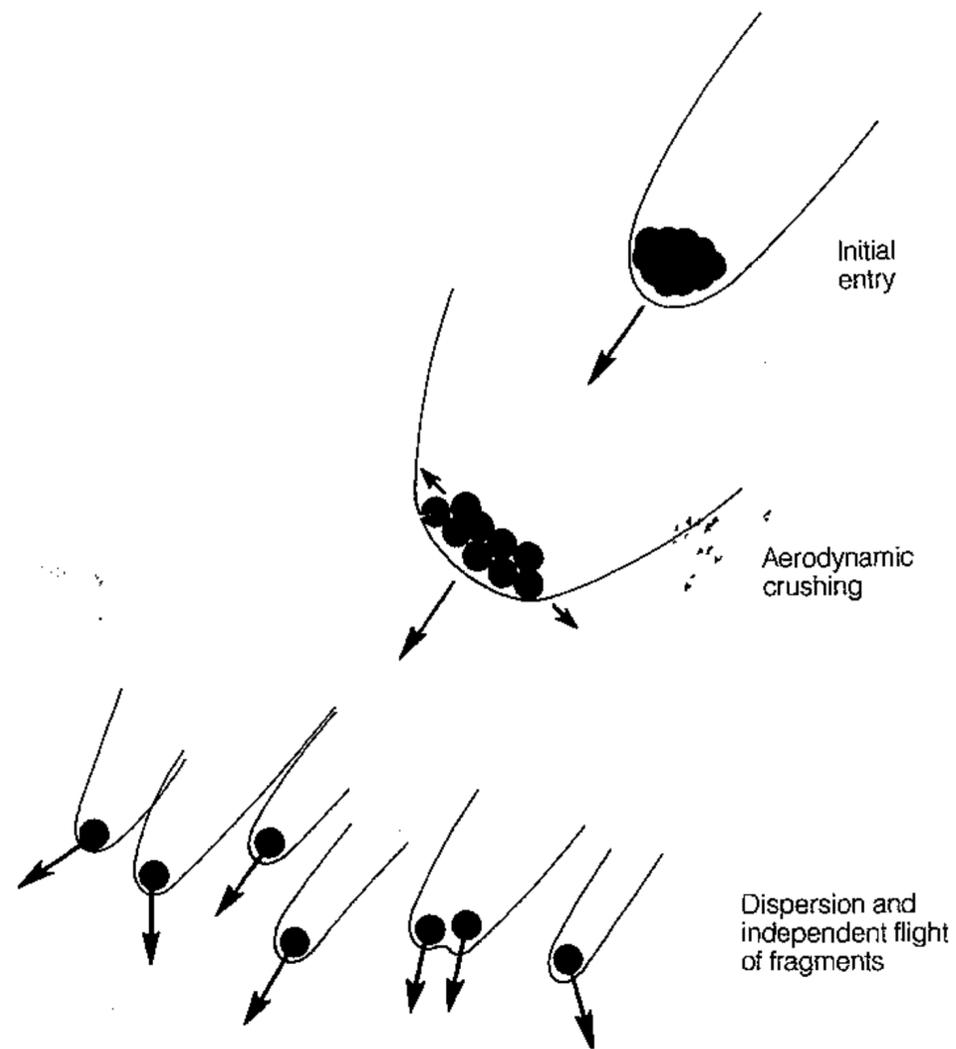
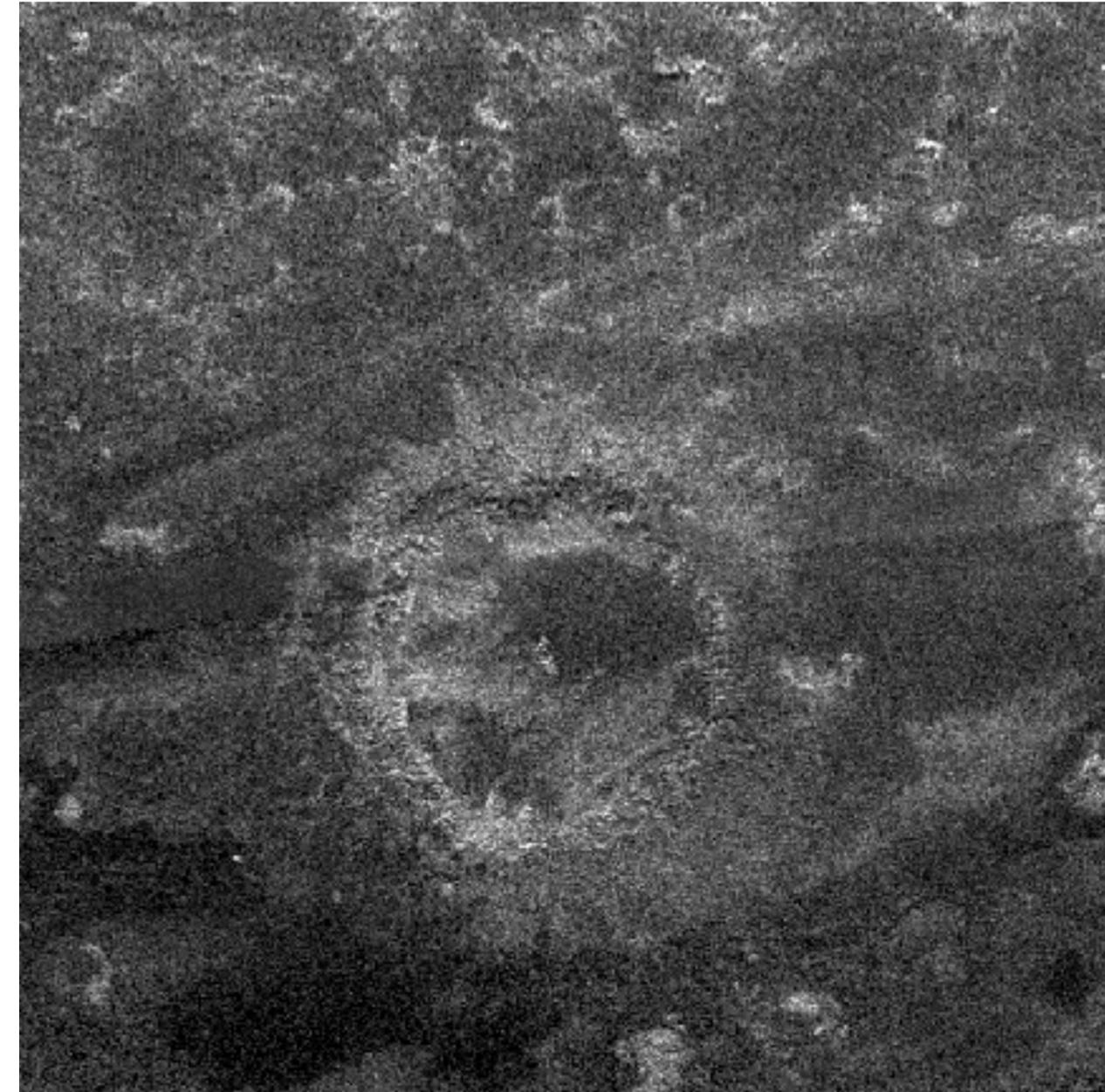


Fig. 11.3 Schematic illustration of the atmospheric entry and breakup of a large meteoroid. Depending upon the meteoroid's size it may strike the ground during any of the stages shown here. If it strikes as a crushed but closely grouped collection of fragments, it produces a single crater that may, however, have an anomalous morphology. If it strikes as a collection of separate fragments, a crater field is the result. Small meteoroids burn up entirely before they strike the ground.

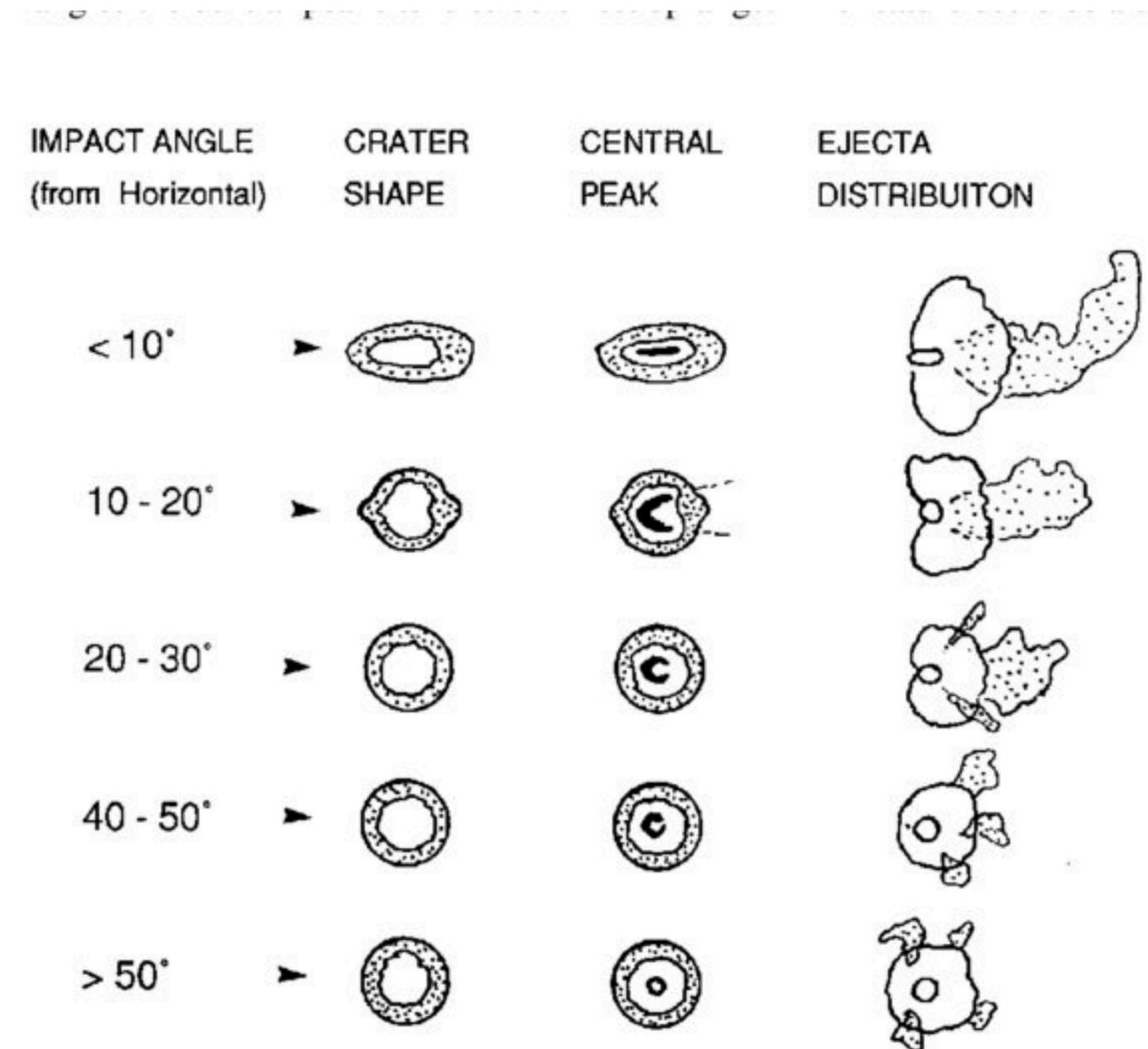
Breakup and Crater Morphology

- Craters resulting from impacts of clustered fragments following a breakup:
 - are more shallow-floored
 - have radial rays/spokes of ejecta in a preferential direction



Breakup and Crater Morphology

- Crater remains round except for most grazing impact angles
- Ejecta distribution more asymmetric for smaller impact angles



For next time

- Reading: de Pater & Lissaeuer Chaper 5, section 5.4.3